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LUNAR UTILIZATION

ABSTRACTS OF PAPERS PRESENTED AT A SPECIAL SESSION OF THE SEVENTH ANNUAL LUNAR SCIENCE CONFERENCE

16 MARCH 1976

SPECIAL SESSION ORGANIZED AND ABSTRACTS EDITED BY

DAVID R. CRISWELL
LUNAR SCIENCE INSTITUTE

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National Aeronautics and Space Administration
LYNDON B. JOHNSON SPACE CENTER
Houston, Texas

Universities Space Research Association
LUNAR SCIENCE INSTITUTE
Houston, Texas 77058

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David R. Criswell

The Lunar Science Institute

3303 NASA Road 1

Houston, Texas 77058

PREFACE

Initially, the motivations which compelled scientists, engineers and administrators to explore space with unmanned probes and then to thrust man into space sprang from the basic human drive to expand both mankind's knowledge and presence to new realms. The results have been spectacular. However, enormous efforts, even when compared to the scale of the United States and USSR economies, were and are required. Thus, the furthering of achievements in space labors against the competition from a myriad of other human activities.

Think for a moment of the experiment in which a rock is dropped into a deep pan of water. High speed photographs of the water, after impact, reveal in beautiful detail the creation of waves and a spray of droplets. Collapse of the temporary crater in the liquid drives one drop of the water vertically at high speed. The ejection pattern is beautiful and dynamic, but also temporary. This situation is analogous to the present systems of governmental support that intermittently divert tiny fractions of the energies of industrial societies into the high speed droplets (manned and unmanned spacecraft) which escape the earth. A fundamental change of the context by which space exploration is supported must occur to insure dynamically stable and expanding space programs. By analogy to the rock and the water, a way must be found by which the water level in the pan is raised rather than concentrating on how to throw the rock harder into the pan. Space industrialization appears to offer a means to raise the water level. What is needed is heavy industry in space involving material tonnages and energy expenditures on the scale of terrestrial economies and capable of servicing terrestrial markets, but also generating new economic systems in space. Real possibilities appear nearer at hand than one would have thought at the termination of the Apollo lunar missions.

Considerable interest has emerged over the last year to consider large scale operations in space. Detailed recent emphasis has focused on construction of very massive ($>10^6$ Kg) solar power stations in geosynchronous orbit, but other possibilities also exist. All such schemes labor against costs projected to be approximately 10^3 \$/Kg (in 1970\$'s) to transport material from the earth's surface to geosynchronous orbit and beyond using present shuttle technology. This enormous transport cost could be circumvented by obtaining the majority of working materials from supply bases on the moon at a cost estimated to be less than 20\$/Kg and possibly far cheaper. Assuming such materials could be processed in large scale facilities utilizing cheap and abundant solar energy ($>4000^{\circ}C$) and assuming production costs and materials throughputs comparable to terrestrial industrial experience then it is estimated that products, such as geosynchronous power stations could be fabricated in space at much lower costs than for deployment of the entire structures from earth.

Engineering experience gained during the Apollo program and the in-depth analysis of the returned lunar samples, photography, geophysical data and theoretical studies conducted by the lunar science community may have created a situation unique in the history of technological development. Expertise exists to plan realistically material supply operations on the lunar surface and the construction and operation of large facilities in deep space. Additionally, the lunar and planetary science community should be able, on the basis of its extensive research, to explore the feasibility of processing lunar regolith materials and their derivatives. These processes will likely be unique to the deep space environment; lunar scientists will also be able to suggest present and future strategies for locating lunar supply sources.

These abstracts are the result of a call to the community of lunar scientists to participate in a special session of the Seventh Annual Lunar Science Conference (15-19 March 1976). There were two primary objectives:

First - to start exploring whether or not our accumulating store of lunar knowledge could be exploited;

Second - to determine whether or not lunar utilization would be a subject of serious interest to the wide spectrum of scientists who participate in the lunar program.

The answer to the second question was clearly yes. A wide ranging collection of abstracts were submitted, in spite of only four weeks notification, and the session was attended by more than 200 of the conference participants. It is clear that the scientific community is interested in an expanded dialogue and meaningful research into the economic exploitation of space. It is also clear from the abstracts, presentations and questions during the session that the extensive lunar research and operations engineering have established major resources of knowledge and far more importantly - knowledgeable people - who are ready to tackle the next steps in determining whether or not realistic economic processes can be developed in near earth space using lunar materials. Abstracts were received on most of the "tickler" topics mentioned in the session announcements:

1. Direct elemental separation of lunar materials by focused sunlight (temperatures up to ≈4000°C) either on the lunar surface or in zero-g.
2. Techniques for in-situ separation of lunar materials by grain size, mineralogy, chemistry, etc.
3. Use of lunar soil in construction.
4. Advanced conceptual techniques for probing the lunar interior--both geophysical (seismic and electromagnetic) and direct (extremely deep drilling-physical limitations).

5. Schemes for ejection into and capture of lunar materials in deep space.
6. Remote sensing and survey schemes for the entire regolith yielding more comprehensive elemental, mineralogical and physical data than achievable during Apollo.
7. Unique factors in the petrology of lunar materials (ex. low oxygen fugacity) which could be advantageous (or not) in further processing.
8. Possible new schemes to shield large space structures against meteoroid and radiation hazards.
9. Relative advantages of locating supply operations in the mare, highlands, backside basins, on the ejecta blankets of large craters, etc.
10. Contamination of the lunar surface by industrial operations.
11. Construction of major components of a lunar supply operation by machines controlled from earth (i.e. unmanned) and requiring minimum initial capitalization.
12. Uses of lunar materials (processed or unprocessed) in low earth and geosynchronous orbits and in deep space operations.
13. Scientific experiments or measurements which would become possible following the on-set of large scale operations on the moon.
14. Potential health hazards working with lunar materials in bulk or continuously.
15. Power requirements for excavation operations on the lunar surface.
16. Fundamental factors determining the costs of large scale industrial operations on the moon.
17. Use of lunar materials in agriculture.

Clearly, many more topics must and will be considered. The important point is that it is now the appropriate time to start asking the question -- "What are some potential applications of my work which might apply to future operations on the moon or in space?" and many scientists and engineers did so. The work has just started.

Several comments regarding the organization of the abstracts volume are in order. The abstracts are arranged by topic following the program of the special session. Questions and answers following each presentation are included after the appropriate abstract. A very extensive index is included which serves both to access the volume, but also as a starting set of "key words" or concepts which can stimulate thoughts of new projects and connections. It is fully realized that many of the concepts presented are controversial and a few may be in error. However, they all contribute in an exceptionally valuable way to expanding our concepts of how to make the resources of the solar system work for mankind.

It is a pleasure to acknowledge the time and interest provided by Prof. R. M. Walker (Washington University) who served as a co-chairman and assisted me in selection of the speakers. In addition, I wish to sincerely thank the scientists and engineers who consented in the formative phase of organizing the session to provide presentations:

Mr. H. P. Davis
Johnson Space Center

Prof. D. W. Strangway
Univ. of Toronto

Dr. G. M. Heiken
Univ. of Calif. - LASL

Dr. K. A. Ehricke
Rockwell International

Dr. D. S. McKay
Johnson Space Center

Prof. G. O. Arrhenius
Univ. of Calif., S. D.

Dr. R. J. Williams
NASA Headquarters
Code SL

and to all others who submitted abstracts and participated in the session.

David R. Criswell
Associate Scientist
The Lunar Science Institute

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*Presentation at Special Session with question and answer session following the abstract. The speaker's name is underlined.

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INTRODUCTORY REMARKS - Robert M. Walker, Washington University, St. Louis, Missouri.

This is a special session on the utilization of lunar material and expertise for large-scale operations in space. I had somewhat mixed reactions frankly when first asked to co-chair this session and I think there will be mixed reactions on the part of many people at this conference. There may be a certain lack of enthusiasm for the subject and even perhaps a certain vague hostility in some cases, and I think this might stem from a variety of causes. First of all, it seems on the surface that it might be partially crackpot. We've all had encounters with the public where the public has asked us about using the Moon as a titanium mine or as a gold mine or things of this sort and had to explain that, "No, that's not what the purpose of lunar exploration was all about," but it gets kind of discouraging at times.

I think the very idea of mixing in practical considerations - and this is supposed to be a practical session - with pure scientific sessions is something that some people feel uncomfortable with in general. Of course, it might turn out if the subject is explored thoroughly that the Moon is not a very good resource base and, if that's true, raising the subject and then knocking it down may have lost one of the at least muted rationales for the program and for future explorations of the Moon. I don't believe that to be the case, but it might turn out that way. I'm sure at least one of the papers on this session is going to cause a visceral reaction on the part of some people as they realize that we're talking about their pure Moon and factories on the surface and creating atmospheres and pollution on that body. I think that will cause something of an emotional reaction. I feel nonetheless personally that the session is both advisable and timely. Most of you who know me - there are some in this room - consider me as sort of an inveterate optimist. In fact, in my more rational moments as I think about the future of the race, I am something of a pessimist. I feel it to be tremendously important for the race to extend itself beyond the boundaries of this planet. I think that's just a question of race survival. I am also convinced - and this reflects I suspect my generation in part - that there's a sort of inexorable growth of space technology. I remember looking at the television screen in the Lunar Receiving Laboratory as the Apollo 11 astronauts' capsule floated down and noting Jerry Wasserburg's awed remark at the time "By God, anything that is possible will be done." And I think, whether I think it's a good idea or not, it will be done. As I say, that represents a certain point of view or a certain generation.

I also think it's a fairly recognized phenomen that scientists by and large are not a particularly imaginative group in projecting growth of

INTRODUCTORY REMARKS -

Robert M. Walker

technology. There's a remark by - I forget it's Isaac Asimov or Arthur C. Clarke, who says that if a scientist tells you that something is impossible because it violates the laws of conservation of energy or one of the other great natural laws, believe him. That's okay, but if he tells you that something is impossible because it's difficult, don't believe him. He lacks the imagination to percêive the future. I think you know back in the 1950's there were precious few members of the scientific community that could perceive with any clarity the possibility of a lunar landing and lunar science conferences of this sort within their lifetime, or within their children's lifetime. So I think it is legitimate that we try to stretch the imagination and look towards the future. Now, much of the discussion in this session and some of the specific subjects will have been stimulated by the articles and lectures of G. K. O'Neill at Princeton, who discusses one particular scenario and one particular rationale for the development of habitable structures in space and what they might mean in practical terms for people on Earth. My own feeling is that I hope the discussion doesn't get too focused along that particular line, but to keep in mind the more general problem of utilizing the the Moon not only as a source of resources for large habitable structures at Lagrangian points, but also as a base for colonization. And there is, in fact, a paper on that subject in this session. I am personally looking forward to this session and to learning a great deal from people who have thought about these things and, quite frankly, I hope it will also serve as a catalyst for people who have a great deal of knowledge about the Moon, but have never thought about it in these terms.

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ECONOMIC
AND
RESEARCH POSSIBILITIES

SPACE INDUSTRIALIZATION - RATIONALES AND KEY TECHNOLOGIES,
David R. Criswell, Lunar Science Institute, Houston, Texas

Industrialization describes the broad range of activities by which man gathers and manipulates materials, using energy to produce the thousands of goods and devices necessary to the support of civilizations on earth. The continuing development of our skill in the manipulation of matter, and especially recently in our ability to make matter manipulate information (for example, computers and communication networks) is the physical foundation upon which advanced civilizations rest. In the broadest context "space industrialization" must also refer to as broad or eventually even a broader range of activities, which will aid the advancement of civilizations on the earth, but will also create a new extraterrestrial economy and culture in space. It is not reasonable at this point in time to attempt a detailed description of the myriad of specific products, devices, and human activities which are necessary to constitute a space industry. Rather, I wish to focus on three primary facets - matter, energy, and skill.

Figure 1 presents one way of grasping the role of matter in an industrial society. This is a qualitative distribution of cost of goods or end-use-material on a dollars ($) per kilogram basis (horizontal axis) versus the total output of goods (billions $) at a given $/Kg-value. It must be noted that this is a qualitative curve based on a general awareness of the features of the United States economy. Mathematically the curve represents the equation

$$y(x) = I/[(e^{\frac{1}{x}})x^2]$$

where x corresponds to $/Kg of end products and y corresponds to billions (10^9) $ of goods at a given $/Kg value. The equation is normalized to an economy with $I=1,000 \times 10^9$ $ annual output of goods. Services are not included. The form of the equation is not qualitatively correct for $x \lesssim 0.2$ $/Kg (left of "3") because water supplies, pollution control and other processes are present in the national economy which account for 10^{10} $/yr, but handle such vast quantities of materials that the $/Kg value is very low. The high $/Kg section (right of "2") of the curve (x> 10$/Kg) is in rough qualitative agreement with a similar analysis by Woodcock (1973). The numbers on the right side (i.e. 9.0, 0.4, 0.1, & 0.0025) indicate the total dollar value of goods with worth greater than 10, 50, 100 and 200 $/Kg respectively in 10^9 $.

Notice that most of the industrial goods are restricted to a very small range of $/Kg values. Probably 99% of the products output of a nation such as the U. S. is restricted to items selling for less than 10$/Kg. The majority

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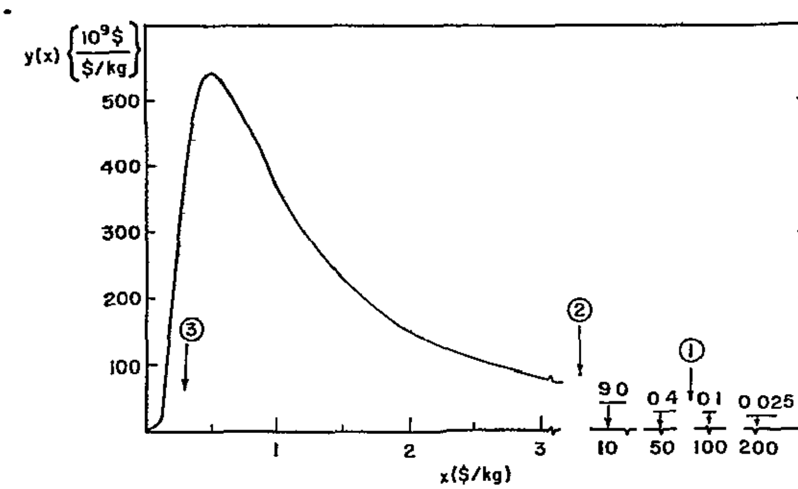
of goods (examples - food, cars, gasoline, houses) fall between 0.1$/Kg and 2$/Kg. The cost of final products will always be more than the weighted costs of the materials which compose them. Thus, if the raw materials which go into a product average 1$/Kg, then the potential market for the final product is restricted to the portion of figure 1 with x > 1$/Kg. This relates to the possibility of producing items in space. If the space shuttle is used to carry the raw materials into low earth orbit, then the raw materials acquire a value in excess of 50$/Kg and thus any products derived in low earth orbit from this material must be worth several times 50$/Kg to be saleable. However, the total value of goods with x > 50$/Kg is rather small when compared to the national economy or even compared to the cost of the shuttle program. Woodcock (1973) estimated the maximum possible market for such goods to be only a fraction of a billion (10^9) $/yr (i.e. the integral of the curve from x = 50 $/Kg to infinity). Even the most advanced schemes for earth to orbit transportation do not forecast launch costs less than 3 to 10 $/Kg by the year 2000. A lower limit on the cost for which material could conceivably be transported up to earth orbit is set by the cost of the energy required. Let us imagine a device exists which converts electrical energy with 100% efficiency into kinetic and potential energy and that 100% of the mass lifted is payload. Then, at a 25 mills/kilowatt-hour electrical rate, one would require approximately 30¢/Kg to eject material into orbit from the earth. Such an achievement would open a vast potential for space industrialization (all the area under the curve to the right of arrow #3). However, no such scheme has even been proposed at this point in time. However, several schemes have been suggested by which material could be ejected from the moon into deep space, or possibly to low earth orbit at low costs. Thus, lunar materials may be able to supply a large fraction of the raw materials necessary to create economically attractive products for use in space and on the earth.

Differential value of all goods in billions of dollars per dollar per kilogram value (B$/$Kg) versus the intrinsic unit value ($/Kg) of the goods in dollars per kilogram.

Figure 1



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Approximate cost analyses have been done on one of the processes involving the use of magnetically levitated buckets containing 10's kilogram slugs of lunar materials (O'Neill, 1974). The buckets are accelerated to escape velocity along a lunar track by linear induction motors. Upon reaching escape velocity, the material is kicked out and travels to a collection point in deep space. The bucket is decelerated and then circled to the return portion of the track and refilled for subsequent runs. It is conceivable that such a system could deliver lunar material to deep space for a few cents(10^{-2}\$) per kilogram following development of the "mature" launch and catching system. This low figure is made possible by the low escape velocity of the moon and the fact that the moon does not have an atmosphere. Only 1/22 of the energy is required to eject material from the moon as from the earth. Absence of a lunar atmosphere means that payloads traveling at lunar escape velocity (≈5700 Km/hour) do not require protection from the atmosphere such as being in a spacecraft. More than 70% of the ejection energy can go directly into the payload. Holbrow and Driggers (these abstracts) suggest the use of gas cannons (closed to the escape of the working gas) which could eject 10-100 kiloton payloads. This last approach offers the possibility of placing a small reaction control system and heat shield on these large payloads. The payloads could be targeted to perform a grazing reentry through the earth's upper atmosphere, undergo a subsequent apogee orbit correction and then be in earth orbit. This may be a manner by which to deliver inexpensively a source of raw materials (particularly oxygen) to low earth orbit.

If one or more of these schemes can be demonstrated and implemented, then a large fraction (next abstract) of the materials necessary for particular space industrialization efforts could be available and many of the economic processes encompassed by figure 1 would become conceivable. It should be remembered that one is after the raw materials at a low cost. The production machines can be far more expensive because such machines process many times their own mass of materials. One could generally afford to ship such processing machinery to orbit in the space shuttle.

Energy is a major factor which encourages us to consider space industrialization. Terrestrial energy needs have increased to such huge levels that serious consideration can be given to constructing large power stations in space which convert solar energy into microwave power and then beam microwaves to the earth for reconversion to terrestrial electricity. Investments of 100's billions of dollars would be required. Such enormous expenditures are comparable with the trillion (10^{12}\$) dollars of capital investment which U. S. utilities expect to make by the year 2000 (O'Neill 1975). In addition, the techniques for concentrating sunlight to run boilers (i.e. - for electrical turbines) or producing electricity by photoconversion insure a source of cheap, clean and inexhaustible energy for industrial operations in space. The basic resources of materials (lunar, asteroidal, etc.) and energy are abundant in the solar system for development of space industrialization. The critical resource, and the one which probably needs the greatest development, is the skill to utilize these inanimate resources.

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Several types of skills will be required. This special session concentrated on the technical aspects - how to get the materials, how to process the materials, implications of lunar or asteroidal supplies and many others. Technically, we appear able to rationally plan how to go again to the moon and start tapping its resources. This confidence is a direct legacy of the Apollo program. The immediate problem is to define an approach whereby such a program can gather support. NASA faces an extremely difficult problem in this respect. Table 1 is useful in understanding the difficulties.

In 1965 (Table 1a) NASA was the significant economic power in the United States with respect to research and development and also was very significant nationally with respect to cash flow or people employed (directly or through contracts). NASA ranked in terms of cash flow as the fourth largest industrial economic entity in the United States. In 1965 NASA could and did firmly guide the major research and development directions of the United States simply by buying the resources necessary to accomplish its appointed goals. This dominant approach is no longer possible or even conceivable in the future. A glance at Table 1b reveals the fundamental changes that have taken place in the national economy and NASA's status in this economy. In 1974 the total NASA cash flow of 3.3B$* placed it between the Borden Milk Company (New York) and Reynolds Tobacco or approximately 47½ on the scale of the Fortune 500. "Business Week" (28 June 1976) presented a detailed report of private research and development expenditures for 1975. Total private R & D expenditures in the U. S. exceeded 15B$ or approximately 5 times that available to NASA. The U. S. government expended approximately 9B$ on private contractors and 11B$ in government facilities for a total R & D expenditure of 35B$. Most of the priorities which dictate how these funds are spent are set by non-NASA considerations, such as environmental protection, engineering development, or consumer product development. For the private R & D approximately 3.5% went to basic science, 20% to applied science projects and 76.5% to development work. This is far from an unhealthy situation for NASA. The point is simply that NASA may not again buy dominance in the R & D market place. Rather, if NASA is to have a significant long term effect on the direction of the nation's technological development it must adopt new strategies. If NASA is to successfully guide the nation into a new capability of space industrialization, it must somehow make the potential gains and risks of industrial operations in space clear to the many private sectors and aid the interested entrepreneurial organizations in establishing real operations in space. Reiterating this point, present efforts by NASA to develop space industrialization in the new context of the space shuttle continue to attempt to buy industrial participation on contract to identify potential products, develop at NASA's expense possible specific industrial processes to manufacture the products and then publicize (i.e. sell concepts) these possible products to industry. The markets for very expensive goods (greater than 50$/Kg) are very limited and, therefore, there are very few entrepreneurs interested in the available possibilities. NASA must reverse the situation. It must be demonstrated that a cheap source of materials (less than 1$/Kg) can be available in space. Thus, a far larger fraction of the nation's entrepreneurs can reasonably consider initiating their operations in space at their own expense. Then NASA can provide the

*B$ = $10^9$$

TABLE 1a

1965 FORTUNE 500 INDUSTRIALS

Rank	Company	Gross Sales	Net	Employees
		(10^9\$)	(10^9\$)	(10^3 people)
1.	GM	17.0	1.7	661
2.	Standard Oil	10.8	1.1	147
3.	Ford Motor	9.7	0.51	337
	NASA	6.9	--	411*
4.	General Electric	4.9	0.24	262
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50.	Dow Chemical	1.1	0.09	33

* NASA SP-4012 (government and primary and subcontractors)

TABLE 1b

1974 FORTUNE 500 INDUSTRIALS

Rank	Company	Gross Sales	Net	Employees
		(10^9\$)	(10^9\$)	(10^3 people)
1.	Exxon	42.	3.1	133
2.	GM	31.5	0.95	734
---	-----	----	----	----
47.	Borden Milk (N.Y.)	3.3	.08	47
	NASA	3.3	---	120*
48.	Reynolds Tobacco	3.2	0.3	32

* NASA historical pocket statistics - January 1975, p. D-12
(government and primary and subcontractors)

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guidance on technical matters necessary to judge the reasonableness of the many schemes. In this manner, far larger economic resources can be attracted to space industrialization than can be provided by NASA.

For space industrialization the goal is the identification of realistic economic functions and their attendant risks rather than specific products. This point is more understandable by referring again to Figure 1. Suppose a source of materials is made available in low earth orbit at a cost of 1$/Kg. Figure 1 indicates that approximately 500B$ of goods might be considered for production from this material. However, the figure gives no aid in identifying what to make or the possible functions and associated costs to produce those goods. One very small, but useful, task would be to identify the products which compose this overall curve and how the curve and mix of goods changes with time. This would allow entrepreneurs to quickly grasp whether or not space production is of any conceivable interest to them for the goods with which they are familiar.

A general strategy should encompass these functions: (1) a clear theoretical exploration of space industrialization; (2) demonstration of the key gathering and processing functions in space; and (3) maximum involvement of private and governmental interests through all stages of these processes. This is a very different strategy than that involved in the development of Apollo or even the space shuttle. In those efforts there was a clear singular technical goal to be achieved. Consider each of the three strategy elements in turn.

(1) A major effort is needed to establish a new field of economics. "Physical Economics" seems an appropriate designator. In this field one considers in detail the many functions that control economic processes and asks the question - "What happens if this process(es) is conducted in space?" This is not simply an examination of the effect of zero-gravity easing the movement of large structures, or even the reconsideration of many industrial processes adapted to space. Rather, it is essentially a new field of study or inquiry which addresses man's demonstrated and projected ability to organize matter, energy, and his society in the three dimensional context of space. It is likely that a variety of new permanent institutions could be formed to address this question and be structured so as to continually involve private, academic and governmental organizations. This effort must be long term and very large, probably involving tens of thousands of people over the next 20 years. The product would be a clear understanding of new and realistic growth directions for industry and society into space, the identification of critical problems, and the creation of a new technocracy capable of managing space industry.

(2) There is an established pattern of government/industry cooperation in the development of new technological hardware. Technical feasibility is established by the government or under government funding and then industry establishes the economically viable industrial operations. Nuclear reactor and aircraft developments are prime examples. This pattern will persist in space industrialization. It seems reasonable that NASA should concentrate on

identifying and bringing to fruition the minimum number of key-systems which demonstrate that supplying material, energy, and initial working facilities to the new industrial activities in space is possible. A major problem and necessary planning constraint is the continuous identification and implementation of short term goals and pay-offs, rather than concentrating exclusively on super programs of 15 to 30 years duration, such as satellite solar power stations. An example of a shorter term goal could be a source of oxygen in earth orbit (derived from lunar materials) for partial refueling of space vehicles.

(3) The programs must actively involve the maximum number of people so as to shorten the learning period for the development of this new widespread expertise in space industrialization, to promote widespread support for the program and to develop the widest range of new concepts to be developed in space.

We face an interesting and exciting problem in the promotion of space industrialization. The expertise in science and engineering clearly exists to create near-earth and deep space habitats from lunar materials and eventually from the asteroidal material. Undoubtedly, the physical, engineering and economic factors of habitat construction and power station fabrication can be clearly defined and then judged as to their worth to us. The immediate and very challenging task is to organize the resources of society now external to the space program to support space industrialization as active participants.

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LONG-RANGE ASPECTS OF A LARGE SCALE SPACE PROGRAM

Hubert P. Davis, Manager, Future Programs Office, Johnson Space Center Houston, Texas 77058

The theme of the special session on Lunar Utilization is the exploration of the possibilities and means for exploiting the lunar materials for the benefit of mankind. Dr. Gerard K. O'Neill of Princeton University has proposed a bold plan to utilize the lunar resource for the production of power generating satellites to serve the energy needs of man's terrestrial society (Ref. 1). This paper describes the long-range need for materials in space for the power satellites rather than directly exploring the possibilities and payoffs of utilizing the lunar resource. A study at Johnson Space Center is characterizing a possible power satellite network and the supporting space transportation and habitation systems based upon materials of terrestrial origin. This paper describes one potential large scale market for lunar materials should the establishment of lunar mining facilities and space manufacturing facilities prove to be economically attractive when compared to the costs of launch services from the Earth.

BACKGROUND

Why are we interested in power satellites? This question must be addressed in two parts. First, our dominant energy source at present and for the last few generations has been petroleum and natural gas. The Statistical Abstract of the United States (Ref. 2) provides tabular data on energy production and consumption. In the past 10 years, the quantity of imported oil has increased by almost a factor of 3 (Fig. 1) and is expected to increase annually. The financial impact on the United States has increased in this same span of time by more than a factor of 13. The 1974 cash outflow for purchased foreign oil exceeded the total FY 1975 disbursements by the Department of Defense to their top ten contracting firms. Obviously, the unavoidable further growth of imported oil will constitute an increasingly severe monetary burden upon the United States.

Second, and of perhaps even greater significance than that of the dollar outlay is the projected availability of this vital resource in the quantities demanded. From whom will we obtain increasing quantities of petroleum? As a historic example, our ability to cope with the 1973 oil embargo was due, in part, to the relatively small percentage of our imports originating from the Arab states. Canada, Venezuela, Nigeria, and Iran supplied almost 2/3 of the 1973 imported petroleum. The government of Canada has since announced that their petroleum reserves

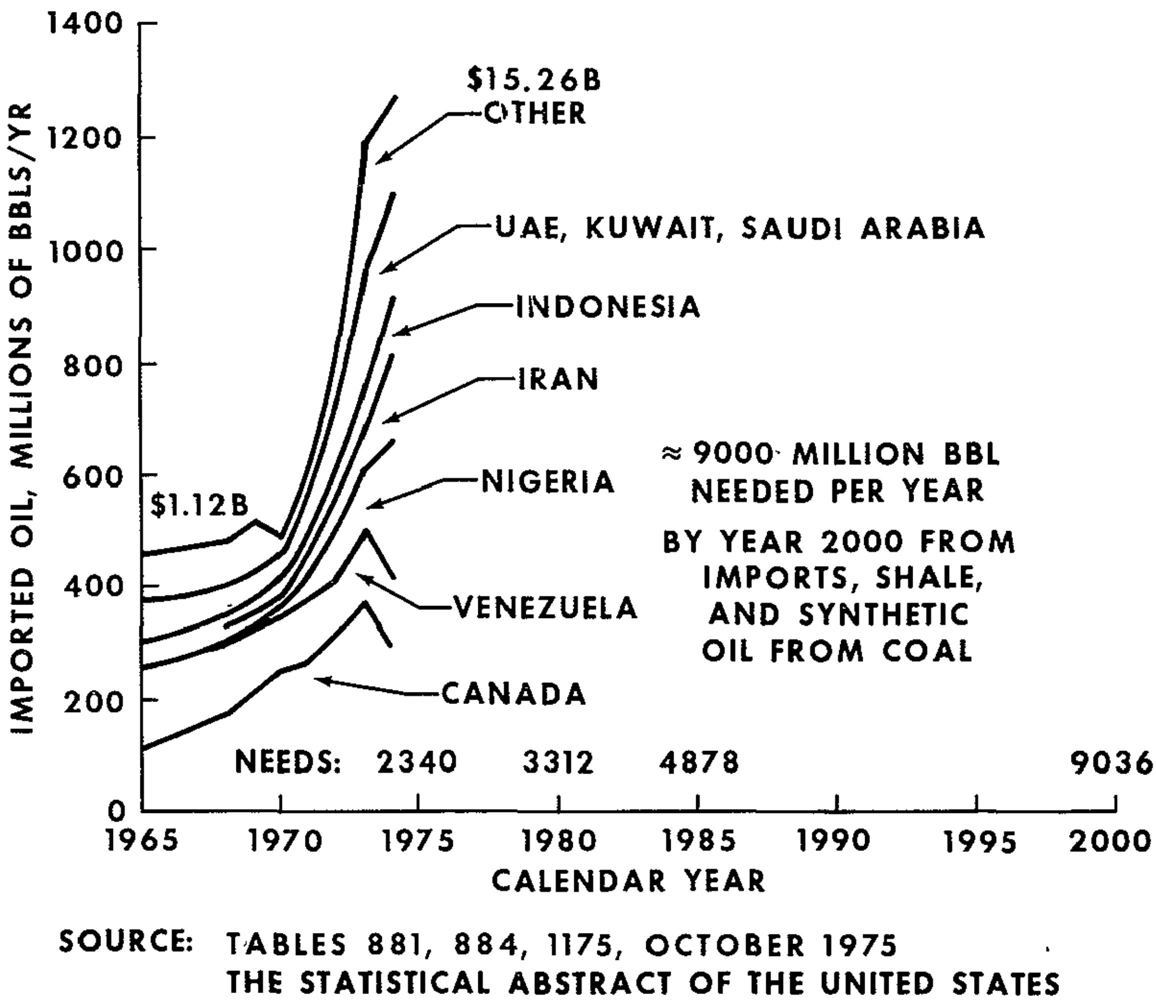


Figure 1. United States Oil Imports

will be dedicated, understandably, to the further development of the Canadian economy rather than to export. This policy was first reflected in thereduced quantity received from that nation in 1974. The U. S. technology of oil exploration and extraction is unmatched in the world and has permitted the U. S. to enjoy, in the past, the desired access to oil from less well developed nations. Hopefully, continued application of this unique technology and expertise will permit us to obtain for use by the United States a large fraction of the "new oil" yet to be discovered. Examination of these historical data and forecasts of comsumption does, however, lead to the disquieting thought that oil in the quantities needed by the U.S. beyond 1990 may not be available at any price. It is for this reason that we are on the leading edge of a major national program led by the Energy Research and

Development Administration (EDRA) to reduce the consumption of energy through conservation and to develop new energy sources, including solar energy in several forms.

SPACE POWER SATELLITE CONCEPT

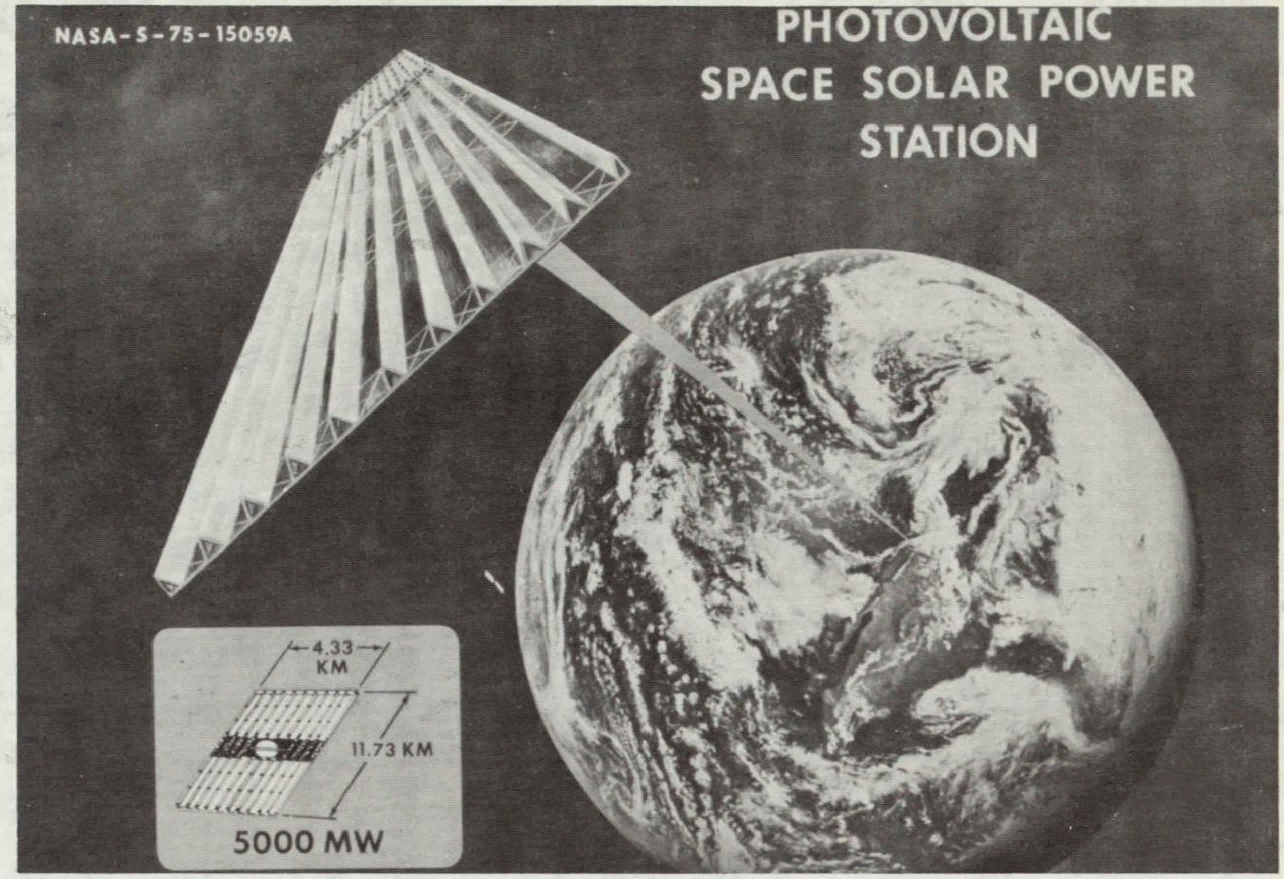
As first defined by Dr. Peter Glaser of A. D. Little, Inc. (Ref. 3) the space power satellite (SPS) concept is one attractive means of employing solar energy to provide the highest quality of energy--electrical energy into the existing national distribution network. The main premise of this proposal is the ability of the satellite to employ the nearly continuous, unattenuated sunlight in geosynchronous orbit (GEO) to produce "base load" electrical power. The terrestrial central solar electrical plant may find first application as a "peaking" system for daytime use. If it is to be utilized for base load power, the terrestrial solar plant requires large energy storage devices and additional plant capacity to sufficiently charge the storage system during sunlight hours, overcome the storage placement and extraction inefficiencies, and simultaneously provide the daytime base load power. The advantage of the satellite is therefore that it need produce only a fraction of the power required of the terrestrial solar electrical gnerating system to serve the same base load requirement. The issue is whether or not the costs of space transportation, construction and operations of this space-based solar power source may be accomplished within the inherent margin of advantage provided by its full time availability.

A photovoltaic space solar power station concept (Fig. 2) has been defined for NASA in an ongoing study of the economics of space solar power (Ref. 4). This satellite has an expanse of over 50 km^2 and a weight estimated to be over 22,000 kg. Obviously, structures of such a scale must be constructed in space. The similarity of the new operations necessary for space power satellite construction is compared on Figure 3 to activities which were necessary to open the conduit to the Alaskan North Slope. To date, no insurmountable barriers to space construction of the scale required have been identified. On the contrary, the absence of gravitational effects upon the orbiting construction site is expected to greatly enhance the productivity of both men and machines, perhaps several hundred-fold compared to terrestrial construction sites.

The SPS concept includes a microwave power transmission system whose feasibility was demonstrated in a Jet Propulsion Laboratory test in the summer of 1975. To simulate the microwave transmission of power from space to Earth (Fig. 4), the Venus Tracking Site antennae at Goldstone was used to illuminate a receiving antennae. This energy transport mode appears to be technically feasible as microwave to DC recption efficiencies above 80 percent for power levels of about 30 kW have been demonstrated.

SPACE TRANSPORTATION AND CONSTRUCTION

Studies have begun on the nature of LEO and GEO operations required to



to build the huge structures in space necessary to collect and convert solar energy to a more directly useful form of energy. Various operations and levels of assembly work of the space power stations components may be delegated to Earth, low orbit and geosynchronous orbit.

The JSC study is examining only Earth-originated materials for satellite power station construction and exploring both low and synchronous orbits as construction sites. The scope of construction and placement options are illustrated on Figure 5.

One option would involve the maximum prefabrication of the parts for the geosynchronous power satellite on Earth and the launch of tightly folded elements into LEO where they would be deployed and assembled into major power producing elements weighing from 200 to 20,000 tons. These elements would then be propelled by electric propulsion devices, drawing power from the payload itself, to the geosynchronous operating orbit. There these major power producing elements would be docked to one another and to the microwave

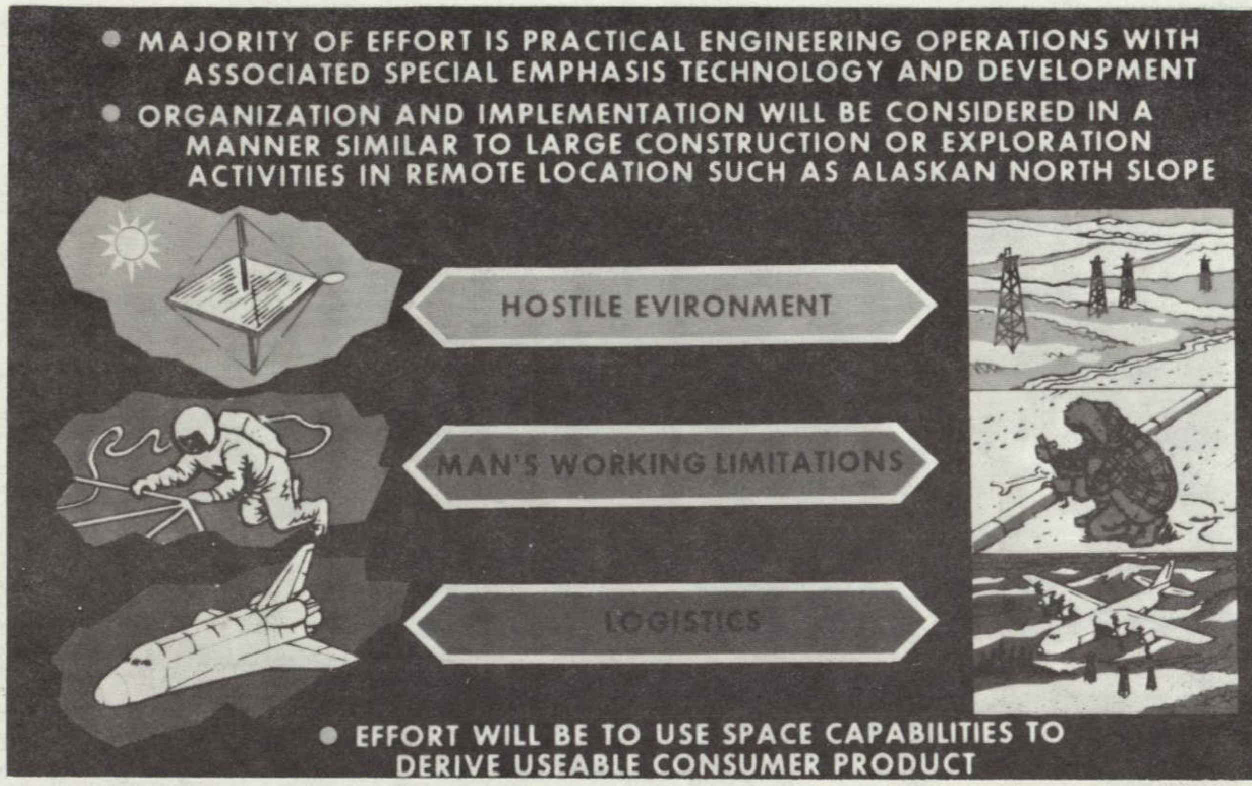


Figure 3. SPS Program Approach

- TRANSMITTER DIAMETER - 26 m
- RANGE (TRANSMITTER TO RECEIVER) - 1.5 km
- MICROWAVE FREQUENCY - 2388 MHz
- SYSTEM EFFICIENCY - 82.5%

Figure 4. Microwave Power Transmission Test

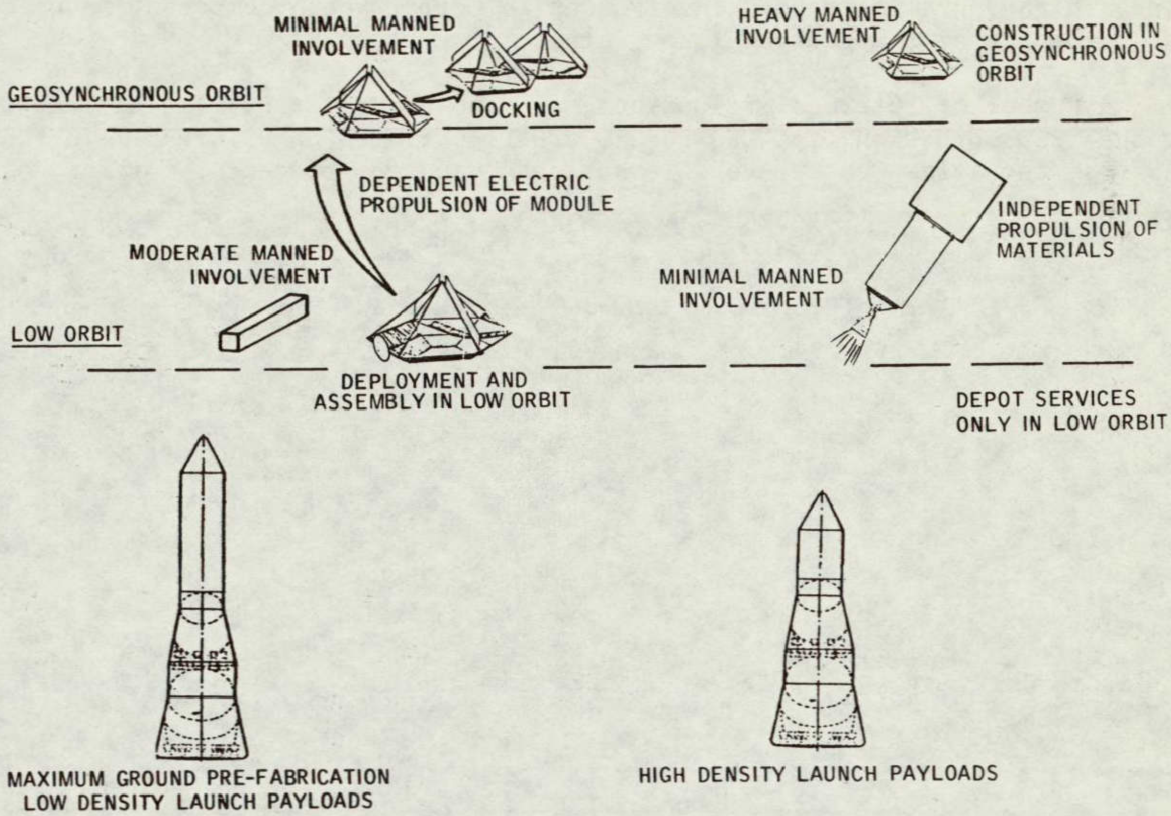


Figure 5. Scope of Construction and Placement Options

transmitting antenna to comprise the power station. This operating mode would involve a moderate degree of manned involvement in the deployment and assembly process of the ground prefabricated subassemblies in LEO. Manned involvement would be held to a minimum at GEO, as the primary operations to complete the power stations would be the the final docking and initialization. The penalty associated with this mode is that the folding of finished subassemblies can proceed only so far, yielding low density payloads. The launch vehicle must then accept very large payloads and be capable of safely housing the low density payloads through the exit from the atmosphere of the Earth.

The other operating mode option would involve launching of high density payloads, consisting of construction materials and piece parts, to LEO where they would be transferred to a propulsive vehicle for delivery to GEO. The only payload function performed in low orbit in this instance would be to offload the payload from the launch vehicle and onload it to the orbit transfer craft. The geosynchronous orbit station would then be utilized to manufacture structural and power generator elements from "strip stock" to construct the power satellite. This would, of course, entail a large facility and a high degree of manned involvement to perform both component manufacture and assembly at the geosynchronous orbit.

A number of intermediate options may also be utilized. The options for cargo transportation from LEO to GEO are illustrated on Figure 6. In the 1970's, the Atlas-Centaur vehicle has been used for placement for many of

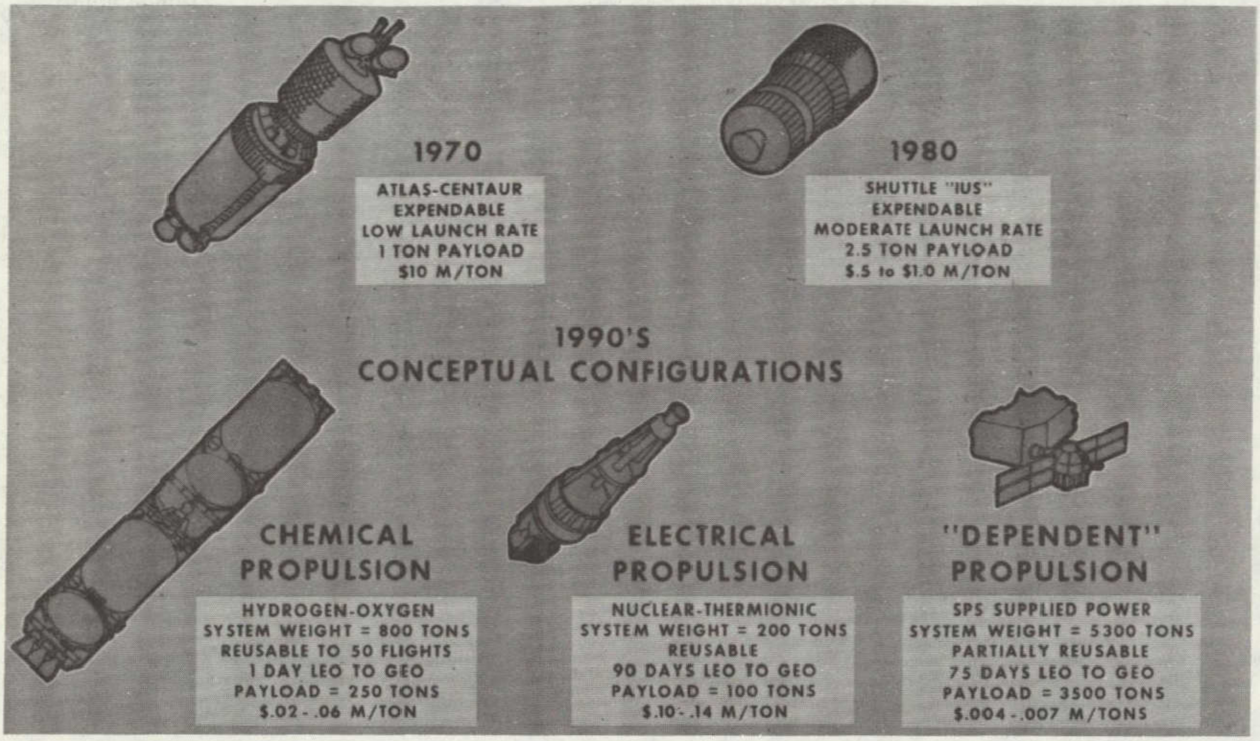


Figure 6. Cargo Transportation--LEO to GEO

the larger geostationary satellites such as Itelsat IV. The Atlas launch vehicle depends upon the Centaur upper stage to complete the insertion into low Earth orbit, hence the Centaur begins the synchronous transfer with less than a full load of propellants. In this operating mode, the Centaur has a payload capability of approximately 1 ton to GEO and results in a cost of LEO to GEO transportation of approximately 10 millions of dollars per ton. The Space Shuttle with the Interim Upper Stage (IUS), to be flown beginning in the 1980 time frame, will improve upon these capabilities. The Interim Upper Stage is a solid propellant two stage expendable rocket vehicle that will be flown at a moderate launch rate of perhaps 20 flights per year. The payload capability is approximately 2.5 tons to geosynchronous equatorial orbit and results in an estimated cost of LEO to GEO transportation of 1/2 to 1 millions of dollars per ton, an improvement by a factor of 10 to 20 over the current Atlas-Centaur. The increased capability and projected lower specific launch costs of the Space Shuttle compared to previous launch vehicles offers promise that the portion of the development of satellite power technology which can only be done in space may be economically conducted and that further development of space transportation technology and systems can achieve the necessary reduction in space flight costs for the operational power satellites placement at the GEO from the Earth's surface.

The time frame of interest for the space power satellite is the 1990's and beyond, and the number of options available to provide this orbit transfer function is much greater and their performance/cost parameters are less well understood. Figure 6 illustrates three of the possible options. The vehicle at the lower left indicates a chemical propulsion system conceptually similar to the Centaur, except that it is used as a two stage vehicle and is much larger in size. This vehicle is presumed to be reusable up to 50 flights, with refueling occuring in LEO upon its return from GEO. The round trip transfer time for resue in low orbit is less than 1 day. The chemical propulsion system shown has a payload yield in GEO of approximately 250 tons and results in an estimated cost of LEO to GEO transportation of between 20 and 60 thousands of dollars per ton. A promising concept suggested by the Jet Propulsion Laboratory is the electrical propulsion scheme utilizing a nuclear reactor power source for energy supply of the electric propulsion thrusters. The start burn weight shown is approximately 200 tons. The payload yield is approximately 100 tons, an improvement of more than 50 percent in payload yield, but the preliminary cost estimates are increased to 100 to 140 thousands of dollars per ton because of the higher cost of the nuclear reactor system. The Boeing Company, in a study funded by NASA, (Ref. 5) encolved an innovative scheme for the transportation of satellite power station elements. The "dependent" propulsion system utilizes the payload itself built to a sufficient level of assembly to supply power to the electrical thrust system for the outbound transportation. The indicated system weight is 5300 tons. It is partly resuable because the propellant tankage is left behind in the high orbit but the thrusters, power conditioners, and guidance systems are returned to low orbit for reuse. It has a 75 day trip time from LEO to GEO and yields a payload of approximately 3500 tons; a quite favorable payload fraction. The transportation cost of this system must be considered more speculative than the other alternatives, but now appears to be in the vicinity of 4 to 7 thousands of dollars per ton.

Due to current uncertainties of the cost of the orbit transfer, the question of where the assembly of power satellites should take place, low Earth orbit or geosynchronous orbit, must remain open. The basic operational feasibility of assembling a large structural element representative of the space power station needs has been studied in detail by the Martin Company in Denver (Ref. 6). The device chosen for this study was the substructure of the 1 kilometer diameter microwave transmitting antenna (Fig. 7) as defined by a previous study based upon the satellite design concept suggested by Dr. Glaser. This study revealed that the Space Shuttle could conduct repetitive flights to deliver to orbit truss members and orbital assembly tools known as "mobile assemblers" that would permit the assembly of this structure in a period of approximately 1 year. The "mobile assemblers" are similar in concept to the Shuttle remote manipulator system being provided to the Space Shuttle program by the Canadian government.

SPS PROGRAM ASPECTS

The question of how many satellites would be produced is basically one relating to the market economics. If studies during the next 3 to 5 years show power from space to be produced at only a marginally attractive rate, the program may not receive a go-ahead. If, however, in its time frame, it appears to be attractive in comparison with the other alternative means of supplying electrical power, it may be given a go-ahead to a pilot plant stage. Subsequent market penetration of operational power satellites will depend almost entirely on how attractive the economics and environmental effects of power from space prove out relative to the competitive power systems. One possible scenario calls for the power satellite concept capturing approximately 50 percent of the new and replacement U. S. power plant installations beginning in about 2010. In that situation, the number of satellites to be constructed in space would exceed 110 by the year 2024 (Fig. 8). It is this illustrative implementation schedule that might be utilized to explore the applicability of lunar materials to the construction of a satellite network. This task has not been accomplished by the JSC study or is it being currently planned.

The distribution of elemental materials required to fulfill the scenario of over 110 power satellites by 2024 based upon the materials distribution reported by ECON, Inc. (Ref. 4) is illustrated on Figure 9. These data may be useful in envisioning the potential scale of a lunar materials plant. Note that large amounts of aluminum, silicon, and oxygen are needed. Most of the oxygen, all of the hydrogen and argon are used to achieve the low Earth to geosynchronous transfer and would be a different set of numbers for lunar surface to geosynchronous orbit transfer.

The Earth resides in a quite deep "gravity bucket" and to overcome the Earth's gravitational field and achieve low Earth orbit poses a large transportation task. The alternative of supplying materials from the lunar surface does appear, if viewed solely on an energy basis, to be very a attractive. Figure 10 illustrates that approximately 4.3 kilometers per second are required to be added to achieve the Earth geosynchronous orbit from the surface of the moon. Over 13 kilometers per second are necessary to be added to acquire geosynchronous orbit from the surface of the Earth. There is an inherent advantage from a transportation view point of utilizing lunar surface materials. The problem resides in the "front end" costs associated with developing the mining, and manufacturing infrastructure necessary to transform the regolith material into useful metal and ceramics and then into finished satellite power stations. Such an analysis would be interesting and perhaps it will be conducted in the months to come.

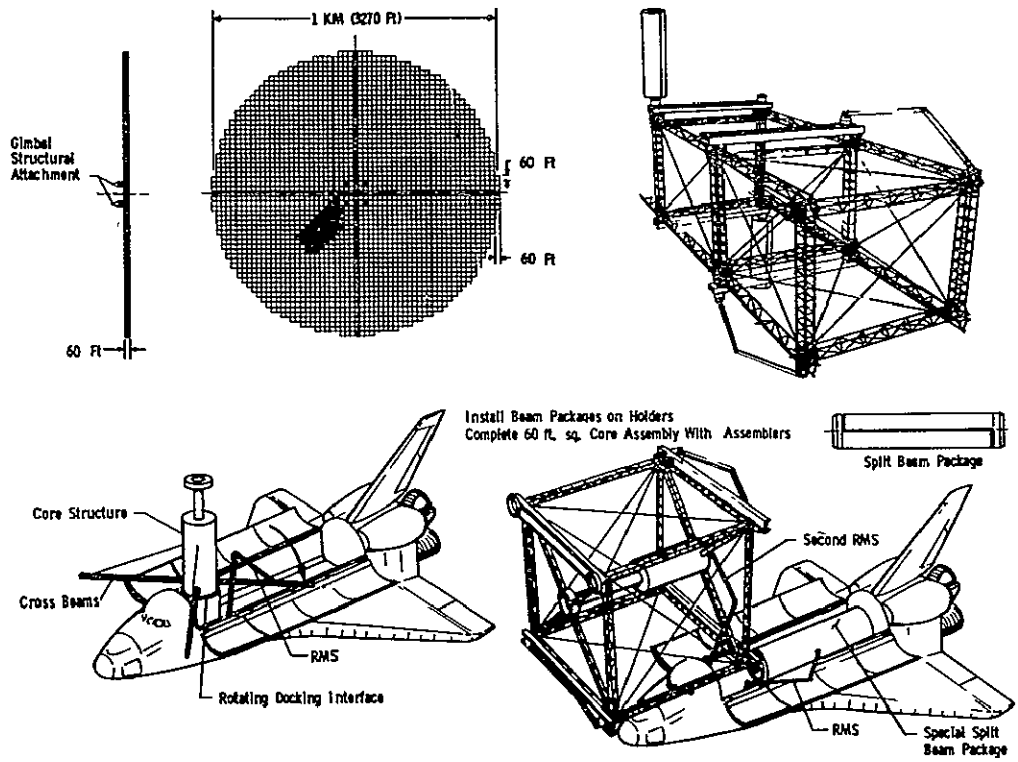


Figure 7. Space Construction of Microwave Antenna

CONCLUDING COMMENTS

In conclusion, the space power satellite program now appears to be one of several very attractive alternative energy sources that must be thoroughly reviewed before the fossil fuel supplies begin to run out. The space power satellite program poses a massive Earth to low Earth orbit transportation task. This task does appear to be both technically and economically feasible, utilizing current and near term state-of-the-art for the large launch vehicles required. The low Earth orbit to geosynchronous orbit transportation option choice interacts with the choice of the construction site and is a complex problem marked by having many options for the transportation system. In the construction arena, more study and development are required to define the techniques and machines to economically achieve the large scale construction in orbit. Decisions need to be reached relative to how much actual manufacturing effort is conducted on Earth and how much is reserved to the space environment and what the productivity of personnel and equipment can be expected in this operating regime. The NASA baseline approach is to utilize materials exclusively from the Earth. The two options

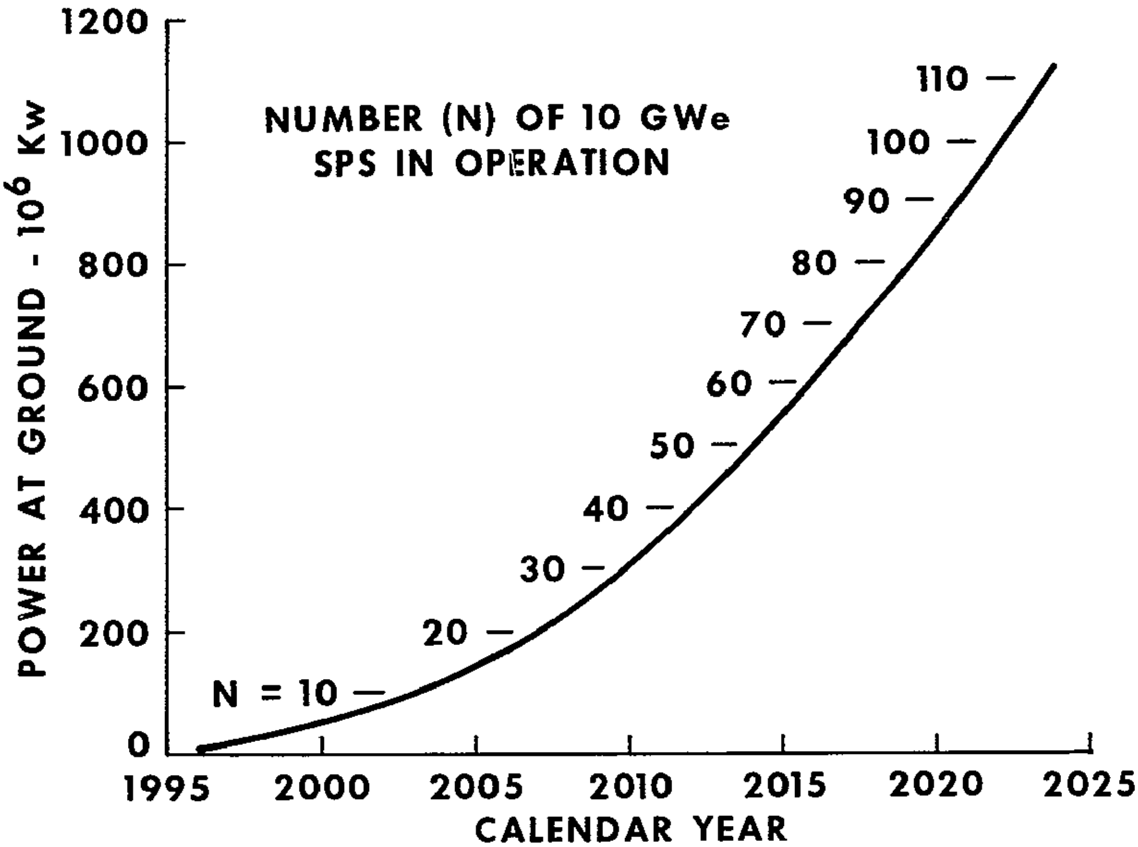


Figure 8. Illustrative SPS Program Scenario

for construction would be the low Earth orbit and geosynchronous Earth orbit. The lunar surface material source is available, as Dr. Gerard K. O'Neill has pointed out in his proposal, to support space power satellite construction at the L-5 Lagrangian libration point in a large space colony. Alternatively, lunar surface materials could be used with the bulk of the construction activity taking place on the surface of the moon or perhaps in orbit about the moon.

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1. Dr. Gerard K. O'Neill, "The Colonization of Space," Physics Today, September 1974.

2. The Statistical Abstract of the United States, October 1975.

3. Dr. Peter Glaser, "The Satellite Solar Power Station: An Option for Energy Production on Earth," Arthur D. Little, Inc., April 24, 1975.

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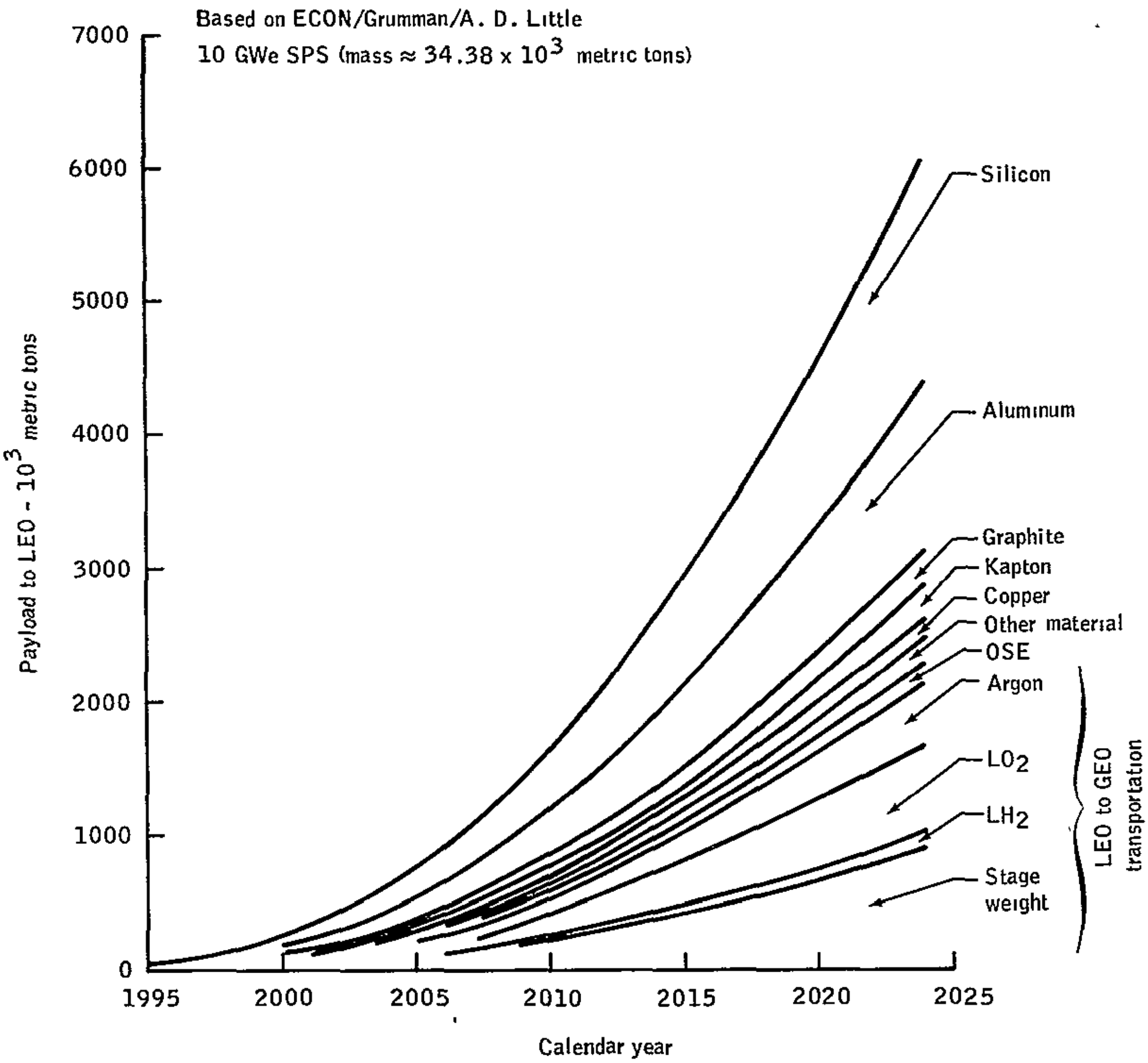

Figure 9. SPS Program LEO Mass Requirements

4. ECON, Inc., "Space Based Solar Power Conversion and Delivery System Study," Contract NAS 8-31308.

5. Boeing Aerospace Company, "Payload Utilization of SEPS (PLUS)," Contract NAS 8-31444.

6. Martin Marietta Corporation, "Orbital Assembly and Maintenance Study," Contract NAS 9-14319.

MISSION		KM/SEC	
EARTH →	LOW EARTH ORBIT	8.99	13.23 km/sec
LOW EARTH ORBIT →	GEOSYNCHRONOUS ORBIT	4.24	
LOW EARTH ORBIT →	EARTH (USING SHUTTLE TPS)	0.09	
LOW EARTH ORBIT →	LUNAR POLAR ORBIT	4.08	
LOW EARTH ORBIT →	L-5	4.08	
LUNAR POLAR ORBIT →	LUNAR SURFACE	2.19	
LUNAR SURFACE →	LUNAR POLAR ORBIT	1.86	4.29 km/sec
LUNAR POLAR ORBIT →	L-5	0.69	
L-5 →	GEOSYNCHRONOUS ORBIT	1.74	

Figure 10. Transportation Options Delta-Velocity Requirements

DISCUSSION (Davis Paper)

SPEAKER 1: Could you say something about the economic rationale for producing this type of power system? Why wouldn't you spread these things out in the Arizona desert? Wouldn't it be cheaper?

DAVIS: Well, the solar terrestrial central powerplant, of course, is a very attractive option. It's one that's being studied by ERDA today and the thing that you're working against here is the fact that in geosynchronous orbit you have 6 to 15 times the solar insolation available that's available on good locations such as the Tuscon area, Saudia Arabia on Earth. This is a consequence of the day-night cycle and the attenuation of the atmosphere. So what you're trying to see is whether or not within that factor of 6 to 15 you can pay for the incremental costs of the space transportation and assembly. Does that respond to your question, sir?

G. ARRHENIUS: The atmospheric attenuation is only 20 percent, isn't it?

DAVIS: Well, someone else will have to answer that. I've seen the numbers but I don't have immediate recall of them. There is a very elegant buildup in the AIAA assessment of solar power on where this factor 6 to 15 comes from. You might wish to review that.

(Editor: The factors of day/night (½), cosine (0.707) and attenutation in the atmosphere are multiplicative and give a minimum diurnal loss of $[(\frac{1}{2})(.7)(.5)]^{-1} \approx 6$).

SPEAKER 2: I wonder if you have any feel for the best way to transport large systems assembled in low-Earth orbit to geosynchronous orbit and perhaps you could specifically comment on the use of carbon arc resistor jets with hydrogen propellant.

DAVIS: I certainly don't have any idea at all of what's best. I have an idea today of what some of the options are and the carbon arc, hydrogen arc jet is one of the options I was reviewing just before I came here today but it's only one of a number. I have no idea of what's best at this moment.

SPEAKER 3: No matter how small the attenuation of the microwave beam coming down is, it's still on the order of a couple of gigawatts total power, where you're losing a couple percent of that. Do you have any idea what the environmental consequences - or is anybody looking into the environmental consequences of attenuation in the atmosphere?

DISCUSSION (Davis Paper)

DAVIS: Yes, there have been some reviews made of that and that as it happens is the criterion that sizes the relationship between the spaceborne and the groundborne antennas: The desire to keep the beam density as it passes through the ionosphere within the safe boundaries - if memory serves - something like 35 milliwatts per square centimeter. So there is a great deal of attention being paid to the environmental effects of it. As a matter of fact, the environmental effects of the space power option is one of the features that makes it very attractive. It's one of the few occasions in which you beat Carnot cycle looses in that the losses consequent to the power generation are dumped not into the biosphere but into deep space by space radiators. You have no particulate effluents as you will in the case of coal and the heat generated by the rectenna is now estimated to be less that the heat density over any populated city area. The ground beneath is shielded by the receiving antenna itself and should be usable for agricultural purposes. So we think it's environmentally an attractive system. For that reason we are encouraging environmental trades between this and the other options.

SPEAKER 4: What happens if you're not quite pointing this thing in the right direction?

DAVIS: There is a reverse conjugate control scheme for the phased array antenna that has its transmitter for the control signal located in the middle of the receiving antenna on the ground and, should the beam drift for mechanical reasons or others, the beam goes incoherent and the energy density dissipates very rapidly to a communication signal level type of intensity. So we think it's got fail-safe control features.

SPEAKER 4: Well, I'm thinking in terms of the emergency cooling systems for nuclear and the concerns about those.

DAVIS: I'm not aware of any equivalent to the nuclear reactor "guillotine failure mode" present in the satellite power station.

SPEAKER 4: It doesn't kill any people or anything like that?

DAVIS: The phased array becomes incoherent and the energy density of this beam, although it's perhaps a 12- or 14-million-kilowatt beam, becomes incoherent with the loss of the pilot signal that's generated at the ground receiving antenna. As a consequence, the energy is spread over such a vast area that it is no longer of any concern. In addition, I understand that there is no easy way to convert this microwave power beam into a weapon.

SPEAKER 5: What if you fly through the beam in an airplane or something like that? Do you get zapped?

DISCUSSION (Davis Paper)

DAVIS: If it's a metal airplane, the answer is pretty clearly no. You're protected by the Faraday cage. I don't know about the fabric and wood airplanes just yet and that's one of the things we'd have to run some tests on. There is concern about birds as well, and there's two very distinctly contrasting opinions relative to birds and the influence of the current radar type microwaves upon them. One school of thought is that it attracts them because it keeps their body warm and they like it and they cluster around it. The other is that it can kill them. My friend who runs the microwave reception test at JPL has assured me that he has never ever found a dead bird beneath their receiving antenna, but he quickly added, "But, of course, we have coyotes."

SOME POTENTIAL IMPACTS OF LUNAR OXYGEN AVAILABILITY ON NEAR-EARTH SPACE TRANSPORTATION; Gerald W. Driggers, Southern Research Institute, Birmingham, Alabama.

The processing of lunar resources in Earth orbit for purposes of obtaining materials for manufacturing has been suggested by O'Neill and others (1,2). A by-product of such processing should be rather copious quantities of oxygen. This observation has led to some thought and analysis concerning the alleviation of requirements for Earth-to-orbit transportation of propellant for orbital operations (3).

The most immediate application of lunar oxygen available in Earth orbit would be orbit-to-orbit or "tug" type transportation. Three cases have been investigated in this context to quantify savings in total Earth launch mass. The ideal mission velocity was determined by the basic requirements to transport mass from low Earth orbit (LEO) to Lagrangian point 4 (L4) or L5 or synchronous equatorial (sync. eq.) orbit. Empty vehicle return was assumed.

The three cases investigated were: (1) O_2 stockpile at L4/L5; (b) O_2 stockpile in synchronous equatorial orbit; and (c) O_2 stockpile in LEO and L4/L5 or sync. eq. orbits. The possibilities are shown schematically in Figure 1. A low cost (probably low thrust) system to place the O_2 in LEO is assumed, so no H_2 fuel is included in Earth-to-orbit mass computations for transport of O_2 to LEO from sync. eq. The results of the analysis performed relative to the sync. eq. mission are shown in Figure 2. The chemical propulsion requirements are compared to an idealized nuclear stage of the NERVA class. The impacts on Earth launch requirements are dramatic.

Another space transportation area may also be affected by the availability of lunar oxygen in LEO. Although it is not immediately obvious, an O_2 stockpile in LEO can make a new and unorthodox Earth-to-orbit operational mode feasible. The ultimate effect is about a four-to-one reduction in system gross lift-off weight (GLOW) for a payload of some 227 metric tons (500,000 pounds).

The operational mode referred to here has been termed suborbital rendezvous (SOR) by the author. The concept is basically to obtain some of the energy required to reach orbit from Earth supplied propellants and the remainder from LEO lunar oxygen. Two vehicles are involved: the Earth launch element (ELE) and the orbital element (OE). The ELE carries all fuel required and some O_2. The OE supplies O_2 and high efficiency engines. Initial velocity (say through 19,000 ft/sec ideal) is supplied solely by the ELE launch. At a point where the vehicle trajectory is appropriately oriented (perhaps parallel

IMPACTS OF LUNAR OXYGEN AVAILABILITY

Driggers, Gerald W.

to the Earth's surface), rendezvous and attachment would be effected with the OE which has descended from orbit. With the elements mated, the OE would supply oxygen and the ELE fuel for the remaining flight to orbit.

Although certainly a more complicated scheme than a single-stage-to-orbit (SSTO), this operational concept offers a substantial advantage over the SSTO. That advantage, as mentioned earlier, is a large reduction in GLOW for a given payload mass.

Equations have been derived to analyze the SOR elements taking three velocity increments into account. The first, ΔV_o, is the OE descent from orbit to rendezvous. H_2 must be supplied from Earth for this increment. The second, ΔV_1, is the velocity imparted at Earth launch to the ELE. The ΔV_2 increment is obtained with the ELE and OE coupled. The relationships between ELE propellant mass, total inert mass (including payload) and GLOW are shown in Figure 3 for a set of assumed performance parameters, also shown on the Figure. Note that although ideal velocity equations were used in the assessments, some 3400 ft/sec for drag and gravity losses was included in ΔV_1.

The potential impact of using the lunar oxygen in the SOR mode is illustrated in Figure 4. The SOR/ELE vehicle with payload comparable to the SSTO is only about one-fourth its size. The OE is computed to weigh 1.81×10^6 lb. prior to de-orbit so the total pre-mission mass is about 7.43×10^6 lb. for ELE and OE combined.

The use of lunar oxygen for orbit-to-orbit or Earth-to-orbit transportation will probably be the result of industrialization of space and not a goal in itself. However, the implications of synergism are obvious since reductions in transportation cost for very large activity levels in Earth orbit would offset a substantial portion of the lunar base establishment costs. Although availability of this oxygen is some time away, its potential benefit is substantial enough to warrant near term study of the possible impacts to all cis-Lunar activity.

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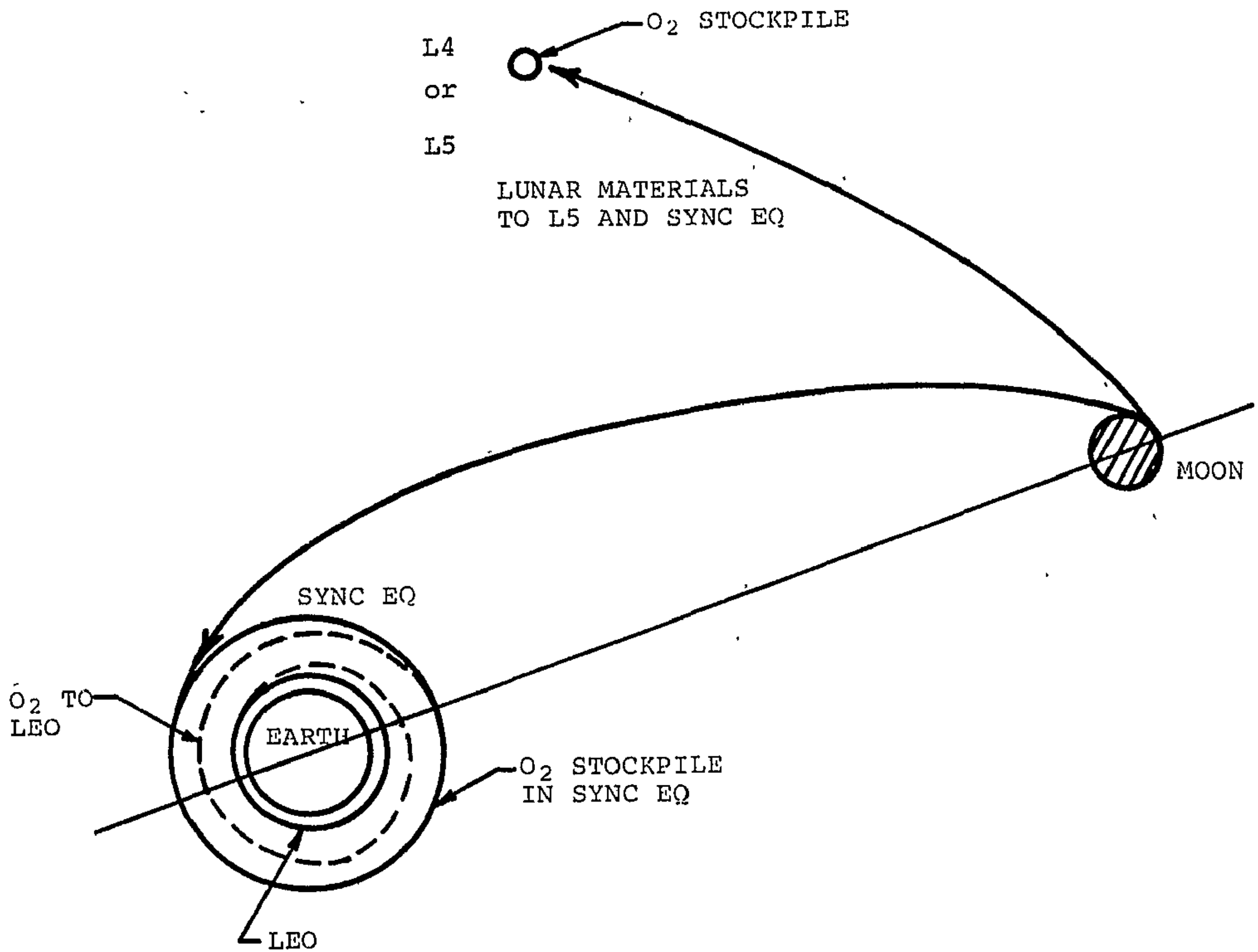

FIGURE 1. SCHEMATIC OF MATERIAL TRANSFER AND O_2 STOCKPILES

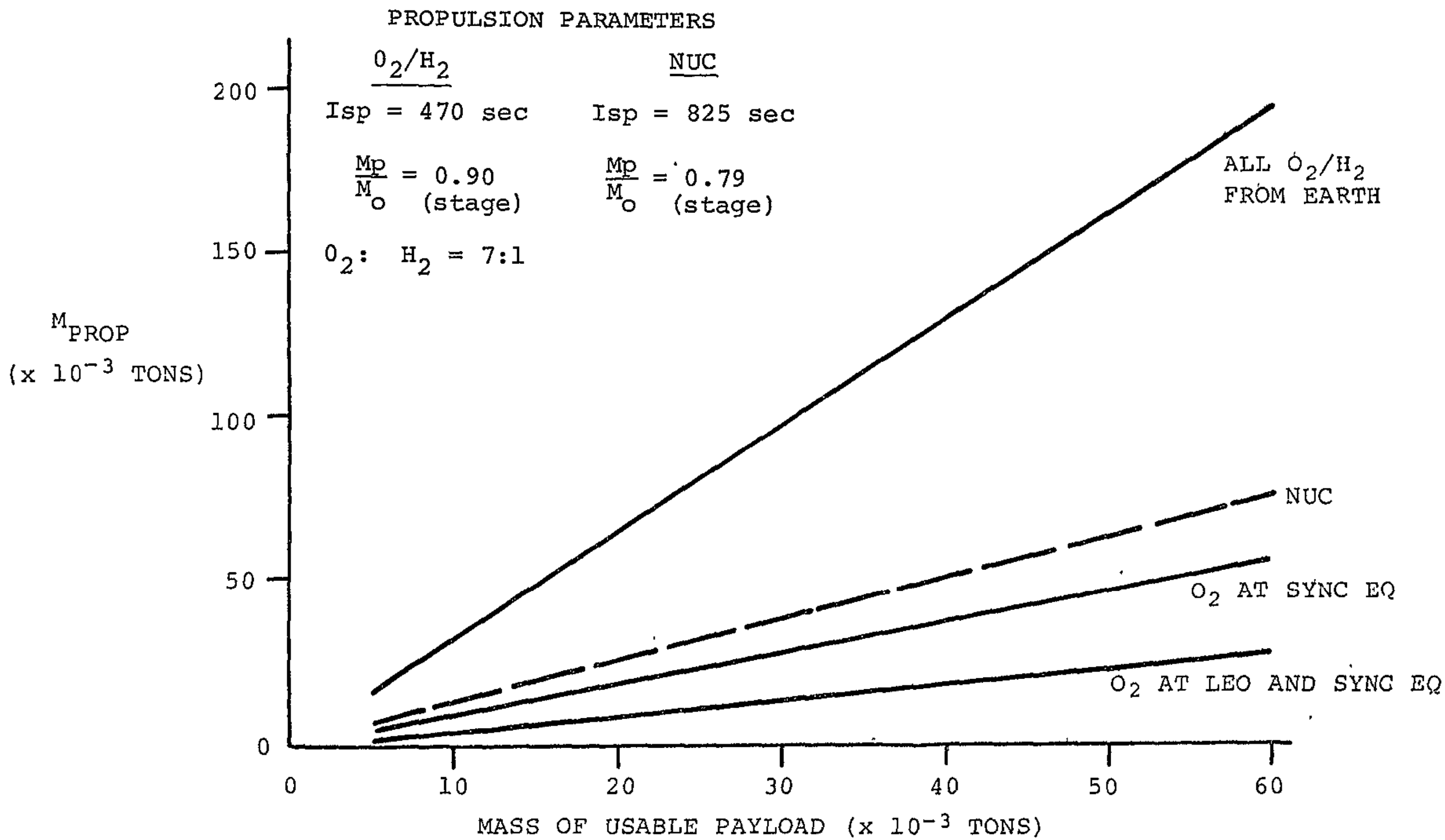

FIGURE 2. COMPARISON OF TOTAL PROPELLANT MASS REQUIRED FROM EARTH AS A FUNCTION OF O_2 AVAILABILITY IN ORBIT

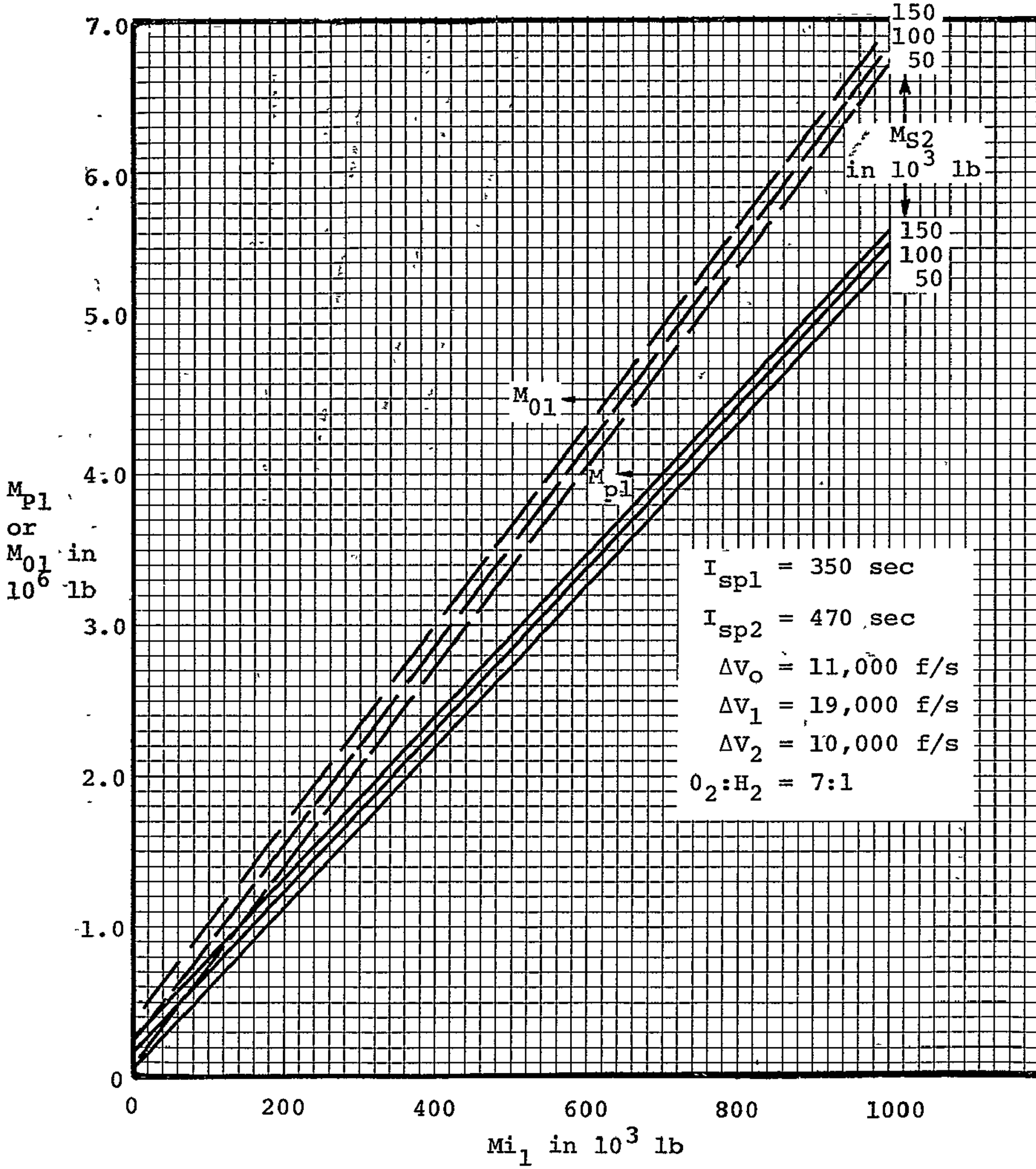

FIGURE 3. EARTH LAUNCH ELEMENT PROPELLANT MASS AND GLOW AS A FUNCTION OF INERT MASS

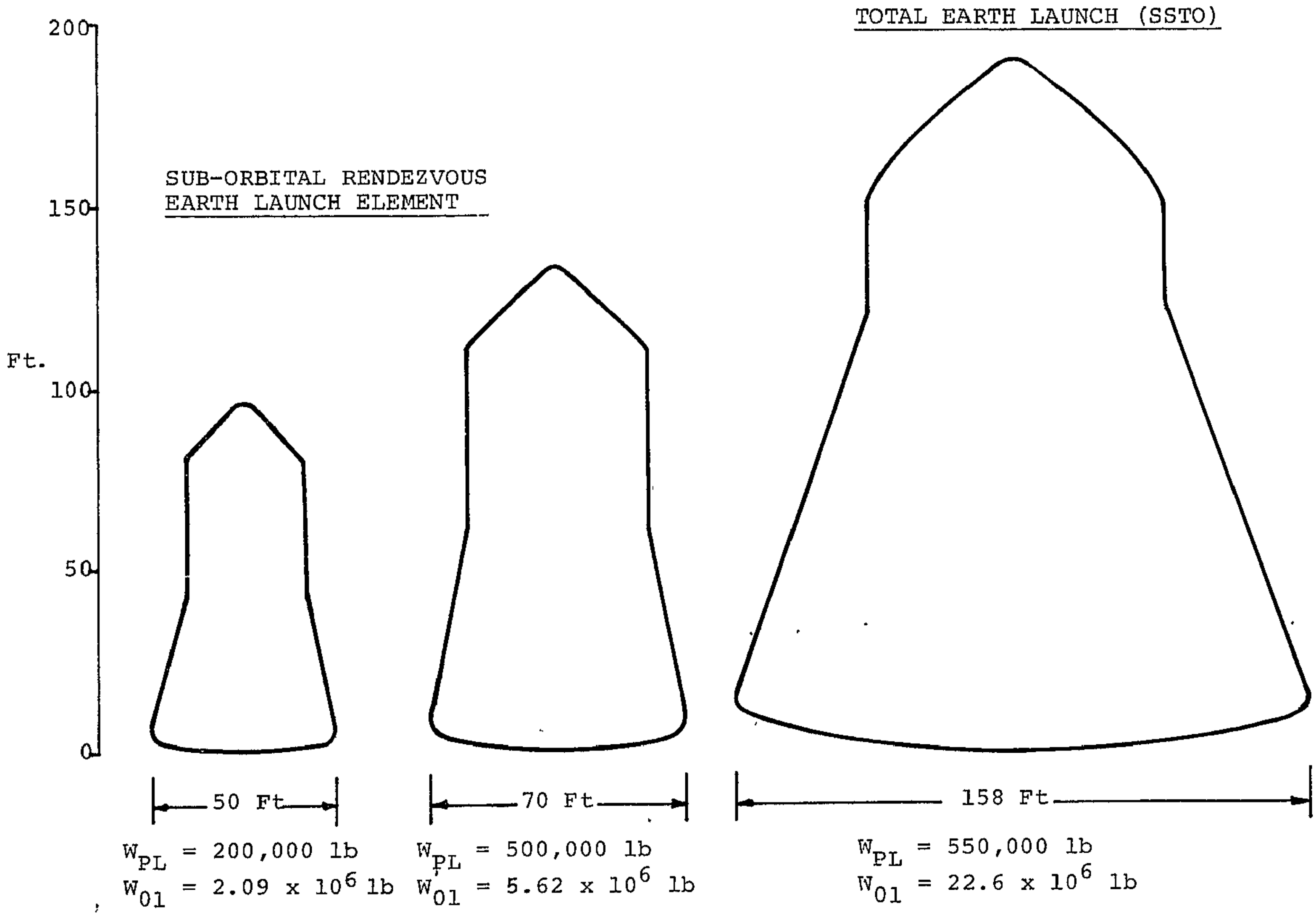

FIGURE 4. APPROXIMATE SIZE COMPARISON FOR TWO SUB-ORBITAL RENDEZVOUS EARTH LAUNCH ELEMENTS WITH A SINGLE-STAGE-TO-ORBIT BASELINE

DISCUSSION (Driggers Paper)

SPEAKER 1: Jerry, I just think a point of clarification might be in order. This did presuppose essentially free source of extraterrestrial oxgyen to support this activity. Is that what your analyses are based upon?

DRIGGERS: Yes.

SPEAKER 2: Jerry, I'm glad you gave this presentation because it builds on some of the material that we studied last summer at Ames. We also treated this problem and found that a round-trip vehicle which made regular trips between low Earth orbit and L-5 would require only about half the propellant, that is, half the hydrogen, to do a round trip with lox available only at L-5 as it would, if it needed to carry all of its propellant from the Earth.

SPEAKER 3: Perhaps this isn't the time to bring up hairy points and perhaps the point isn't as hairy as I think, but has any study been made of the mechanism for converting rocks on the Moon surface into LOX at L-5 or any other point in space, and how much that will cost? Not in terms of money, I mean in terms of mass lifted from the Earth?

DRIGGERS: Well, you have to talk in terms of, again, the overall system concept. You've got to have a base on the Moon; and you're going to convert the material to gain the oxygen in orbit and you've got to have a transportation base on the Moon and a receiving and processing base on orbit. I think the possibility you're talking about is processing on the Moon and then transporting the oxygen.

SPEAKER 3: No, not at all. I assume what you're saying, from your first picture, was that you get a bag of rocks in orbit and first it gets into orbit magically, and then it gets converted to lox magically. And I was wondering if you have any wizards that have worked on the magic recently.

DRIGGERS: Tom Heppenheimer was mentioning the summer study last summer, and this was concentrated on to some extent. The - taking a look at the energy requirements, the mass you're talking about - take those numbers and divide by 0.4, assuming roughly a perfect process, and you'll get the mass of rocks required, assuming 40 percent by weight oxygen. Am I still missing the question?

SPEAKER 3: How do you get it into orbit?

DRIGGERS: Oh, how do you get it there?

DISCUSSION (Driggers Paper)

SPEAKER 3: Yes.

DRIGGERS: There's several schemes, one of which will be talked about this afternoon. Our last paper is going to discuss one possibility for that. Jerry O'Neill's suggested the electromagnetic leviation device as a mass driver.

SHCULD WE COLONIZE THE MOON BEFORE SPACE? C. H. Holbrow Colgate University *

A number of recent proposals for lunar utilization have suggested a small base on the Moon for mining raw materials with a large permanent community performing manufacturing somewhere in space (1), (2), (3). A major argument against a large, permanent colony on the Moon has been the cost and difficulty of lowering and raising people and supplies in and out of the Moon's gravitational potential well. This argument may still be valid, but viewed against the complex engineering problems of designing and shielding a rotating space colony, the issue is not clear cut. The purpose of this note is to point out some of the advantages of colonizing the Moon first; mention is also made of some of the difficulties.

Problems of Colonizing Space

The most recent and detailed study of the colonization of space is the Stanford-Ames study (SAS) made during the summer of 1975. (3) SAS proposes a colony of 10,000 people in a torus 1790 m in diameter and rotating at 1 rpm to simulate earth-normal gravity. To keep radiation exposure below the 0.5 rem/y dosage permissible by U. S. safety standards for individuals in a general population, the torus is to be surrounded with 10 million tonnes of non-rotating shield.

Such a large rotating structure is a source of formidable engineering problems. Access must be through non-rotating docking ports connected to the torus' rotating hub. Because the radiation shield also insulates the interior, heat must be removed from the rim of the torus by heat pipes through the six spokes to a large despun radiator attached to the rotating hub.

At 1 rpm the rotation of the torus will move the 2-cm thick aluminum walls of the habitat at 93.7 m/s (210 mph) through its tunnel of shielding. Clearly, maintaining proper alignment of the rotating torus and its surrounding shell of shielding will be a critical control problem. Moreover, the alignment and control of the system of mirrors which bring in sunlight will also demand a high level of engineering accomplishment. Despite the substantial problems there is considerable reason to believe that the aerospace engineering profession could successfully overcome these difficulties.

Shielding presents a less tractable problem. The very scale of an effort to place over 10 million tonnes in orbit at a large distance from the Moon requires technology not yet developed. Even at a rate of one million tonnes a year, the undertaking is impressive not to say daunting. The matter

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must be hurled from the Moon at high rates of launch by electromagnetic launchers whose engineering yet remains to be fully specified. The launch velocity must be controlled to an accuracy of about 4 parts in 10 million. The ways of collecting the launched material in space and delivering it to the colony are at best presently imagined only conceptually.

Moreover, before any manufacturing in space can begin we must have the raw materials; therefore, launching from the Moon must begin before manufacturing. Consequently, the initial materials and power for this launching can come only from Earth. To launch from the Moon the amount of material called for by SAS would require 200 MW of electrical power on the Moon. For reliability and availability of continuous power, SAS called for setting up a 200 MW nuclear power plant on the Moon. The very availability of this large amount of power on the Moon suggests other design possibilities.

Advantages of Colonizing the Moon

By placing the principal body of colonists on the Moon and rotating a work crew to factories in lunar orbit, most of the problems of a large rotating system and massive radiation shielding in space could be avoided. On the Moon shielding could be achieved by using underground residences in tunnels or simply under heaps of bulldozed lunar material. Five meters of regolith would probably be sufficient to bring radiation dosages below the .5 rem/y limit. Gravitation would be provided by the Moon's attraction although at only 1/6 of Earth normal.

To use the high vacuum, abundant sunshine and weightlessness available in space a factory of the size of the construction shacks proposed by Driggers (4) could be built in lunar orbit. Work crews of 2000 people would spend 120 days there each year and then return to the permanent colony on the Moon for the remainder of the year. Experience with Skylab indicates the workers could stand zero g for 120 days with no irreversible effects, so a non-rotating structure could be used.

Work crews are not "general public", (for example, they do not include children or pregnant women) and can be designated as "radiation workers". For this category U. S. standards limit radiation dosage to no more than 5 rem/y. In 120 days under normal circumstances they would not receive the annual dose in the absence of shielding or even from radiation due to secondary ionizing particles generated in the mass of the structures around or near the workers. Thus, extensive, massive radiation shielding would not be necessary.

One exception must be noted. Solar flares can produce bursts of radiation sufficient to kill unprotected humans. There would need to be available a shelter sufficient to protect the entire work crew against solar flares for a few days. Adequate protection against flares may be tricky because of difficulties in predicting them. If a permanently shielded

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factory were necessary the principal argument for basing the colony on the Moon might be weakened. Nevertheless, a fully shielded sphere 100 m in diameter (i.e. a typical construction shack) would still require only 1.4% of the shielding required by the SAS colony, a substantial reduction of the problem.

To see how circumstances might favor colonization of the Moon, let us consider an example. SAS calls for 192 MW on the Moon just for launching lunar material. In space another 191 MW are to be used to extract annually ∿ 50 kt of Al and ∿ 44 kt of O_2 from the material. Some glass would also be manufactured, but the bulk of the material would be used as shielding. A simple calculation shows that if on the Moon the aluminum bearing anorthosite minerals were refined to alumina at a cost of 76 MW then it would be necessary to launch each year only ∿ 100 kt of alumina in order to extract the desired amounts of Al and O_2. The power required for launching this amount would be 19 MW. Thus the total expenditure on the Moon for refining and launch would be 95 MW rather than 192 MW. This calculation does not take into account that if construction shacks were built in space instead of full scale colonies the demand for Al might be reduced by as much as 50%. The main demand for Al in space would be for the manufacture of satellite solar power stations as in all the other designs. (2) There would, of course, now be a substantial demand for refined aluminum on the Moon which would counterbalance savings due to reduced demand for aluminum in space.

Eight thousand people living on the Moon will need more power than 150. In space they would have used 131 MW, 101 MW of direct sunshine for heating, lighting, and growing plants plus 3 kW/capita of electric power. Because of the periodic variations of insolation, direct sunshine would not be as convenient to use on the Moon as in space although some could be used, especially if its energy could be stored for the two-week-long nights. The total power needs of 8000 people on the Moon, including refining and launching, come to roughly 220 MW, only 10% more than was planned in SAS for 150 people on the Moon. Thus the Moon base proposed in SAS could support a colony rather than a mining camp if the requirement of launching enormous amounts of matter were eliminated.

The energy requirements in space would drop from 131 MW for life support and 191 MW for industrial purposes to 6 and 110 MW respectively. Not only would there be some savings of capital equipment necessary to collect and use the energy in space, there would be a large decrease in complexity because the complex of mirrors would no longer be needed.

The energy savings would be offset because the use of the Moon as the colony and the rotation of crews to and from the factory in space imply a substantial investment in transportation. Two thousand people and the supplies for them and their industry must be lifted off and soft-landed on the Moon every four months. Transporting about 720 t of passengers and 4400 t of supplies each year would be a large and expensive undertaking. Would it be as expensive or as complex as setting up the colony in space? Further study is needed to tell. The main point is that taking into account the complexity of design of large rotating systems plus the magnitude of the task of launching one million tonnes of lunar regolith each year, the answer is not obvious.

Problems of Lunar Colonization

Two problems with the foregoing arguments must be noted. It has been assumed that people can live without ill effects indefinitely on the Moon at 1/6 earth gravity. We have no evidence for this. If the assumption is false, then providing earth-normal gravity for large numbers of people on the Moon would probably be much more difficult than in space. If the assumption is true, then it is fair to imagine rotating systems that supply 1/6 g instead of 1 g. The engineering problems of these would be more tractable and a wider range of options would be available than in 1-g systems. However, the telling argument still remains the enormous mass of material to be launched from the Moon.

A second problem is pollution of the Moon. A growing colony of thousands of people with frequent launches and landings would eventually begin to build a tenuous lunar atmosphere. (5) It might well be that the Moon should be only lightly settled as a staging point for subsequent exploration and use of the asteroids. Only then would the real colonization of space begin.

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* *Attendance at the Seventh Lunar Science Conference (Houston, Texas) supported by the Colgate University Research Council.*

DISCUSSION (C. H. Holbrow)

SPEAKER 1: That is a very interesting idea, but how about doing one little variant on it and put the workers on Earth, and the station do the final processing in geosynchronous orbit. Then you don't have the worries about polluting the Moon; you don't have the dependents of those workers being supported all the way out on the Moon colony. You have all the dependents on the Earth. And you have a bigger work force to choose from.

HOLBROW: It depends where they're going to get their materials. Are they going to get them from the Moon? If so, you are going to have a base and you are still going to the Moon. If not, you pay an enormous price in transport up from Earth plus a price in environmental damage to Earth.

HOLBROW: I guess I'm not going to argue that alternative with you, Ralph. I would certainly consider it. I have an open mind on the subject. I just wanted to make sure that this one got a hearing.

SPEAKER 2: Can I ask one question? Are you assuming protection against solar flares? Presumably that's the major source of radiation hazard.

HOLBROW: Yes, but there are two sources. There are also the cosmic rays - particularly the high Z, very ultraenergetic heavy ions component of cosmic rays creates a serious problem. And they will, with a modest amount of mass around the person, say about 100 grams per square centimeter, produce perhaps 20 rems per year of radiation exposure from the secondaries. And the solar - if you finally get enough shielding against the cosmic rays, you're also protected against solar flares.

EVALUATION OF A LARGE RADIO-TELESCOPE ARRAY ON THE LUNAR FARSIDE;
Roy Basler, George Johnson, and Richard Vondrak, Radio Physics Laboratory, Stanford Research Institute, Menlo Park, California 94025.

The construction of a large radio telescope system has been proposed as part of a program to search for microwave signals being emitted by extraterrestrial civilizations. The design of one such earth-based system has been described in detail and is generally referred to as Project Cyclops. The Cyclops design is based on an incremental approach, starting with a single dish 100 m in diameter, and adding additional dishes only after a search with the existing system has proved unsuccessful. If no signals are detected with initial searches, it may eventually prove necessary to build receiving systems extending up to kilometer dimensions.

At the present time we are making an independent evaluation of alternative antenna design concepts to determine the most promising approach that could be followed in developing an interstellar communication system. In particular, we expect to establish whether the antenna system should be built on earth, in space, or on the moon.

The primary attraction of the moon as the site for a large radio telescope array is the fact that the far side of the moon is completely free from radio frequency interference from transmitters, either on the earth or in orbit around the earth. Secondary benefits are derived from the absence of a substantial lunar atmosphere and from the relatively weak gravitational force on the moon. A serious disadvantage of a lunar site is the high cost for transportation, construction, and operation.

Two basic types of radio telescopes have been considered: free-standing parabolic dishes (similar to the 100 m Bonn antenna) and spherical dishes constructed within lunar craters (similar to the 305-m Arecibo antenna). The abundance of lunar craters of all sizes makes possible a significant improvement in the design of a lunar Arecibo-type system compared to an earth-based system of this same type. A major cost of the actual Arecibo antenna is in the tall towers that support the feed. On the moon it would be possible to reduce the cost of the antennas substantially by only partially filling a lunar crater with the reflector surface and by suspending both the feed and the dish on long cables extending from the crater rim.

The ideal location would be a flat surface near the farside equator, such as mare surface or the flat floor of a large crater. Examination of available topographic maps indicate the availability of acceptable sites within the crater Mendeleev, and it is expected that other additional acceptable locations could be easily found.

In addition to evaluating the required size and preferred design of such a system, our study includes a cost estimate for both the antennas and the lunar colony to house the construction and maintenance workers. The analysis has identified several key items that determine the overall cost and that are relevant to an evaluation of any large-scale operation on the lunar surface. In estimating values for these items we assumed that the antenna systems and colony would be constructed with advanced technology in a time period of 1990 or later. Some of the key cost parameters are:

1. Utilization of lunar resources. Appropriate processing equipment would be brought from earth and would process each year lunar metals equal to seven times its own mass.

2. Basic earth-moon transportation cost. We assume high level of space activity with material transport costs of $264/kg in 1975$. We also assume that the round trip cost for each person is $264,000.

3. Productivity of lunar workers. Each construction worker would process lunar materials and fabricate two tons of general equipment per year. Antenna structures for the Arecibo-type antennas would be fabricated at one-sixth that rate.

4. Degree of independence of lunar colony. A 200-man colony module would be shipped from earth and additional colony structures would be processed from lunar material. We assume that resupply is required for the first five years, but after this we assume the colony is self-sufficient. We also assume that the standard tour of duty on the moon is ten years.

5. Ratio of support staff to working staff on the lunar surface. By analogy with current Antarctic operations, we assume the support staff would be equal to the number of workers. Further, we assume that three-quarters of the total support staff would be on the moon and the remainder on earth.

Costs were computed for antenna systems of various sizes. In addition, in our parametric analysis we determined the sensitivity of the total cost to variations in several of the key cost items. All the lunar systems are more expensive than their terrestrial counterparts, and generally by a factor of two. However, if the cost of the lunar colony is not included, the overall cost of an Arecibo-type array on the moon is comparable to that of a Cyclops-type array on earth.

DISCUSSION (Basler et al Paper)

SPEAKER 1: Were you assuming that this array would be used solely for searching for civilizations, or would you have it being used for other functions as well, on a simultaneous or a part-time basis?

VONDRAK: Yes, that again was a free parameter that we used in our analysis. Radioastronomy would be something that would benefit, quite obviously. We allowed between 10 and 50 percent of the time for radioastronomy use. This system would represent about a two-order or three-order magnitude increase in sensitivity compared to radioastronomy devices that we have now. Also, for the Earth-based systems, we suggested that you might be able to use the antennas for solar energy collectors during the daytime and search at night, and then you'd pay back some of your initial investment. That proves to be promising.

SPEAKER 2: I wonder if you could comment on the sensitivity of your conclusions to the assumed search strategy. You appear to favor an Ozma-type strategy of searching the stars which are nearby one by one. What about the alternative of searching entire galaxies, having an entire galaxy fit within your beam and looking for particularly powerful individual transmitters?

VONDRAK: Yes, well, the Cyclops search strategy is something that we were not asked to consider. We were concerned just with an engineering analysis for a system where the strategy had been specified. And since I wanted today to discuss primarily some points that I think are applicable for construction on the Moon, Cyclops search-strategy decisions are probably best discussed elsewhere.

SPEAKER 3: You need the location on the farside of the Moon for the radio purposes. But isn't it true that other uses of a lunar base would be better on the nearside?

VONDRAK: I guess you mean for the transport linear accelerator?

SPEAKER 3: It would seem to me, for communications reasons, that the nearside would be the obvious place to establish the first lunar base.

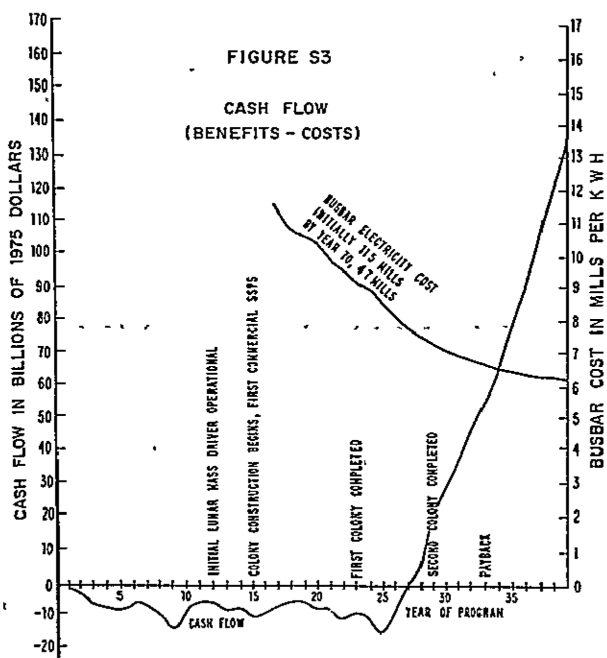
VONDRAK: Well, the location of the first lunar base is a separate decision. The farside base would communicate to the Earth by having a relay satellite at the L-2 point, and then it would communicate back to a satellite in geosynchronous orbit so that we would have a continuous communications link from the Earth to the farside.

A PRELIMINARY COST BENEFIT ANALYSIS OF SPACE COLONIZATION: ABSTRACT

Mark M. Hopkins Harvard University, Cambridge, MA

This abstract summarizes the first draft of a paper entitled, "A Preliminary Cost Benefit Analysis of Space Colonization" (1). The paper has been submitted to the Federal Energy Administration for checking. It is available from the author. The data upon which it is based were primarily obtained from the NASA-Stanford 1975 Summer Study of Space Colonization (2).

The economic aspects of the Space Colonization program are summarized by the cash flow diagram given in Figure S3. All costs in this abstract are in terms of 1975 dollars. During years 1 through 12 of the program the major costs are related to the establishment of facilities on the moon and at L-5 (the fifth librational point of the earth moon system). Mass drivers are the major component of the lunar facilities; their operation begins in year 12. These drivers consist of long tracks upon which buckets containing pellets of lunar material are accelerated by electrical power. When the pellets reach the end of a track they are slung into space while the buckets remain behind to be re-used. The lunar materials thus obtained are taken to L-5 where they are processed and fabricated into useful materials by a labor force which is initially housed in a construction shack. For the next 3 years these materials are used to build additional construction shacks and a SSPS (Satellite Solar Power Station) which will be used to provide power needed for expansion of the system. Only a small part of the mass for these items must be brought from earth. In year 15 the first commercial SSPS is built and within a year transported to geosyncronous orbit where it begins to transmit power to the earth. Construction of the first colony, a permanent habitat for 10,000 space workers and their dependents, also begins then. After year 12 costs are dominated by the building of SSPS's.



BENEFIT COST RATIO = 13

A PRELIMINARY COST BENEFIT ANALYSIS OF SPACE COLONIZATION: ABSTRACT

Mark M. Hopkins

The program is set up so that from the first year in which commercial SSPS's are produced, their level of output is always set equal to the demand for them. The U. S. market was assumed to be equal to the market for new plants. This market comes about because of growth and because existing plants eventually wear out. The foreign market for our exports in the case of nuclear plants has been about one-half the size of the U. S. market. It was assumed that this would likewise be the case for space colonization power. Because of the risk inherent in new technology, the demand in a given year is not initially equal to what was called the market size in the above. Rather the market must be penetrated over a period of time; in our case, we have estimated 10 years. After this time, demand is equal to the sum of the U. S. and foreign markets. The market size was assumed to grow at 5 percent per year. This is consistent with the 5.7 percent rate of the Energy Research and Development Administration's intensive electrification scenario. Colonists start to arrive in year 20, and have all arrived at the colony by year 23. By this time costs have become roughly proportional to the number of new SSPS's produced in a year, while benefits are roughly proportional to the total number of SSPS's that have been built. SSPS's are assumed to have a lifetime of 30 years. As a result, benefits rapidly climb with respect to costs.

Benefits were taken to consist of the revenue obtained from sale of electricity plus the benefit obtained by U. S. consumers due to lower electricity prices. Other benefits, although likely to be substantial, were ignored. It was assumed that electricity must be sold at 14.1 mills per kilowatt-hour or less to be competitive. (In 1974 electricity from nuclear plants was 15 mills and from coal-fired plants, 17 mills.) The value of 14.1 was set by an optimistic projection that the cheapest alternative source of electricity, nuclear, would be 14.1 mills during the period of interest. The savings to consumers was calculated subject to the conservative assumption that demand for electricity, if available at 14.1 mills, would not increase if the price were lower.

The total cost of the program through completion of the first colony is $111.5 billion. This figure excludes the costs of commercial SSPS's and latter colonies. Payback of costs occurs 18 years after the first commercial SSPS is built. Figure S3 also gives the costs at busbar of producing electricity by the use of commercial SSPS's. They start in year 16 at 11.5 mills and reach 4.7 by year 70. These costs cover everything except research and development costs which are taken to be the $111.5 billion mentioned above. The analysis employs a 10 percent real discount rate. Loosely speaking, this means that the net costs in any given year include intersts on the outstanding debt, at a real rate of 10 percent. This real rate includes the effects of inflation; that is, if the inflation rate in a given year were 8 percent, then the interest would be 18 percent in terms of the manner that interest rates are normally stated. The benefit cost ratio is 1.3. This implies that even if the costs in every year were 1.3 times larger than was estimated, the program would still be worthwhile.

A PRELIMINARY COST BENEFIT ANALYSIS OF SPACE COLONIZATION: ABSTRACT

Mark. M. Hopkins

To conclude, the tentative economic results of this analysis do not mean that several billion dollars should be spent on space colonization next year. They are too uncertain for that. Rather, these results indicate the desirability of further study. If it happens that they are confirmed, then space colonization should be undertaken.

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EXPLOITATION OF A LUNAR-BASED NUCLEAR ECONOMY: IMPLICATIONS FOR SOLAR SYSTEM COMMERCE; Gary C. Hudson, The Foundation Institute, Suite 704, 810 Thornton St., SE, Minneapolis, Minn. 55414 (612) 332-6621.

Technological civilizations are built on the foundations of power, resources, transportation and communication. This paper addresses the three former topics, and discusses ways in which a nuclear economy based on the moon can lay the foundation for future exploration and exploitation of the solar system as well as provide the underpinnings of solar system commerce.

At this time, the fundamental ways of obtaining thermal or electric power are from the sun (fossil fuels, solar photovoltaic conversion, etc.) or from nuclear reactions (fusion, light or heavy metal fission). While solar sources have their utility, mostly for small scale heating and electric power generation on earth, space vehicles and communities will be forced to depend upon nuclear energy sources almost exclusively. The exceptions may be in certain moderately sized space colonies of the type suggested by O'Neill[1] and others[2], or at lunar factories mass "refining" the regolith in preparation for selected materials extraction and gas processing.

Nuclear reactions will be necessary to provide compact, lightweight, easily transportable power sources. These will be used, first and foremost, for life support and propulsion. The energy required for life support systems will always be small compared with propulsion requirements and can probably be accommodated by nuclear thermionic batteries or Rankine/Brayton cycle generators[3,4]. Fuel requirements for these systems can economically be met from earth-based fission stockpiles, but the fuel needs of propulsion systems are a different matter altogether.

Several types of nuclear propulsion schemes may find niches where they have unique attributes or economic utility. These systems include gaseous (plasma) core nuclear engines,[5,6,7,8,9]. Orion fission bomblet pulse motors[10], and pure fusion pulse engines [11,12,13]. It should be noted that all the mentioned propulsion schemes have the attributes of both high specific impulse as well as high thrust-to-weight. The advantages of such a combination are of overwhelming economic importance in the commercialization and utilization of the solar system, and this has been convincingly, indeed eloquently, pointed out by Hunter [14,15,16].

However, to produce the low costs necessary (ranging from a few cents per pound to a maximum of a few dollars per pound, depending on total ΔV required), large scale nuclear operations will be necessary on the lunar surface. A number of potential activities of a nuclear nature are possible on the moon which would be excluded from practical utilization in the biosphere of earth for environmental reasons. These include manufacturing large scale lots of fissile materials through the use of simple breeder reactors, hybrid reactors (fusion breeders employing a fertile thorium blanket to produce U-233), or "bomb" breeder systems. The latter system uses the cheap neutrons produced during the detonation of thermonuclear devices as a neutron source for an "open-air" breeder; the bombs are simply detonated a few thousand meters above a distributed mass of depleted uranium[17]. Certain problems exist with this method, not the least of which is the low binding energy of high-Z materials, such as uranium contrasted with the high energy of neutrons and gamma rays deposited in the material. In any case, by using the inherent advantages of the moon, including its location, free vacuum, and population sparsity, the manufacture of nuclear materials should be unencumbered by many of the constraints present on earth which drive the costs of nuclear facilities up.

The existence of significant amounts (thousands of metric tons) of weapons-grade materials will make very large engineering projects possible, including nuclear excavation on the moon and planets, movement of asteroids and similar small bodies within the solar system, and will allow reconsideration of the Orion concept launch vehicle as a device for the transport of lunar materials to Lagrangian points or to geosynchronous orbits for solar or nuclear power satellite stations. Masses in excess of 300,000 metric tons could be moved from the surface of the moon with no substantial advance in the state-of-the-art over work done originally by General (then Gulf) Atomic Corporation in the early 1960's.

Certain potential hazards exist in the concept of a lunar-based nuclear economy, not the least of which is the safe-guarding of ton lots of fissionable materials, and the prevention of the diversion of many thousands of very small fission bomblets used in the Orion ships. However, the moon is far more difficult for potential thieves to reach than earth-based power plants and reprocessing facilities and design precautions can be taken which would prevent the unauthorized use of the Orion bomblets outside of the Orion vehicle. Ultimately, the use of pure fusion detonations would obviate the problem completely, while also permitting very high speed transit among the bodies of the solar system.

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MATERIALS RESOURCES

THE REGOLITH AS A SOURCE OF MATERIALS. G. Heiken, Los Alamos Scientific Laboratory, Los Alamos, NM, 87545 and D. S. McKay, TN6, NASA Johnson Space Center, Houston, TX, 77058.

It has been proposed that the lunar regolith be used as a source of raw materials for lunar colonies and space colonization (1,2,3). With this in mind, a brief review of some basic facts concerning the properties of lunar soils was prepared for this meeting. The O'Neill concept (1,2) places quarrying operations on the lunar farside; with this in mind, we will cover the general characteristics of nearside highlands and mare regoliths and compare them with what we may find on the farside.

Regolith is the layer of unconsolidated debris, overlying bedrock, which covers most of the Moon's surface (4). Nearly all lunar investigators have concluded that this debris was formed mainly by impact-cratering processes (5,6). The presence of shock-metamorphosed rocks and minerals, micro-craters on particle surfaces and impact-generated melt within the soil supports this interpretation.

Turkevich (7) has determined "average" soil compositions of mare and highlands regoliths, based on analytical data from Apollo, Surveyor, and Luna landing sites and orbital measurements (Table 1). These compositions are greatly simplified, but representative of the two settings. Soils of the highland regions have been derived mainly from anorthositic rocks and the complex breccias and impact melt rocks developed during the early, large-scale cratering events. In bulk, the soils are rich in Ca and Al relative to the regoliths developed on mare surfaces. Soils from mare regoliths consist of mostly lithic, mineral and glass fragments formed by the comminution of Fe- and Ti-rich basaltic lava flows. Regolith soils are composed mostly of locally-derived particles, with only minor contributions from craters in distant provinces and meteorites.

The most ubiquitous component of all lunar soils which have been characterized is the agglutinate, which consists of lithic, mineral and glass fragments bonded by glass droplets. The irregular dark brown to black particles are heterogeneous and are crossed by bands of iron droplets 20 Å to 10 μm in diameter. The amount of Fe° in agglutinates ranges from 0.1 to 1.7 wt.% (8). Due to the presence of Fe°, agglutinates are easily separated from the bulk soils magnetically. Most of the total Fe, however, is present as FeO in the glass and not as the iron droplets. Agglutinitic glass is generally vesicular, with vesicles ranging from less than 1 μm to several cm in diameter. Agglutinates generally make up 10 to 60%, by volume, of lunar soil samples. The proportion of agglutinates increases with the length of time a soil was exposed at the lunar surface (9,10,11), as indicated by particle tracks, solar wind components, etc. Most investigators agree that agglutinates are formed by the mixing of melt from micrometeorite impacts and soil particles (reviewed in Ref. 5). The increase of agglutinates in a regolith effectively lowers the albedo, a characteristic which may be useful in the search for regolith quarry sites by remote sensing of the lunar surface (13). Rhodes *et al.* (12) determined that agglutinates are enriched in iron and titanium relative to the bulk soils (Table 2). This enrichment may be due to the selective melting of mafic soil components.

THE REGOLITH AS A SOURCE OF MATERIALS

G. Heiken

When treating the regolith as a source of materials, remember that it is already partly processed; the crushing and sorting is well along, thanks to the millions or billions of years of pounding and turnover by meteorite impact. Most lunar soils are fine grained; the samples collected on Apollo and Luna missions have mean grain sizes of around 100 to 200 μm (Table 3). The description, in terrestrial terms, which best fits an "average" lunar soil, in both mare and highlands areas, is that of a "cobble-bearing silty sand."

Based on studies of core samples and theoretical models of regolith formation, there is considerable variation of grain size with depth in a regolith. This variation is random, but generally coarser with increasing depth. If fine grain sizes are most desirable in a lunar quarry, then fresh craters, characterized by coarse grained soils, should be avoided.

Finer grained soils are best to process for many reasons: 1) they are easy to quarry, 2) minimal energy is spent for crushing, 3) they are richer in agglutinates and therefore richer in Fe°, FeO and TiO_2, 4) there is more surface area and therefore more solar-wind derived hydrogen, and 5) they are more easily sintered to form compressed soil blocks for construction or transport.

The process of concentrating fine-grained, agglutinate-rich soils as an ore has been studied by one of the authors (DSM) and is outlined in Fig. 1. The purpose is to make a concentrate which would have economic potential for oxygen and hydrogen extraction and for the extraction of metallic Fe, Ti, Al, S, Co, Cr and Ni. It involves a closed-system water slurry and size and magnetic separations.

Regolith thicknesses have been estimated by such techniques as measuring minimum depths of blocky craters, seismic data from Apollo sites and observation of rille and crater walls. The thicknesses range from 3 to 5 m for mare regoliths at the Apollo 11, 12 and 15 sites to 12 m of regolith at the Apollo 16 site in the lunar highlands. Observation of trenches and cores from the regolith indicate that at least the upper 3 m consists of soil layers which vary from a few mm to several tens of cm thick. There are changes in grain size, composition and soil fabric from layer to layer within individual sections, reflecting complex histories of impact comminution and mixing.

Quarry sites should not be located near large craters. For example, the cluster of craters in the northeast corner of the Valley of Taurus-Littrow had ejecta blankets which were sintered to form vitric breccia units. Such breccias may be difficult to quarry and will require energy for crushing. Large bodies of impact melt should be avoided for the same reasons.

If lunar soil is used as raw material for factories in space according to the concepts of O'Neill (1,2), the quarries and soil transporters must be on the lunar farside in areas with low topographic relief for a distance of 200 km. These restrict the location of the quarries to large farside basins such as Mare Moscoviense, Mendeleev, Korolev and Jules Verne.

Old plains areas such as the floor of Mendeleev Crater have high Al/Si ratios and are similar in appearance to plains areas of the lunar nearside. The abundance of smooth-rimmed craters is one indicator of a thick regolith characteristic of highlands regions. Basins with low albedos, such as Tsiolkovsky, Mare Moscoviense and Jules Verne have lower Al/Si ratios and, by analogy with nearside maria, more Fe°, FeO, and TiO_2 in their regoliths than those of the adjacent highlands. The relatively featureless crater floors satisfy the terrain limitations on sites.

If a site is chosen, for example, in Mendeleev, only small areas will be affected by the quarrying. Assuming a bulk density of 1.7 gm/cm^3 and mining the regolith to a depth of 8 m, a 1 km^2 quarry will supply 13.5x10^6 mtons. According to O'Neill (2), a soil transporter, with maximum use, could launch 940x10^3 tons per year. At this rate, the 1 km^2 quarry would last nearly 15 years.

For this brief review, we have used only what is known from nearside landing sites and orbital γ-ray and XRF data from narrow bands around the Moon. It is probable that, by analogy with what is known about samples from the nearside and from the farside orbital data, we may reasonably assess the physical properties and composition of quarry sites on the lunar farside. For a more detailed exploration program we need the following:

- Better studies of available orbital photography to assess regolith thicknesses.
- More orbital geochemical data.
- Topographic profiles of regions where quarries may be established.
- Radar and infrared data to interpret surface roughness and limits on grain size of the regoliths.
- Lunar orbiter multispectral measurements of soil maturity (grain size, agglutinate contents) similar to those made of the nearside by Earth-based observations (14).

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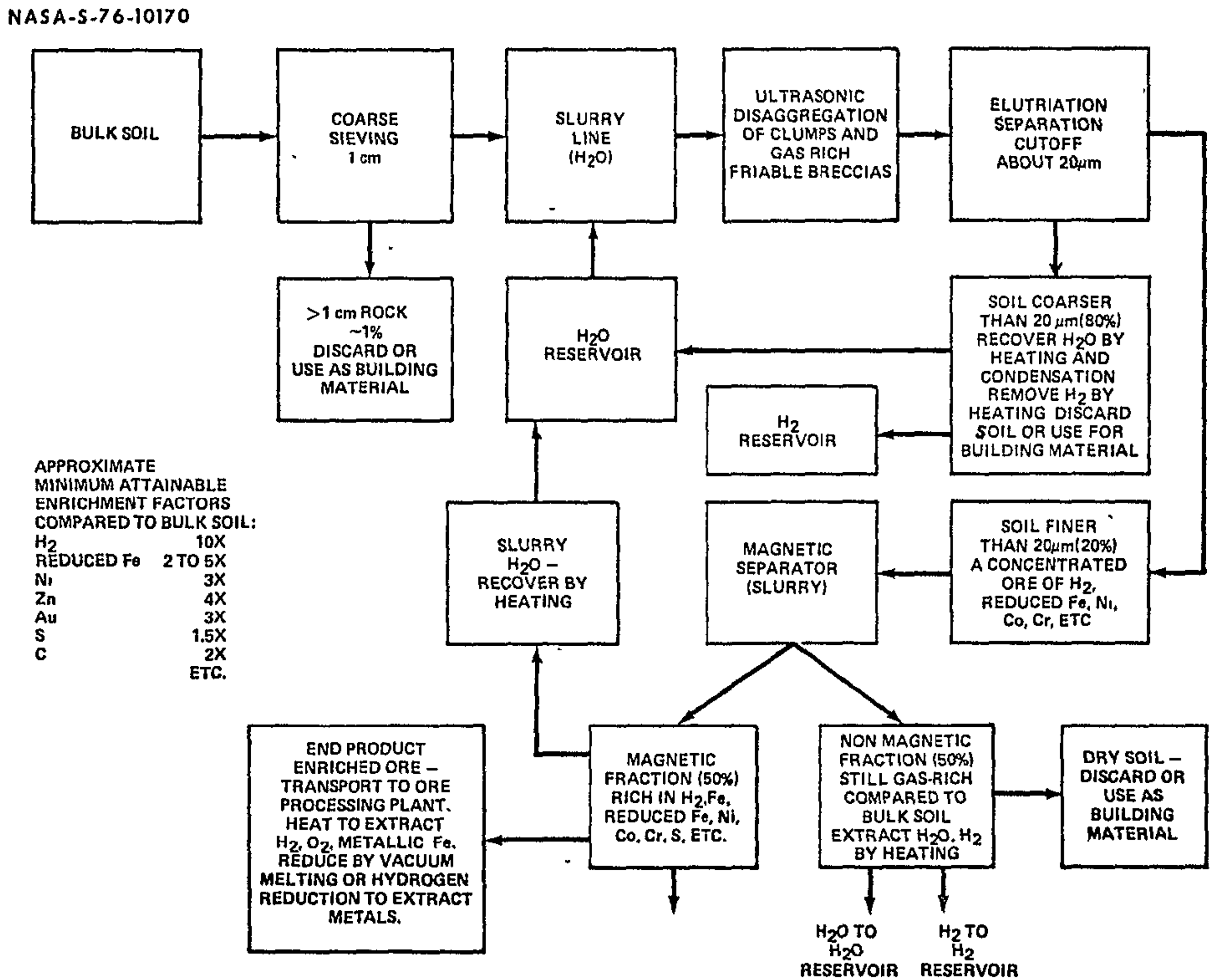

NASA-S-76-10170
BULK SOIL
COARSE SIEVING 1 cm
SLURRY LINE (H_2O)
ULTRASONIC DISAGGREGATION OF CLUMPS AND GAS RICH FRIABLE BRECCIAS
ELUTRIATION SEPARATION CUTOFF ABOUT 20μm
>1 cm ROCK ~1% DISCARD OR USE AS BUILDING MATERIAL
H_2O RESERVOIR
SOIL COARSER THAN 20 μm(80%) RECOVER H_2O BY HEATING AND CONDENSATION REMOVE H_2 BY HEATING DISCARD SOIL OR USE FOR BUILDING MATERIAL
H_2 RESERVOIR
APPROXIMATE MINIMUM ATTAINABLE ENRICHMENT FACTORS COMPARED TO BULK SOIL:
H_2 10X
REDUCED Fe 2 TO 5X
Ni 3X
Zn 4X
Au 3X
S 1.5X
C 2X
ETC.
SLURRY H_2O – RECOVER BY HEATING
MAGNETIC SEPARATOR (SLURRY)
SOIL FINER THAN 20μm(20%) A CONCENTRATED ORE OF H_2, REDUCED Fe, Ni, Co, Cr, ETC
END PRODUCT ENRICHED ORE – TRANSPORT TO ORE PROCESSING PLANT. HEAT TO EXTRACT H_2, O_2, METALLIC Fe. REDUCE BY VACUUM MELTING OR HYDROGEN REDUCTION TO EXTRACT METALS.
MAGNETIC FRACTION (50%) RICH IN H_2,Fe, REDUCED Fe, Ni, Co, Cr, S, ETC.
NON MAGNETIC FRACTION (50%) STILL GAS-RICH COMPARED TO BULK SOIL EXTRACT H_2O, H_2 BY HEATING
DRY SOIL – DISCARD OR USE AS BUILDING MATERIAL
H_2O TO H_2O RESERVOIR
H_2 TO H_2 RESERVOIR

THE REGOLITH AS A SOURCE OF MATERIALS

G. Heiken

Table 1
"Average" Chemical Composition of Highlands and Mare Regoliths (Ref. 7).

	Maria (wt.%)	Highlands (wt.%)
SiO_2	45.4	45.5
TiO_2	3.9	0.6
Al_2O_3	14.9	24.0
FeO	14.1	5.9
MgO	9.2	7.5
CaO	11.8	15.9
Na_2O	0.6	0.6
	Atomic %	
O	60.3	61.1
Si	16.9	16.3
Ti	1.1	0.15
Al	6.5	10.1
Fe	4.4	1.8
Mg	5.1	4.0
Ca	4.7	6.1
Na	0.4	0.4

Table 2
Concentration of Elements in Bulk Soils and Agglutinate Fractions (12)

Major Elements (Wt.%)	Highlands (64421)		Mare (71501)	
	Bulk	Aggl.	Bulk	Aggl.
SiO_2	44.97	44.85	39.82	38.96
TiO_2	0.53	0.68	9.52	9.98
Al_2O_3	27.82	26.32	11.13	10.87
FeO	4.71	6.07	17.41	18.16

Table 3
Grain Size Characteristics

	Apollo 16 (Highlands)	Apollo 17 (Mare only)
Mean Grain Size:	101 to 268 μm	67 to 169 μm
Sorting:	2.3 to 3.45ϕ (poorly to very poorly sorted)	2.03 to 3.33ϕ (poorly to very poorly sorted)

DISCUSSION (Heiken and McKay Paper)

SPEAKER 1: I don't want to beat this point to death, but I still don't understand why the farside is the location of the first lunar colony.

HEIKEN: Ask someone in the O'Neill group, if they are here. I believe it's because you can't get things to L-5 from the lunar nearside.

McKAY: Yes, just one additional comment: I think that there was maybe one more slide in Grant Heiken's group. Could we have the last slide please? (See flow chart in abstract) Grant alluded to the idea of processing and concentrating on lunar soils in the regoliths. And if we think of lunar regoliths as ores, then we have to think in terms of concentrating them. And this is a simple scheme, I'm sure there are many and better schemes of concentrating the fine-grained fraction, the sub-20 micron in this case. This scheme uses a combination of elutriation or sedimentation combined with magnetic separation to concentrate the fine-grained fraction. Now, why do we want to do this? Well, it turns out the fine-grained fraction is highly enriched in some elements; for example hydrogen might be enriched by a factor of 10 over the bulk soli. Reduced iron is enriched. Nickel is enriched, zinc, gold, sulfur, carbon; other elements are all enriched in this fine-grained fraction which we can concentrate by elutriation and by magnetic spearation. We have to start now to think in terms of concentrating this portion of the soil, I think. This happens to be a closed-water-slurry system. I'm sure there are other systems that will do the same thing.

SPEAKER 2: What are the minimum concentrations of iron and titatniun that are needed in the soil so that the mining process will be practicable? How well does the geochemistry of the soil have to be known to actually instigate a mining process? The aluminum-silica ratio - the only aluminum-silicon ratio of the back-side basins that are known - is the aluminum-silicon ratio of Tsiolkovsky.

HEIKEN: There is also an aluminum-silicon ratio for Mendeleev. Am I correct? I'm pretty sure there is. We quoted one recently, we looked it up. As far as the processing goes, you've got me, I look at what's there and put it out and say, okay, here are the elements, and I think there are going to be several other talks on the processing, later in this session. That's the reason they're here.

SPEAKER 3: You must also depend on the - how much the energy costs. You're willing to say, "I've got lots of solar energy, and it doesn't cost you anything." That's one boundary condition. Not a very realistic one.

DISCUSSION (Heiken and McKay Paper)

SPEAKER 4: One comment on the siting requirement. That siting requirement on the backside of the Moon was for direct launch either to L-4 or L-5. If you change it so that you can launch to the unstable Lagrangian points in front and back of the Moon, then you can do your siting anywhere.

HEIKEN: We're just going on the assumption that L-5 or L-4 was most desirable.

HYDROGEN RESOURCES FOR THE MOON; Richard J. Williams, Code SL, NASA Headquarters, Washington, D. C. 20546.

If abundant supplies of hydrogen and oxygen are available on the moon, a viable economy based on the reaction of hydrogen and oxygen to produce water can be constructed. The uses of hydrogen, oxygen, and water are manifold: Biological, power production, and propulsive systems can all effectively function on this hydrogen economy. If the use of such an economy is proposed, then largely independent of any other assumptions, the magnitude of the hydrogen and oxygen resource needs is the same as the stoichiometric ratio of hydrogen to oxygen in water--that is, 0.125 by weight.

Oxygen, combined as oxides and silicates, is relatively abundant on the moon, comprising in excess of 50% by weight of lunar materials (1). The average lunar hydrogen resources are the order of 0.01% by weight; no significant indigenous water is present in the returned lunar materials. The ratio of hydrogen to oxygen is 0.0002 on the moon, and consequently effective exploitation of lunar oxygen resources will require the importation of hydrogen to the moon. The basis of such an economy is a series of chemical reactions, and any analysis of the economics of importation should be normalized to moles of material. If mass delivery is the primary cost driver for importation, then hydrogen which has the greatest number of moles per unit mass of all the elements would be the most economical material to import. Because of the extremely small quantities of indigenous lunar hydrogen and the large quantities of hydrogen necessary to match the lunar oxygen resources, it is doubtful if an economy independent of imported hydrogen can ever evolve.

The lunar hydrogen economy can be summarized as the following two steps:

1. Hydrogen is reacted with lunar material to produce water via reactions like--$H_2 + MO = M + H_2O$ (in which M represents a metal or metals);

2. The resultant water is used for biological purposes and, in part, decomposed to free hydrogen and oxygen for biological and other uses.

In theory such a system can be closed so that once a stable steady state is attained, nothing but energy need be added to keep the system cycling. In practice, however, unintentional losses--leaks--and intentional losses--fuels for propulsion and other exports--will occur. The system is open; and, in addition to energy, lunar soil and hydrogen must be continually added to maintain a viable system. Both the energy and resource requirements of the open system will be larger than the equivalent closed system; the net economics of such a system can only be judged in the context of the larger system of which it is a part.

A metals industry can be formed on the basis of the reaction given in step 1 above. The process would be a form of zone refining based on the relative reducibility of the various materials. The general reaction given involves gases--hydrogen and water--on opposite sides of the reaction, and thus it can always be made to proceed to the right to some extent by adjusting the ratio of hydrogen to water--that is, the rate at which hydrogen is admitted to the process relative to the rate at which water is withdrawn from it. Thus, a desirable adjunct to a lunar hydrogen economy would be a substantial metals industry. Eventually a net export of metals should be attained. This export might form the base for an economically self-sufficient lunar colony.

The production processes would also produce by-products. Some, such as carbon (10-80 ppm), nitrogen (40-120 ppm), and helium (5-25 ppm), are useful and not harmful; others, such as sulfur (500-22,000 ppm), are potentially useful, but also harmful. As examples, carbon could be used in steel production; nitrogen, after conversion to ammonia, as fertilizer; and helium, as a dilutant for oxygen in the breathing atmosphere. Sulfur would probably be released from the process as hydrogen sulfide and would be highly injurious to plants and animals and damaging to many aspects of the physical system of a colony, for example, fuel cell membranes. Any system design must account for these by-products by putting them to desirable uses and neutralizing their undesirable effects.

Some of these physical resources, products, and by-products are systematized in the table below:

Minimum Biological Needs (per man per day at 100% chemical efficiency)(2)

Resources (grams) -	
Hydrogen	250
Lunar Mare Material	4320
Products (grams) -	
Water	2160
By-Products (grams) -	
Iron	230-500
Sulfur	2-95
Nitrogen	0.17-0.52
Carbon	0.04-0.35
Helium	0.02-0.11

These quantities do not appear to be disturbingly large until the process is scaled to colonies of 10,000 people and the needs expanded to more than just the biologically necessary minimum. On such scales, sulfur accumulations in excess of a metric ton per day would occur while at least 100 kilograms of helium would be freed per day.

In summary, a hydrogen economy based on the use of lunar materials and imported hydrogen would be useful in space colonization. Such an economy includes a large metals industry as a natural adjunct. It may be possible for such colonies to become economically self-sufficient by exporting metals. Many other by-products would result from the reaction of lunar material with hydrogen to produce water. Some of these have properties which make them useful; others have undesirable properties and could pollute the system. Although the present discussion has been directed toward a lunar colony, most of the comments would be relevant to the exploitation of asteroidal resources or of those other satellites. Planning of a colony based on a hydrogen economy should incorporate the facts that at least hydrogen will have to be imported and that the by-products of the processes are not minor, useless, or harmless.

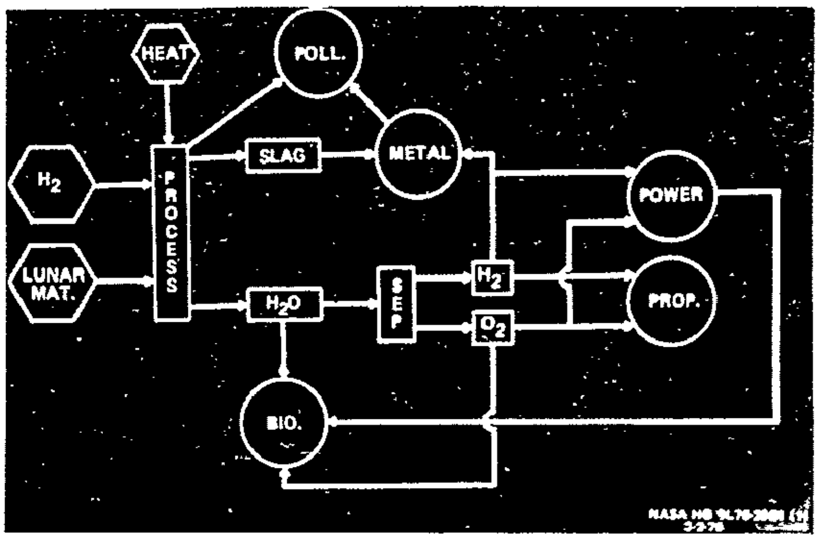
NOTES

1. This and other abundance data have been retrieved from various papers in the Proceedings of the Lunar Science Conferences, 1 through 6. They refer to mare basalt chemistries and in many cases have been converted from original data into the units used in this paper. A basic, but not as complete, reference would be S. R. Taylor (1975) Lunar Science: A Post-Apollo View, Pergamon Press, Inc., New York, 372 pp.

2. Many investigators have studied the resource and technology needs for a lunar colony. Those in Design of a Lunar Colony, 1972 NASA/ASEE Systems Design Inst., Rept. on NASA Grant NGT 44-005-114 summarize much of the earlier work and have been used as the basis of the ideas present in this study.

HYDROGEN RESOURCES FOR THE MOON

Richard J. Williams



A flow chart for hydrogen in a lunar economy. The biological (BIO.), pollution (POLL.), and propulsion (PROP.) aspects of the system have not been analyzed and are considered only as resource sinks.

DISCUSSION (Williams Paper)

SPEAKER 1: To dilute your oxygen for breathing purposes, I will propose that the helium might be more abundant and equally useful component.

WILLIAMS: It might well be. That is indeed another of the socalled byproducts that I neglected in the analysis. But, yes, that would be a very effective medium.

SPEAKER 2: You mentioned the availability of nitrogen. Could you give us some idea of what the fraction of nitrogen might be?

WILLIAMS: It's approximately 100 ppm. You have a fairly abundant supply of it.

SPEAKER 3: I want to point out again that nitrogen is highly enriched in the fine-grain materials, so there's an advantage there in concentrating that material.

WILLIAMS: Yes, this whole aspect to the concentration to the fine-grain material is something that has to be looked at carefully. It depends on what levels of concentration you really do get when you take the effort to concentrate it, which requires the input of energy and work to do it; where that balancing out occurs determines whether you really can use the finest fractions to get all the resources you need. I have not seen that analyzed in a straightforward, complete manner, where I can say, yes, it is worthwhile to do that in terms of the net functioning of your economy.

SPEAKER 4: It wasn't clear to me, but was your last calculation of your energy requirements to support a human being based on the binding energy of the water molecule which he drinks during a year?

WILLIAMS: No. It was based on the fact that your economy has to run basically on the separation of hydrogen. I may have mentioned drinking but I meant the breathing, the supply of oxygen due to that decomposition.

SPEAKER 4: Why do you have to decompose the water molecule to supply the human body with water?

WILLIAMS: No, to supply him with oxygen. To-breathe.

SPEAKER 5: Surely you're considering the possibility of supplying the oxygen biologically. If you have to raise food, why aren't you thinking about a photosynthetic plant?

DISCUSSION (Williams Paper)

WILLIAMS: You can close your cycle that way, but at low efficiencies.

SPEAKER 5: That is, of course, the same solar energy that you might use with solar cells or other things, but it's pretty readily available.

WILLIAMS: Right. But I think, again, the point is that, no matter how you do it, you've got to pump energy into the system and it's got to be a lot of energy and it is of the order of that decomposition reaction for water for scaling purposes.

SPEAKER 6: For an importation of oxygen and hydrogen simultaneously, I feel that the hydrogen peroxide is a good material to transport because itself is unstable already at the higher energy level, so it takes less energy to take apart the hydrogen and oxygen; thus you save a lot of energy need.

WILLIAMS: Well, I think initially, what you find is that the driver is the amount of material, in my terms the amount of moles of material that you supply to the system per unit weight going up. I'd much prefer to import hydrogen because I get more moles per gram of that than anything else. I think the economics of transporting things work out that way fairly well.

WATER ON THE MOON

James R. Arnold University of California, San Diego, La Jolla, CA

The problem of long-term operations on the moon is a problem of resources. On earth human beings use more water than anything else, by far. There is plenty of oxygen in lunar soil and rocks, and solar wind hydrogen in the lunar soil is an obvious though expensive source of the other component. Thorough outgassing would yield hydrogen for one liter of water from a few tons of soil.

The real water mines on the moon are almost certainly to be found, as Watson, Murray and Brown point out (J. Geophys. Res. 66, 3033-3045, 1961), in the permanently shadowed regions near the poles. They estimate a steady-state temperature < 120° K, but it is probably much lower than that. It the heat flux from below and solar wind energy input are the dominant terms, as seems reasonable, the temperature must be of the order of 40°K. At such temperatures not only ice but other volatiles, even CH_4, should be retained. These unseen features, at least 2×10^5 km^2 in area, and extending down to at least 60° latitude, are the repository of a significant fraction of all the water vapor emitted from the moon since the poles reached their present position.

The bombarding meteorite flux has two effects: it evaporates some solids (which in part re-condense), and it buries material beneath the surface.

The mass of volatiles so trapped is of course very uncertain. It seems unreasonable to suppose that the orbital plane of the moon has been fixed since the earliest stages of melting and differentiation, or even during and since the period of mare basalt deposition. However, it may not be too radical to postulate that the poles have been approximately fixed with respect to the sun since about 3×10^9 years ago. Nearly all the major topographic features producing the shadows were formed before this. If such "recent volcanic" events as the formation of the Aristarchus plateau and the Marius Hills have taken place since then, I estimate (guess) that the deposited ice at the poles may exceed 100 km^3, or 10^{11} tons of H_2O. This would be a layer of the order of one meter in thickness. If present, it is vastly larger than any imaginable mass of water which could be carried by humans from the earth. Other sources of H_2O, such as comet ice released on impact with the moon, and re-emission of solar wind hydrogen as H_2O, are also capable of making major contributions. The uncertain status at present of observations of lunar transient events raises a question about inclusion

WATER ON THE MOON

James R. Arnold

of this potential source.

The detection of this icy material, and measurement of its regional distribution, can be accomplished by the gamma-ray chemical mapping experiment proposed by the author and his colleagues for the Lunar Polar Orbiter (recently renamed Terrestrial Bodies Orbiter-Lunar). The capture of neutrons by ^{1}H produces a characteristic 2.22-MeV line. Such a study must of course precede attempts at exploitation.

The recovery of the ice should be easy, since it is located at or near the surface. Impact gardening has mixed the lunar surface to a depth of a few meters in the last 3×10^{9} years here as elsewhere, and one may guess that the surface material will be "dirty ice" rather than icy dirt. In the absence of direct sunlight energy for mining and extraction must be supplied from the outside.

The two resources required in largest amounts for human operations on earth are water and soil. The area of the moon is comparable to that of Columbus's New World, so soil is no problem. Colonists must in any case treat water as precious, but the presence or absence of these polar ice caps may still be decisive for the practicality of colonies, either on the moon itself, or at the lunar Lagrange points as proposed by O'Neill. Other resources such as carbon, nitrogen, oxygen and iron are unlikely to be a serious problem, if the abundant solar energy can be suitably exploited.

DISCUSSION - (Arnold Presentation)

SPEAKER 1: In their (Watson et al) calculation of the stability of water in this shaded region against thermal, solar insulation, did they calculate or take into account the energy deposition due to impacting particles?

ARNOLD: No, they did not. I've thought about it a little bit. My impression, and I haven't really solved the problem, is optimistic for the following reason. If I'm right about the 40 degrees K, then the volatility of water at that temperature isn't grossly different from the volatility of silicates at room temperature. What I expect would happen if there were an impact is, just as in the case of craters in soil, there would be a vaporization of a few times the projectile mass and then perhaps a melting of another similar layer and then thousands of times as much material excavated and thrown about. On that basis, there would be a small amount of water lost, some of which would recondense in this very cold area, some of which would be lost in space. The surface of the soil, if there were a lot of very small scale impacts (and, of course, the small particles dominate), would rather quickly be covered with a layer of soot or debris, which would be an effective thermal shield against any but the larger impacts. This is something people need to study, but I would bet anybody that the answer will be favorable.

SPEAKER 2: Didn't some of the Apollo missions go to areas that were shielded, for example, around boulders and areas where you would expect to see meters of water or ice as you would suggest?

ARNOLD: No, the Apollo missions were all confined to near equatorial latitudes. On Apollo 16 they went under a place called Shadow Rock to collect some permanently shadowed soil. There are a lot of things about that that are completely different. The rock itself reaches a daytime temperature of the order of 400 degrees K and reradiates. The lateral distance is of the order of a meter for thermal conductivity rather than a kilometer and diffusion goes as the square of the distance. Besides, the region they happened to select was not permanently shadowed. I don't think they had the opportunity to do a real test of this hypothesis. The large permanently shadowed regions do extend down to about 60 degrees latitude. There are a few places where there are high walls, but none of those have been sampled. There were high-inclination lunar orbiters that have been up there, but, of course, they're photographic sensors and they don't see the dark places.

SPEAKER 2: Could you say again how you compute 10^{11} tons as being the total amount there would be and the few meters depth that you estimate?

DISCUSSION (Arnold Presentation)

ARNOLD: All I did was to say there is an area about $2 \cdot 10^5$ square kilometers (which is like Lake Superior or the Caspian Sea). I then made a calculation based on an absolute guess as to the degassing rate. Aristarchus degassed so much material and then I used Watson, Murray, and Brown's ballistic calculations that about 1 percent of it, a fraction roughly equal to the area of traps, will arrive in these cold traps by ballistic degassing. You can read in their paper what I think is a sound argument. So, it was on that basis that I arrived at a guess, which I happen to think is a rather conservative guess, as to the amount of material there.

SPEAKER 3: Given the amount and extent of this ice deposit, and the known rate of impacting of objects of various sizes, should there have been transient events detected by mass spectrometers emplaced? That puts a limit of sorts.

ARNOLD: I haven't frankly thought that either. I would kind of doubt it.

SPEAKER 4: I've done that kind of calculation that I'm supposed to be talking about over at LSI this afternoon. I'm going to mention it before their panel discussion this evening. But I did calculate for an outgassing event like at Aristarchus what you would have to have in order for it to have been detected by the ALSEP instruments. And, it turns out that an event like Kozereff has suggested and has been reported for a TLP, that SIDE would have detected it, had one occurred in the last few years. Also, as far as numbers go, if there's an impulsive event of a few hundred kilograms to maybe 1000 kilograms, it would have been detected by the ALSEP experiments (R. Vondrak).

SPEAKER 5: If I've read all those abstracts right, they say nothing's (transient events) happened. So the question I'd like to ask you, Jim, is since all of our lunar samples are devoid of water, why should we think that there's any water in the youngest volcanic materials. There's gas, but there's no evidence it was water.

ARNOLD: We know what the primordial material is. We know what the meteorites are. We know what the cosmic abundances are and we start with an object that was made from that material. The only question is, how completely the Moon did fractionate in the various processes of its formation, the large amounts of water that were originally present. Indeed, one sees things now which are very dry. It's obviously much easier to degas the outside of an object than the inside of an object. I'm simply, Bill, relying here on a chemist's intuition that the last traces of water are hellishly difficult to get out anything. Take the glass in a piece of Pyrex - the amount of water contained in a piece of Pyrex tubing in a vacuum system is of the order of the sort of thing I'm talking about; of course, that Pyrex was formed in an Earth environment. But, it may be that all the water was degassed down to a part per million or a tenth of a part per million. I would regard that as exceedingly strange, but the world, of course, doesn't have to behave as my intuition dictates.

DISCUSSION (Arnold Presentation)

SPEAKER 6: I'm glad you raised that Watson, Murray, and Brown paper because I feel it's possible to criticize it on several grounds in the light of what we've learned since 1962. First, as for these allegedly permanently shadowed regions, this assumption of their permanence assumes that the Moon's obliquity had remained unchanged in geologic time and recent work by Bill Ward at SAO shows that this is not the case and that the lunar obliquity in remote ages was very markedly different from what it is today. And a second major criticism, of course, is the fact that, in view of the degassing of the returned lunar samples, it's not entirely clear that there is water of hydration anywhere. And in particular, Watson, Murray, and Brown proposed that serpentine and other hydrated rocks would be found in the vicinity of wrinkle ridges, which they attribute to volcanic activity. Again, it's not clear in the light of returned lunar samples that we would find serpentine or similar rocks there or anywhere. Perhaps you could comment on these points.

ARNOLD: The last one seems to me trivial, I must say. Of course, these people in 1961 had no idea of the lunar chemistry and were bound to make wrong guesses as any one of us would have. The question of whether indeed the rocks were completely degassed, I think we've been around on. Admittedly, that is a source of great uncertainty. Admittedly, the Moon is much drier than they thought it was. The numbers I've given can be criticized as quesses, but I don't think there's any information either to confirm or deny them at present. As far as the obliquity of the pole, I certainly hope that I'd taken that into account. Had I assumed that the poles had been in their present position 4.5 billion years ago, I would have been very much more optimistic than I am because there certainly has been an enormous amount of differentiation and evolution, thermal processes in that earlier period. I took as a ground rule that the pole had arrived at its present position only after the major mare events had taken place. If that's false, then the story is very much strengthened.

PROSPECTS FOR FINDING THE MOST VALUABLE POTENTIAL RESOURCE OF THE MOON: WATER P. M. Muller Jet Propulsion Laboratory Under Contract NAS 7-100

If free water can be found and extracted easily in quantity on the moon, the resulting supply of cheap rocket fuel makes an immense difference in the practicality of large scale lunar operations and colonization. Unfortunately, petrological analyses and most resulting models of lunar interior evolution appear to contraindicate the presence of water in the moon. It is suggested that these and other observations are not yet able to finally disprove the presence of water-ice trapped below the surface. On the other side of the question, compelling evidence that the sinuous rilles are positive water indicators is reviewed. There is also the possibility of a definitive experimental test. The Radar Sounder Experiment results from 15mhz observations reported at this conference show unexpectedly strong echoes at depths between roughly 200m - 1km in the *margins* of Serenitatis and Crisium. It is a suggestive observation, because even a small amount of water, under the trapped ice for example, is consistent with this data and the fact that the experiment radar fails to see anything more *below* these areas. The locations agree with the distribution of sinuous rilles, and in depth with the earlier suggestion that the moon acts as a water-ice trap between depths of about 100m and the 0°C isotherm for any internal outgassing or impactive (*e.g.* cometary) deposition of ice. On a more speculative level, the presence of transient events, cinder cones, eroded craters, ghost craters, sinuous rille deltas, and mare shoreline benches/beaches, is at least consistent with the early presence of water even on the *surface* for short durations. In view of the critical role of water to lunar industrialization, we must be conservative, and view the question of water trapped below the surface as at least scientifically *open.* It is also essential to note that *if* the water-ice is present, we do know where to look, and can expect to find it at a feasible depth for recovery. It is concluded that further studies of the water situation scientifically, and eventual direct search for water in likely lunar areas, should receive very high priority in any lunar resources program.

The basic key to practical use of the moon as a manufacturing base for space exploration, is the availability of materials suitable for refueling rockets. This follows from the tyranny of Celestial Mechanics (in the required Δv for space flight), and the practical limitations of chemical rocket fuels. This is well known, but an example is pertinent. It is cheaper to operate a rocket from the surface of the moon to low earth orbit ($\Delta v \simeq$ 6km/s), than to reach low earth orbit from the earth's surface ($\Delta v \simeq$ 7km/s plus atmospheric drag loss and fighting the 1g environment). The moon-to-orbit

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shuttle need not be aerodynamic, nor capable of high accelerations (>1g) to operate efficiently. Operating from *lunar* orbit, refueling the lunar orbit station from the lunar surface, it is possible to operate a *round* trip, one stage, moon-orbit to earth-orbit to moon-orbit shuttle ($\Delta v \approx 8$km/s) with substantial payloads. This profile is orders of magnitude cheaper than an operation mounted from the earth's surface, and surely makes the difference between viable, and prohibitively expensive, earth-moon industrialization.

The best, and perhaps the only *practical* form for this resource is water directly obtained as H_2O. Dissociation to liquid H_2 and O_2 should be economic with solar power because of the absence of a significant lunar atmosphere (*e.g.* aluminum foil reflectors in excavations or craters etc). Alternatives such as removing the very small amounts of hydrogen found in the lunar soils[1], coupled with extracting the abundant but tightly bonded oxygen, are probably orders of magnitude more costly. It would therefore be very fortuitous indeed if free water in useable quantities could be found and exploited in a manner similar to earth's petroleum.

Unfortunately, in the view of most scientists, there is no free water on the moon[2]: "Water is effectively absent from the moon." Petrologists and others have looked almost in vain for evidnece of water from the samples, and even the so-called *rusty* rocks[3] are more likely to have arisen from volcanic, fumarolic, or contaminatory processes. In fact, the consensus of petrologists is that the lunar material did not even *arise* under conditions including water, contrary to the earth (and probably Mars) where it is generally accepted that the atmosphere and hydrosphere were baked out of the interior of the planet. Despite this strong argument, we have learned from the History of Science that it is very difficult to disprove a plausible hypothesis by the process of eliminating all possibilities. It is not difficult to conceive of possible alternatives: (a) moon formed cold, water only near surface or driven up as the moon heated, not involved in fractionating, but trapped, and giving rise to sinuous rilles where released; (b) moon formed fractionated except for mare lavas which formed deep in water free environment, leaving water trapped in the crust which the mascons show has remained cold. It would be very unconservative to view all possibilities as presently disproven.

On the other side of the question, sinuous rilles stand as the strongest indicator of where to look for trapped water. This was first suggested[4], but other non-erosion explanations including lava tubes (drainage channels)[5] and ash flows[6] have been advanced. These seem difficult to support[7], and [7] makes a strong case for sinuous rilles as the result of a very special kind of erosion. This can take place without the need to invoke a significant lunar atmosphere, and the water can be held to pressure under an overburden of ice[8], or as subsurface flow under soil and ice etc. There was, and remains some criticism of this model[9], but this can be answered[10], and the erosion explanation stands as plausible, and in my view, the most likely. Sinuous rilles generally begin in craters, and they are distributed around the

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circular maria[7]. We therefore know where to look.

As to the origin of water initially, comets[11] and trapped outgassing[12] have been suggested. This latter argument particularly, convinces me that the probability of finding trapped water-ice is too substantial to ignore. The near-surface lunar temperature is below 0°C, and 100m of lunar soil overburden will preserve ice on the airless moon for geological time[12]. The moon therefore acts as a water-trap, and a substantial fraction of emplaced or outgassed water (if it was ever present), *must* be trapped between the 0°C isotherm and 100m below the overburden. If the ice is present, it is within a practical recovery depth.

Other than sample analysis, only one Apollo experiment gives us the chance to identify deposits of ice, and this is the Radar Sounder. The data calibration has been very demanding and the experimenter's quick look results are only now becoming available in this conference [13]. The 15mhz results show surprisingly bright returns, which come up from deep below the maria Serenitatis and Crisium, to within 200m - 1km of the surface at the shores, sometimes appearing also below the higher surrounding territory. Ice itself is not easy to see compared with the expected rock (dielectrics near 3 for ice, 4 for regolith), but even a very small amount of water below the ice, would give rise to precisely the observed result. It is particularly significant that the radar fails to see anything *below* this final bright return level, as though its dielectric was very high: water≈ 80. This observation agrees in location with the distribution of sinuous rilles, and in depth with the ice-trap argument, and further study is warranted.

On a more speculative level, we have indication of transient events[14], and photographic evidence of apparently volcanic cinder cones, eroded craters, ghost craters, sinuous rille deltas, and mare shoreline benches/beaches[15]. While there are other explanations for these phenomena, it is curious that the presence of active water (probably under an ice overburden) on the surface for a short time in the absence of significant precipitation, could explain all of these photographic observations simultaneously. There are great difficulties with trying to place water on the surface, but there may be ways of satisfying all constraints[16].

The point of this paper is not to attempt a demonstration that trapped water on the moon is likely, though I personally believe that it is probable. The argument of this paper is that: (a) water is probably the most valuable natural resource we could find on the moon to support large scale lunar industrialization; (b) the arguments against water in the moon are strong, but not yet definitively able to rule out its presence; (c) there *is* provocative evidence on the positive side of this question; (d) therefore, *conservatism* of science demands that we treat the question of trapped water-ice as *open*, and; (e) pursue with vigor the further study of the question, and undertake an adequate search, as a very high priority part of any lunar resources program.

PROSPECTS FOR FINDING: WATER

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LUNAR HYDROGEN SOURCES; John A. O'Keefe, Goddard Space Flight Center, Greenbelt, Maryland 20771.

Introduction: During the 1950's and 1960's, the idea that the moon is cold attained intellectual dominance, under the leadership of the founders of planetology. In terms of cold-moon thinking, the idea that the moon might contain economically significant reservoirs of hydrogen, at depths where they could be released, was inconceivable. The Surveyor data suggested, and the Apollo samples confirmed the fact that the moon has had a history of volcanic activity on a very large scale; but the new thinking has preserved the belief in a dead moon in our times; it is supposed to have ceased volcanic activity at about -3.0 b.y. Now, however, the seismic data make it clear that the moon remains hot in its interior; although it has a thicker crust than the earth, its asthenosphere seems to be nearer to melting than the earth's asthenosphere.

It is of great importance to re-examine critically the ideas of the cold-moon epoch in the light of the newer data.

Volcanic Origin of Ray Craters: In particular, we must re-examine the belief that most lunar craters are the product of impact. The most interesting craters here are the ray craters, like Tycho, Copernicus and Aristarchus, whose floors are, on any basis, much younger than 3 billion years.

What is known about Aristarchus is that it is now emitting small quantities of gas; the accompanying radon has been detected by Gorenstein (1). A large number of reports, going back for centuries and including some of the best observers (2) point to occasional displays, often of orange or reddish light, in Aristarchus, usually lasting less than an hour. A spectrogram obtained by N. A. Kozyrev (3) shows, he reports, lines of molecular hydrogen, including one measured at 463.4 nm $\pm$ 0.1 nm, which presumably corresponds to the strong pair of lines at 463.2 and 463.4, both of intensity 9, and the only lines of this intensity in the visual spectrum to the violet of 490.0 in the H_2 spectrum.

The existence of the so-called bright rays, which radiate from these craters, is also evidence of continuing activity. The lunar surface is subject to deposition in most places, at a rate on the order of 1 g cm^{-2} $(my)^{-1}$ (4). It follows that observable markings on the moon ought to be obscured in a few million years at most. The only way that lunar rays could be imagined to survive is if there is some agency on the moon which from time to time sweeps the dust off parts of the surface. For instance, when the lunar module took off for the earth, the rocket exhaust cleared the dust off

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the local rocks in just this way, leaving a bright spot which was later photographed from orbit. The agency, presumably gas, which clears off the ray areas, clearly radiates from the ray craters. However, it does not come out from the center of the crater (as it would on the impact hypothesis), but from the walls, where much of the current activity appears to be (e.g. the lava flows, or some of the Aristarchus red glows). If we were to start from the data now available, with an open mind, it is very doubtful whether we would reach the conclusion that most lunar craters are due to impact, though some must be. In particular, the old argument that rays are rock flour, ground up by the impact, has lost its force; we now know that lunar fines are darker than the rock, not lighter.

Tektites: From the viewpoint of the cold-moon era, the idea that tektites, which are recent granitic differentiates, could come from the moon was anathema. We now know, however, that the moon does produce granitic glasses which bear the characteristic marks of tektites: low H_2O, low Fe^{+++}/Fe^{++}, low abundance of trace elements which are volatile at 1000°C, and, in the major elements, higher abundances of mafic oxides and lower abundances of alkalies (especially soda) than would be expected for the high SiO_2 content (5,6,7). Occasionally these glasses also resemble microtektites in their morphology and internal structure (7).

The popular idea that tektites are the product of meteorite or comet impact on the earth leads to a series of absurd or impossible conclusions (8) and must be given up. (E.g. craters 300 kilometers in diameter and, initially, 40 kilometers deep, or glass of good quality produced instantaneously in zero gravity).

The lunar origin of tektites demands volcanism (since tektites are not a random sample of the lunar surface). The volcano must be powered by hydrogen, because only hydrogen has an acoustic velocity at magmatic temperatures, which exceeds the lunar escape velocity of 2.4 km s^{-1}. Very large quantities of hydrogen are demanded, because the terrestrial strewn fields involve hundreds of millions of tons of glass; and in addition, one to two orders of magnitude more presumably never reach the earth, but go out into space.

It follows that underneath some of the lunar ray craters, there probably exist very large reservoirs of hydrogen.

On the Earth: Geothermal wells have been drilled to tap similar reserves of volcanic gases, chiefly steam. They have ranged from 300 to 1300 meters in depth (8). The wells do not have to be cased throughout their depth; there is always an impermeable rock on top of the reservoir. The probability of success is apparently much higher than with oil wells; in one field, out of 75 wells, only five were dry holes. Blowout preventers must be used in drilling. From the known oxidation potential of the rocks, it appears that at magmatic temperatures on the moon, the equilibrium is 80% hydrogen to 20% water.

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LUNAR
AND
SPACE UTILIZATION

METALLIC IRON AS A POTENTIAL FUEL FOR PRODUCTION OF HEAT ON THE LUNAR SURFACE Charles B. Sclar and Jon F. Bauer Dept. of Geological Sciences, Lehigh University, Bethlehem, Pa. 18015

Metallic iron alloyed with small but variable amounts of nickel and cobalt is an abundant constituent in both the highland and mare regolith (1, 2, 3, 4). Some of the iron occurs as either unlocked (liberated) or partly liberated particles which may be separated relatively easily from the silicate and oxide minerals of the regolith by conventional dry magnetic-concentration methods. The grade and recovery of this potential particulate iron product would, of course, depend on the strength of the magnetic field employed and the degree to which the loose regolith material is divided into size fractions by screening and dry-elutriation procedures prior to magnetic separation.

It is well known that the oxidation of metallic iron to either FeO, Fe_3O_4, or Fe_2O_3 is highly exothermic. The corresponding reactions are:

$$Fe + \tfrac{1}{2}O_2 \rightarrow FeO \ -65 \text{ kcal} \quad (1)$$
$$3Fe + 2O_2 \rightarrow Fe_3O_4 \ -267.4 \text{ kcal} \quad (2)$$
$$2Fe + 1\tfrac{1}{2}O_2 \rightarrow Fe_2O_3 \ -197.3 \text{ kcal} \quad (3)$$

Enthalpic values related to these equations are given in Table 1. For comparison, the heat of combustion of carbon in oxygen is -94 kcal per mole of CO_2, per mole of carbon, or per mole of oxygen. Inasmuch as the supply of iron from the regolith may be considered to be virtually unlimited, oxygen is the limiting factor in the combustion of iron on the lunar surface. Consequently, the most favorable reaction with respect to the evolution of heat is Fe $\rightarrow$ FeO (equation 1). Clearly, the evolution of 65 kcal per mole of product (FeO) or per mole of iron when iron reacts with oxygen to yield FeO is not as favorable as the yield of 94 kcal per mole of CO_2 or per mole of carbon from the combustion of carbon. However, if oxygen and not the fuel is the limiting factor, it is important to note that the reaction Fe $\rightarrow$ FeO results in the evolution of 130 kcal per mole of O_2 whereas the reaction C $\rightarrow$ CO_2 results in the evolution of only 94 kcal per mole of O_2. This argument, of course, is valid only if reaction rates are sufficiently high at elevated temperature so that the reaction Fe $\rightarrow$ FeO goes to completion. A hypothetical schematic flowsheet for the iron combustion process on the lunar surface is shown in Figure 1.

Although there are alternative sources of energy on the moon (e.g. solar energy), it appears to us that metallic iron in the lunar regolith constitutes the only easily recoverable mineral that might be utilized as a combustible fuel.

POTENTIAL FUEL FOR PRODUCTION OF HEAT ON THE LUNAR SURFACE

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Table 1. Heats of Combustion of Metallic Iron (ΔH in kcal) at 25°C, 1 atmosphere (5).

Reaction	kcal/mole of product	kcal/mole of Fe	kcal/mole of O_2	Mole of O_2 Required per Mole of Fe
Fe → FeO	-65	-65	-130	0.5
Fe → Fe_3O_4	-267.4	-89	-133.7	0.66
Fe → Fe_2O_3	-197.3	-98.7	-131.5	0.75

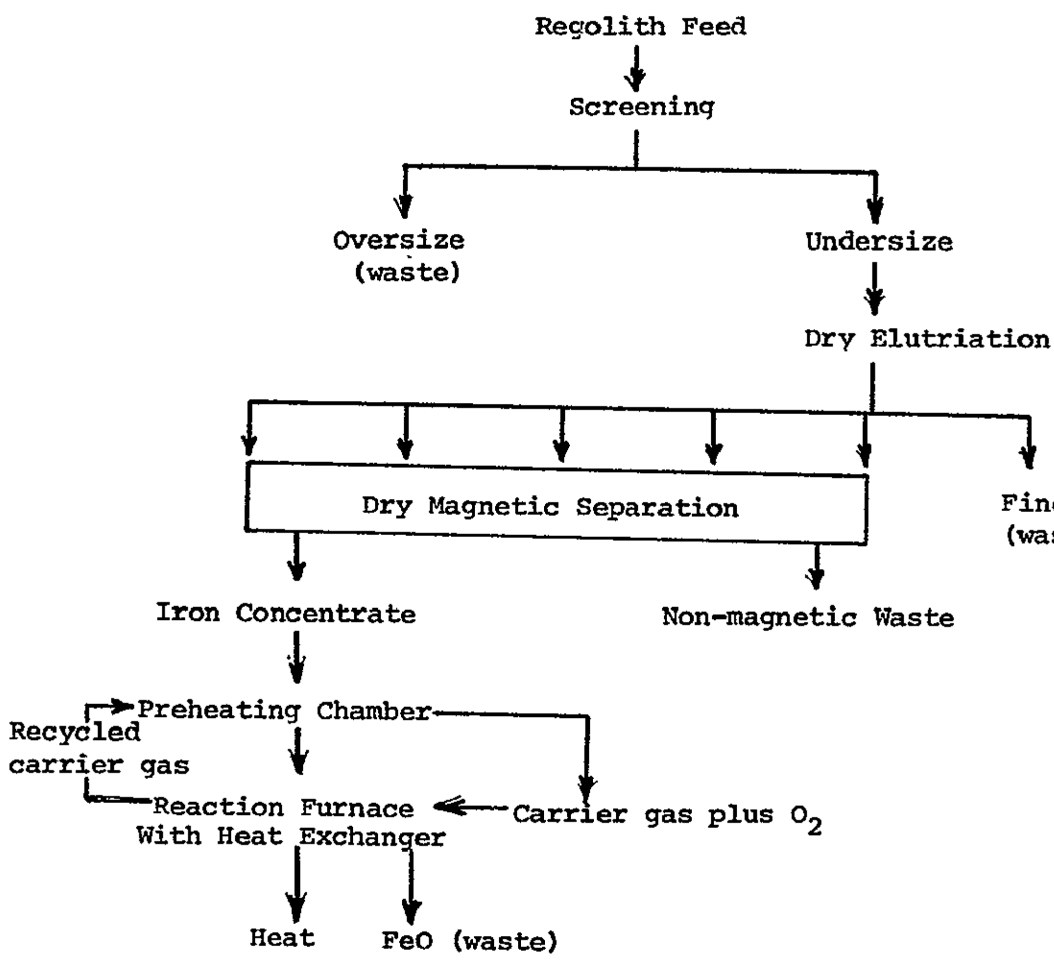

Figure 1. Hypothetical Flowsheet for Iron Combustion Process on Lunar Surface.

POTENTIAL FUEL FOR PRODUCTION OF HEAT ON THE LUNAR SURFACE

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DISCUSSION - (Sclar and Bauer)

SPEAKER 1: In magnetic separation, do you end up with anything besides iron?

SCLAR: No, not if you control the magnetic field strength properly so as to reject all materials with a magnetic susceptibility lower than that of iron, which should be the most magnetic material on the lunar surface.

SPEAKER 1: In our looking at the Moon as a place to do work, one of the big problems is sunlight being available part of the time. This (iron) would form an ideal battery where you wouldn't have to take the mass of the battery from the Earth. You could process the oxygen and the iron from the lunar material, separate them, and use them as battery during lunar night.

SCLAR: Okay, I accept all contributions of oxygen to this scheme. I just thought myself, and my colleague I think agrees, that if this ever came to pass, the first attempt would be with oxygen brought to the Moon. But, if there are alternative sources of oxygen, that would be even better.

SPEAKER 2: I just can't resist remarking that all of that waste that you had indicated there looked very good to me. You know, one man's waste is another man's resource, I guess.

SCLAR: You can look at the FeO as an iron ore but, then you're going to have to reduce it back to iron. It seems sort of silly to have to do that. Might as well keep some of the iron and process it directly.

SPEAKER 2: If you want the nitrogen and things of that kind, we're going to want to select for fines, and that was one of the things that you were throwing away. There may be a lot of compatible operations that could be involved.

SCLAR: Reaction kinetics are obviously the key here and obviously this is something that would have to be checked out on a laboratory scale initially.

EFFECTS ON THE LUNAR ATMOSPHERE RESULTING FROM LARGE-SCALE MANNED OPERATIONS; Richard R. Vondrak and John W. Freeman, Stanford Research Institute, Menlo Park, California 94025 and Department of Space Physics and Astronomy, Rice University, Houston, Texas 77001.

The present lunar atmosphere is a collisionless exosphere with surface number densities less than 10^7 cm^{-3} and a total mass of approximately 10^4 kgm. This tenuous state is maintained by the solar wind which promptly removes the majority of the ionized gas from the lunar vicinity through the action of the interplanetary electric field. The mean atmosphere life of an atom or molecule is the ionization lifetime (typically 10^6 to 10^7 seconds). This process determines the loss rate for all except the lightest atoms for which thermal escape dominates. The accelerated ions have been directly detected for both the natural lunar atmosphere and gasses associated with the Apollo missions (1). For the Apollo exhaust gases decay times of the order of one month were observed (2).

This solar wind loss mechanism is the dominant process only so long as the solar wind has direct access to the majority of the atmosphere. As the atmosphere becomes more dense, newly formed ions of atmospheric origin load down the solar wind and cause it to be diverted around the moon. Furthermore, the solar wind can carry away no more mass from the planet than its own mass flux to the planet. Venus and Mars each lose about 10 gm/sec to the solar wind. This represents about 1% for Venus and 20% for Mars of the mass flux of the solar wind through the respective planetary cross-sectional areas.

We wish to explore what happens if the atmospheric source rate from natural or artificial sources exceeds the solar wind's ability to carry off the gas. As the atmosphere becomes more dense, the base of the exosphere will rise above the surface and we expect the exospheric temperature to become greater than that of the lunar surface. Thermal escape will then become the dominant loss mechanism for the majority of the atmosphere and the atmosphere may become long-lived, since thermal escape times are thousands of years for gases heavier than helium.

The transition from a thin to a thick long-lived atmosphere is difficult to evaluate quantitatively because of our lack of understanding of exactly when a bow shock wave will form to begin to deflect the solar wind around the moon. Also, anomalous ionization may take place via Alfvén's critical velocity mechanism (3). We may simplify the problem by assuming the upper limit of mass loss due to the solar wind to equal the solar wind mass flux

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intercepted by the lunar disk, or about 50 gm/sec. Assuming source and loss equilibrium and a mean time to ionization of 10^7 seconds, this means an atmospheric mass of 5×10^5 kgm. We may further assume that this represents the critical mass and source rate beyond which thermal escape can become the important loss mechanism. Thermal escape will remain small, however, until the exospheric temperature rises. A quantitative evaluation of these atmospheric loss mechanisms is shown in Figure 1.

Finally, we estimate that for a total atmospheric mass of 10^8 kgm and an exospheric temperature of 800°K the thermal escape loss rate would be 60 kgm/sec. For atmospheres in excess of 10^8 kgm the loss rate cannot increase substantially and the atmosphere can grow indefinitely if the source rate exceeds 60 kgm/sec. Therefore, a constant addition rate of the order of 100 kgm/sec is required to transform the lunar exosphere into a long-lived state (4).

Figure 2 shows the ultimate atmospheric masses which result from various constant gas addition rates, Q. The effect of inducing a transition from an exosphere with rapid loss to a thick atmosphere with slow loss is illustrated by considering the result when the gas source is shut off (Q=0). The thick atmosphere decays with an exponential lifetime of several hundred years, whereas the thin exosphere decays in a few weeks.

Each Apollo mission deposited nearly 10^4 kgm of rocket exhaust in the lunar environment. A permanent base might be expected to release gas at the rate of 10^{-2} kg/sec.-man assuming supply traffic equal to one Apollo mission/man-month. Small colonies would not be expected to produce a long-lived atmosphere. However, even modest exploration releases gas much faster than the present natural rate of about 20 gm/sec, resulting in a lunar atmosphere in which the gases of natural origin would be only trace components.

Vigorous exploration or industrial production could result in gas rates greater than the 100 kgm/sec necessary to form a long-lived atmosphere.

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EFFECTS ON THE LUNAR ATMOSPHERE RESULTING FROM LARGE-SCALE

Richard R. Vondrak and John W. Freeman

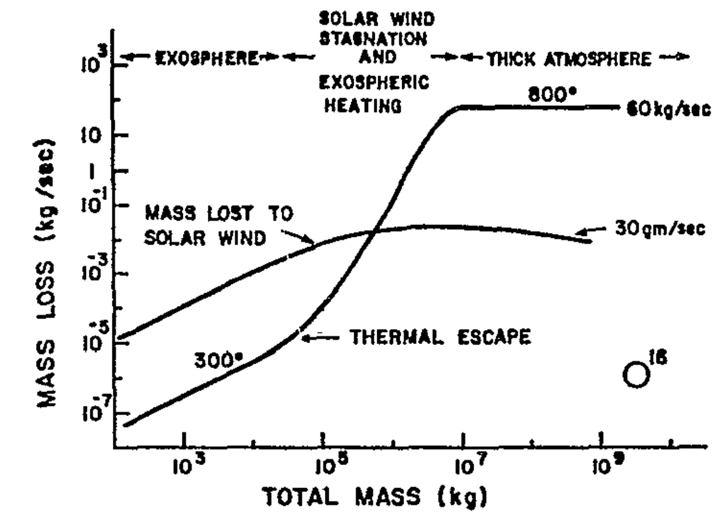

Figure 1. Loss rates from an oxygen (mass 16 a.m.u.) atmosphere

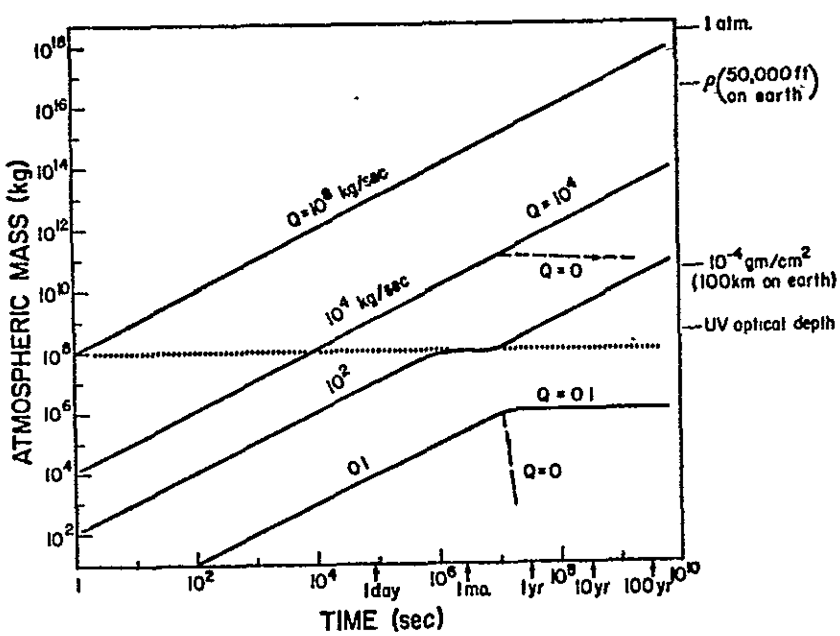

Figure 2. Growth curves of the lunar atmosphere. Dashed lines indicate decay in total mass if the gas source is shut off.

DISCUSSION - (Vondrak and Freeman)

SPEAKER 1: This is perhaps a comment rather than a question. Again, trying to compare a space colony and a lunar surface colony, I'm sure that in a space colony one would go to enormous efforts not to release gas simply because it was a valuable commodity and you could recycle it. I don't know what the economics would be on the Moon, but I think it's at least suggestible that the recovery of gas might be an equally important value and that you might turn out not to vent as much gas as terrestrial or Apollo experience would indicate.

FREEMAN: Yes. I think that's certainly a valid comment.

SOALR-COSMIC-RAY VARIABILITY

Robert C. Reedy, Los Alamos Scientific Laboratory, Los Alamos, NM

The exposure of men and materials to radiation-damage is a recognized problem in space exploration. Usually there is little need in space for much shielding against cosmic rays. However, there are occasional times, such as during early August 1972, when such large fluxes of energetic particles are emitted from the sun that astronauts in an Apollo-like spacecraft could be seriously injured, possibly fatally, from the radiation dose that they would receive. Thus, one important part of any space colony or space manufacturing facility will be thick walls for shielding against cosmic-ray particles (and meteoroids). The question considered here is what is the maximum flux of particles from solar events that should be considered in designing the shielding for a space habitation. The activities of various radionuclides measured in the top few centimeters of lunar rocks are used to examine the variability of solar-cosmic-ray fluxes over the last five million years.

Away from the trapped-radiation belts around the Earth, two types of energetic particles are encountered: the galactic cosmic rays (GCR) and the solar cosmic rays (SCR). Both types are mainly protons, but include about ten percent alpha particles and a couple of percent of heavier nuclei. The GCR particles have energies from several MeV to 10^{14} MeV or greater with an average energy of about 1 GeV. The flux of these particles is a few particles per cm^2 per second (1). The flux of GCR particles with energies below about 1 GeV varies several tens of percents during the eleven-year solar cycle, being diminished during periods of maximum solar activity. Measurements made on meteorites show that the average GCR flux over the last 4.5 Gy was not very different than the present-day flux.

The SCR particles have typical energies of tens of MeV, relatively few particles having energies above 100 MeV, and are emitted from the sun over periods of hours or days. Such solar events occur very infrequently, usually during periods of solar maximum. Over a typical solar cycle, the average omnidirectional flux of solar protons with energies above 10 MeV is about 100 protons/cm^2 sec (1,2), although the peak flux of protons above 10 MeV during the August 1972 solar event was about 10^6 protons/cm^2 sec (3). Near solar minimum, the flux of SCR particles is very low. Solar protons have been studied regularly only since 1956. Because of their low energies, SCR particles produce radionuclides only in the surface of objects in space. On meteorites this surface layer is ablated during passage through the Earth's atmosphere.

SOLAR-COSMIC-RAY VARIABILITY

Robert C. Reedy

The flux of solar protons for solar events during solar cycle 20 (1964-1974) is well known from satellite measurements, and the activities of 78-day ^{56}Co observed in lunar rocks were well predicted by the satellite data (2). The average flux of solar protons above 10 MeV during solar cycle 20 was about 82 protons/cm^2 sec, with 70% of these protons coming during August 1972 (1,3). The fluxes of protons during cycle 19 (1953-1963) were not well measured and estimates of the fluence for that cycle vary considerably (1,3). The activity of 2.6-y ^{22}Na in rock 12002 (2) implies an average cycle-19 flux of about 155 protons/cm^2 sec (above 10 MeV), about twice that measured for cycle 20.

Another important quantity describing the flux of particles during an SCR event is the spectral parameter which gives the energy distribution of the particles. The energy spectrum of solar protons is usually described by an exponential rigidity shape with R_o as the spectral parameter (1). The larger the value of R_o, the more high-energy-particles there are relative to low-energy particles. The energy distribution (and R_o) of the particles varies from event to event. The August 1972 flare was described with an R_o of about 100 MV, and the sum of the rest of the events for cycle 20 had a spectral parameter of about 55 MV. Including the August 1972 flare, cycle-20's average R_o was about 90 MV. The R_o for all events in cycle 19 was estimated from the ^{22}Na data to have been approximately 75 MV.

Spots on the surface of the sun were discovered by Galileo in about 1610. Starting about 1755, each eleven-year solar cycle has been given a number, the years of solar maximum in the middle of a cycle being those with the most sunspots. During the last 20 solar cycles, the sunspot numbers at solar maximum have varied by less than a factor of four (3). The annual-mean sunspot number at the maximum of cycle 19 was the largest ever observed, and was 71% greater than that for cycle 20. Thus it seems that sunspot numbers and SCR fluences are correlated. The sunspot data for the last 20 cycles are often interpreted as implying that the sun is very regular. However, there was a 70-year period from 1645 to 1715 when sunspots (and auroral displays in Scandinavia) appear to have been extremely rare (4). Unfortunately there are no appropriate radionuclides produced in lunar rocks with which to examine the SCR flux during this period. Over the last several thousand years, the production rates of ^{14}C in the Earth's atmosphere have varied, probably as the result of changes in solar activity. The activity of 5730-y ^{14}C in rock 12002 implies an average flux over the mean life of ^{14}C of about 200 protons/cm^2 sec (above 10 MeV) with an R_o of 100 MV (5), although there are several uncertainties in interpreting the measurements (the cross sections for the production of ^{14}C not being well known and some of the ^{14}C on the surfaces of lunar rocks possibly being of solar-wind origin). The activity of the 80 000-y ^{59}Ni in lunar samples produced by solar alpha particles is not very different from that predicted using present day alpha-particle fluxes (6).

Many faunal species on Earth have become extinct during periods of reversals in the polarity of the geomagnetic field and Reid et al (7) have argued that such extinctions were caused by large fluxes of solar protons. (They propose that, without a geomagnetic field, the solar protons reach and ionize the stratosphere, producing NO which then destroys the ozone layer.) To get significant ozone depletions during such reversal periods (which last perhaps one thousand years or more), they require solar flares one or two orders of magnitude more intense than that of August 1972. Six cases of species extinctions have occurred during polarity reversals during the last 2.5 My (7). This time period is intermediate between the mean-lives of 0.74-My ^{26}Al and 3.7-My ^{53}Mn. The ^{26}Al and ^{53}Mn activities measured in the tops of lunar rocks 12002 and 14321 imply average solar-proton fluxes of about 80 and 90 protons/cm^2 sec, respectively, and R_o values of 100 MV (8). (The ^{53}Mn result has some uncertainty because the erosion of the rock's surface significantly changes the activity profile produced by solar protons and the erosion rate must be fairly well known to determine the incident SCR flux (8).) The SCR-produced activities in lunar rocks suggest that superflares significantly larger than the flare of August 1972 could not have occurred very frequently during the last million years.

Additional measurements of radioactivities in lunar samples and of cross sections for certain reactions would help in further unfolding the history of the solar cosmic rays. There are only a few other long-lived radionuclides produced by the low-energy SCR particles which could be used for such studies (e.g. 12.3-y ^{3}H and 21 000-y ^{81}Kr). Several lunar rocks are available with short surface exposure ages determined by GCR interactions, and the activities of radionuclides in their top surfaces could be used to study the SCR fluxes during the surface-residence times of these rocks (9).

Although the sun may not be as regular as often believed (the irregularity viewpoint also being shared by astrophysicists trying to explain the very low observed solar neutrino flux), measurements of radionuclides in the top surfaces of lunar rocks show no major irregularities in the SCR fluxes averaged over several time periods. In all likelihood, the distribution of solar-proton fluxes is log-normal, although the possibility of superflares occurring can not be excluded. Thus space colonies will probably not be exposed to fluxes of solar particles significantly greater than those observed during the last 20 years, and the data for these recent solar events could be used in planning shielding requirements.

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(10) Discussion with J. R. Arnold and J. A. Eddy were very helpful in preparing this work. Financial support for much of the research related to this work was provided by NASA.

DISCUSSION (Reedy Paper)

SPEAKER 1: One detail, Bob. The 20th Century depression of the carbon-14 is not due to a decrease in production. It's due to industrial burning of fossil fuel. As far as we know, which is a considerably big uncertainty, that falloff in the 20th Century matches what's calculated from the models for the burning of fossil fuel. I would guess that the production is not particularly different.

REEDY: Well, it looks like some of the similar cycles that one has seen. I'll accept your comment.

SPEAKER 1: There is a perfectly known cause which would certainly make a contribution of this order of magnitude.

SPEAKER 2: Make a comment, too, that you really don't know that you won't sporadically once every 100 or 1000 years have a really giant super-flare.

REEDY: You can't exclude it, no.

SPEAKER 2: You can't exclude it, and hence it would be prudent to have in any such space colony little shelters because, after all, one of the happy properties of solar flares is that they don't last very long.

REEDY: Several days would be wise, but they are not going to get them every decade or every 100 years. I think that's the point I wanted to make. A lot of people say that the solar cosmic rays have only been studied for 20 years and in a sense, that's not really true.

SPEAKER 3: In the Ames study, the shielding design was based I think, largely on a flare that occurred in 1952, which was supposed to be an alltime biggy, and even to the extent that it was penetrating to the Earth at the equatorial region. Now I don't know, you didn't mention such a flare.

REEDY: I knew there was some earlier ones before 1956 that had ground-level events; I'm not really aware of the parameters on that.

SPEAKER 3: The other point is that, of course, the thing that burns you is the relativistic protons that come out very high energy and very fast so you don't have much warning and shelter approach is difficult under those circumstances. You have to have some kind of precursor event which tells you that there's going to be a flare.

DISCUSSION (Reedy Paper)

REEDY: Usually in a solar flare there are very few relativistic protons.

SPEAKER 3: Again, I refer to the baseline event that we were using.

REEDY: These things decay very steeply with increasing energy, at least all that have been really studied.

SPEAKER 4: Even relativistic protons take some time to defuse and you do get light and X-ray emission which travels with the velocity of light. So there is some time.

LARGE-SCALE PROCESSING OF LUNAR MATERIALS; Krafft A. Ehricke, North American Space Operations, Rockwell International, El Segundo, California.

Large-scale processing of lunar materials is defined as quantity production and value addition (at least to the level of refinement, if not of semi-finished and finished products) on an industrial scale and mode of operation. Industrial developments have two major aspects: technological and socio-economical. Although the presentation concentrates on the technological aspects, socio-economical considerations represent a part of the rationale underlying the methods considered most promising and economically competitive for the large-scale processing of lunar materials.

The two fundamental premises used are those pointed out by the author at the 23rd International Astronautical Congress in 1972:

1. The large-scale exploitation of lunar raw materials can become attractive not because lunar abundances of industrially important elements exceed terrestrial ones (in fact, the opposite is the case), but because the biological nature of the terrestrial environment places more stringent constraints on the exploitation and associated acceptable technologies of exploitation of increasingly poor deposits than the lunar environment. In other words, the primary advantage of lunar industries appears to be that it offers the option of separating processing space and living space (production and consumption) rather than offering materials not or insufficiently available on Earth. This also implies that the lunar environment should, if and when economically viable, be used not only for primary industrial purposes (raw material extraction), but for value-adding (manufacturing) processes as well.

2. Large-scale use of space for manufacturing can unfold only in conjunction with lunar resources (although certain Earth resources must be added). Orbiting factories near Earth are restricted to special products, because large-scale refining (e.g., of bauxite to aluminum) or production of non-special semi-finished products does not offer hope of becoming economically competitive, even for the most energy-intensive processes, because of the energy required (and the thermal, if not other, waste released into the biologically relevant atmosphere) to transport the raw materials into space. The Moon offers a low-g vacuum environment on the surface and a relatively easily accessible zero-g environment in circumlunar orbit. Both environments can be used advantageously as processing space for

LARGE-SCALE PROCESSING OF LUNAR MATERIALS

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secondary industries. In the case of the surface, this means that the lunar extractive industry should not degrade to a relevant extent the existing vacuum environment, least of all with a chemically aggressive gas such as oxygen, which is the main "waste product" of a lunar extractive industry. Because of the gravitational conditions in the Earth-Moon system, space manufactured quantity productions, based predominantly on lunar resources, can be provided to the terrestrial and extraterrestrial market at lower cost and lesser environmental burden than near-Earth orbital quantity productions (other than low-mass high-value products) based on terrestrial resources.

The first of the above points defines the reason for the potential attractiveness of large scale lunar processing; the second point stipulates the basic modes for maximum utilization not only of lunar resources, but of lunar environments as well and its potential economic superiority (except for special products) over large-scale terrestrial resource processing in near-Earth space.

In this frame of reference, the discussion covers the four principal sectors of large-scale lunar processing--methods of extraction and refining a manufactured products spectrum and products transportation. The primary energy source importantly affects the quantity capacity and the economics. The use of nuclear (non-steady) energy and solar energy are compared.

In the extractive sector, the choice also has a bearing on whether the extractive process is based on indigenous concentrations (IC method) or on prior concentration enhancement (CE method). The IC method can use solar or nuclear detonation energy. The CE method must use the latter. It is shown that nuclear detonation processing (NDP) is more economical, at least initially, but more likely on a permanent basis. The IC method can be carried out above ground or underground. In the latter case, the use of concentrated thermal energy from nuclear detonations is even more advantageous over the use of solar energy than for surface operations. The EC method must be carried out underground. In neither case, depths of more than 50 to 75 m appear necessary. Underground extraction is favored because it appears to be the only economic option to assure maximum protection of the lunar vacuum environment. It is realized that postulating the use of nuclear charges does not conform with the letter of the present nuclear test ban treaties, but it does not conflict with their spirit which is aimed at the prevention of hostile uses. If Man should move into space within a frozen plasma field of terrestrial distrust and antagonism (although space ventures are supposed to have the opposite purpose and effect) a rational modification of the ban of nuclear energy charges may not be attainable and large-scale extraction of lunar materials must be based on higher initial cost and on the IC method. In the Soviet Union, nuclear charges for canal construction projects to increase the water supply of the Caspian Sea have reportedly been tested successfully.

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The refinement of the enriched material will occur initially on the lunar surface (above or underground) but could also take place in part in circumlunar orbit after an economical transportation system, requiring a minimum of Earth-supplied fuel has been introduced. The electromagnetic accelerator, variously suggested during the past twenty years is particularly suited for quantity transportation from surface to orbit, since it is fully compatible with the preservation of lunar surface vacuum. The production of industrial liquids (at minimum supplies from Earth) and suitable methods of refinement are pointed out. Special attention is given to the processing and use of the large amounts of oxygen obtained as side products of the extractive industry.

Semi-finished and finished products involve a wide variety of products, including, for the terrestrial markets, large quantities of electronic components, high-temperature alloys for improved thermal conversion equipment, ultra-hard alloys, special bearing alloys for transportation systems, foam metals, special alloys for sea water resistant structures, and brine resistant geothermal power equipment, to name only a few of the initial product lines; for the extraterrestrial market, large structures for lunar and circumlunar factories and dwelling units, for large structures in geosynchronous and even in near-Earth orbit. It is shown that second generation lunar material processing can advance to the level of organic chemical industries which pose particular ecological burdens on Earth.

Central to the development of geosynchronous and terrestrial quantity markets and to the evolution of an organic chemical lunar industrial capability is a low-cost transportation system. It is shown that electromagnetic acceleration from the lunar surface beyond the circumlunar orbit to geosynchronous orbit or Earth is not the optimum solution. Two low-cost non-nuclear interorbital transportation systems achieving between 1300 and 4000 seconds terrestrial propellant specific impulse are described, which make the above development of large-scale processing and marketing of lunar materials possible.

<u>Editors Note</u> - For specific details and references see -

Ehricke, Krafft A. (1975) Space Industrial Productivity - new options for the future, (Presentation to subcommittee on Space Science and Applications 22-30 July 1975). North American Space Operations, Rockwell International, El Segundo, California.

DISCUSSION (Ehricke Paper)

SPEAKER: I was intrigued by your last slide. Could you explain what an orbitron is and an asteron.

EHRICKE: Yes, in addition to the electromagnetic accelerator on the ground I have a total electromagnetic system operating with an electromagnetic accelerator on the lunar surface and one in orbit. Now you see, since the length of the track is porportional to the square of the velocity, you are really better off if you have two delta V's rather than one very large delta V, in terms of overall mass. So I'm merely launching into lunar orbit. Then in lunar orbit, I'm launching out of lunar orbit, in this electrical scheme, with a similar lunar - accelerator. Now the term lunatron stems from Bill Asher from NASA, Huntsville, about 15 years ago or so, and I just adopted that term, and the orbitron is named similar to it. Now by launching a mass toward Earth on the orbitron, of course, you are changing the orbit, an elliptical orbit. You then slowly turn the accelerator around and now accelerate in opposite direction lunar supply materials or lunar rocks, which then restore your circularity again. Now this is a little bit involved. The chemical system initially seems to be simpler and have considerable advantages. The next two slides too show the orbitron under construction and the total system based - and the one thereafter, based on the electromagnetic system. Here is the orbitron, here is the lunar factory in its orbit, and here are the various ground phases of it, and here is the ground system. But I believe the chemical system utilizing - and if I may show one slide more please, utilizing the advantages of transporting the oxygen into near-Earth orbit in order to finance, so to say, the transport of hydrogen into the lunar orbit leads to specific impulses of - the effective specific impulses of this order of magnitude. In other words, I'm using here a concept that is similar to the term fuel-specific impulse in air breathers. You know, where you get very large specific impulses simply because the oxygen is available free, so to say. Now the launch system that you saw there a moment ago, the oxygen-hydrogen runner, is actually recuperating the exhaust gasses again so that therefore the launching of oxygen into lunar orbit, even by chemical means, can be done with almost no contamination of buildup or gas release into the atmosphere and constant resue of the oxygen-hydrogen, then decompose again to water, burn again to oxygen-hydrogen, captured, chilled, redecomposed, and so forth. This gives you some very favorable economic conditions.

SPEAKER 2: Concerning the use of nuclear explosives, (on the Moon), I wonder if you would comment on two points. First of all, the existing structure of international treaties and their application to the utility of

DISCUSSION (Ehricke Paper)

of nuclear explosions in this light; and secondly, the problem of radio-activity.

EHRICKE: Very briefly, first of all, the nuclear treaty merely is designed to be a weapon system ban. I think it can very easily be modified to allow peaceful nuclear detonations under controlled conditions. Number 2, the Russian's themselves are right now again planning and have actually tested nuclear detonations to build large channels to refill the water level in the Caspian Sea. That's going on on Earth here right now, so it's being done, so I don't think this is really much of a problem. The radioactivity is, on Earth, for a 5- to 10-kiloton bomb in the order of 3 months, low enough that you can go into the cavity. These are the experiences in Nome, Ranier, and some other underground detonations. So it's merely if you phase it right you would have to wait perhaps to wait 3 months to get into that particular cavity, but if you plan your cavities ahead, so to say, then you're getting to them when you can get into them. In addition to this, some of the nastier materials as far as radioactivity is concerned are less abundant on the Moon, especially in depth, for example, sodium and so forth which I think are more toward the surface. So as a result of which, I would expect that you probably could get even a little bit faster into the cavity. And thirdly, I'd like to deploy as few people as possible. People are very expensive, and as many machines as possible, so that the cavity - and the bringing out of the basic material into another cavity or into a higher level still underground would primarily be done by machines, so they're insensitive to some radioactivity.

SPEAKER 2: When you mentioned the particular nuclear species, the new type found there, I presume you're particularly referring to things like strontium and iodine which are indeed rare.

EHRICKE: That's correct.

SPEAKER 2: And that's a useful observation. When we're talking about the treaties, I have in mind particularly the outer space treaty which does forbid any nuclear explosion for any purpose.

EHRICKE: Yes, I'm aware of that, but I do think that the reason for it is weapons. It is not actually a peaceful application. Once a peaceful application becomes clearly apparent, can be controlled, I do believe that underground detonations on the Moon could be permitted.

GEOTECHNICAL ENGINEERING ON THE MOON; W. David Carrier, III and James K. Mitchell, Bechtel, Inc. and University of California, Berkeley.

Some of the geotechnical engineering considerations in large-scale operations on the moon are discussed in this paper. Constructing and operating a large base on the lunar surface entails special problems as well as special advantages not present on earth. Considerable soils data and experience were obtained from the Surveyor and Apollo programs which can now be applied to the design of future bases on the moon. Topics of particular importance are discussed below.

Insulation

It will be necessary to make use of the lunar soil as a construction material. It is very likely that lunar structures will be placed in shallow cuts and then covered over with lunar soil. Self-supporting, inflatable structures may be used. One to two meters of lunar soil cover will provide adequate insulation against thermal extremes, radiation, and micrometeorite impact. The soil could probably be placed in a loose condition and would have a density of about 1 g/cm^3. Even if it were compacted, the density would be less than 2 g/cm^3, and a two-meter layer would impose a stress of less than 7 kPa (1 psi), which would be considerably less than the internal atmospheric pressure. Loose soil could be placed on slopes of 2 horizontal to 1 vertical. The thermal conductivity of this insulating layer would be about 1 to $2x10^{-4}$ Watt/cm-K^o (1). Heating system design for the structure would be simplified due to the constant, albeit cold, temperature of about -20°C at 1 to 2 m below the lunar surfaces (1) in contrast to the requirements for an above-ground structure.

Housekeeping

The lunar surface is dirty. The soil is a silty sand with a median particle size by weight of about 70 microns. Dust adheres to almost everything and will tend to migrate everywhere. Housekeeping will be a constant and frustrating activity, necessitating special brushes, vacuum cleaners, brooms, filters, air-locks, etc.

Soil Stabilization

Vehicular traffic will churn up, rut, and scatter the lunar soil. Permanent spacecraft landing pads will be an intermittent source of destructive high-velocity dust. In these areas, it will be necessary to stabilize the ground surface. Chemicals, such as polyurethanes and resins, could be sprayed, injected into the lunar soil, or mixed in place and rolled to produce a smooth, tight, compacted surface. Haul roads for mining operations will have to be similarly stabilized.

Separation of Soil Particles

Because of the small particle size and cohesiveness of the lunar soil, as well as the low gravity field, mechanical separation would be an extremely inefficient operation on the lunar surface, except for the coarsest particles (>1 cm), which make up less than 1% of the soil. Other methods, perhaps electrostatic, will have to be developed if separation is necessary for some potential industrial process.

Excavation

Excavation of the lunar soil will be very easy. Bulldozers will be used to move small amounts of soil for constructing bases. Large-scale mining will be performed either with drag lines or bottom scrapers. Large-scale transport of soil will be by bottom scraper, dump truck, or perhaps conveyor. Vehicles should be designed to operate at a wheel bearing pressure of approximately 7 kPa which will result in approximately 1 cm settlement in undisturbed soil. The power requirements will depend primarily on the design load, velocity, and climb characteristics of the vehicle. Thus, if it is desired to have a vehicle with a gross lunar weight of 100 kN that will negotiate a 10% grade at 20 kph, the required power would be approximately 60 to 70 kW (80 to 90 HP), including an allowance of 5 to 10% needed to overcome the rolling resistance due to the soil.

Deep Drilling

If large-scale mining or deep storage is contemplated, then much deeper drill holes will be necessary than the 3 m depths attained in the Apollo program. The drill holes would be used to establish the depth of easily excavatable soil as well as the chemical and mineralogical properties of the deeper soil and rock. It should be emphasized that the geophysical methods used to date (such as active seismic, traverse gravimeter, and surface electrical properties) have not provided unequivocal information on the depth of the soil to rock. Unfortunately, the data can be interpreted in different ways. Direct evidence from deep drill holes in conjunction with geophysical data will be essential in studies comparing open-pit mining with strip mining.

Slope Stability

The lunar soil has typical shear strength parameters of: cohesion = 1 kN/m^2; friction angle = 35^o. With a density of 2 g/cm^3, the soil will be stable in a vertical cut over 2 m deep. However, it would be prudent to limit vertical cuts to 1.5 m, as is required by OSHA on earth. Very deep cuts, as in an open-pit mine, would be cut in a series of benches, with the over-all slope controlled by the friction angle. Such an excavation could be constructed at 1-3/4 or 2 horizontal to 1 vertical with the usual factor of safety of 1.25.

Settlement

Most structures on the lunar surface will be very lightly loaded and flexible and will not be adversely affected by settlement. The modulus of subgrade reaction for the lunar surface is typically 1000 $kN/m^2/m$, based on Astronaut bootprints. A footing applying a pressure of 10 kN/m^2 would normally settle approximately 1 cm, but could settle as much as 10 cm or as little as 0.1 cm. Where differential settlements are important, as in an observatory, it would be necessary in the absence of specific site data, to design the footings assuming a lower modulus. Based on available density distributions, if it were necessary to limit the settlement to less than 1 cm with a probability of 95%, a modulus of 200 $kN/m^2/m$ would be used and the footing pressure would be reduced to 2 kN/m^2. Other means are also available to minimize the settlements; e.g., surface compaction, excavation to place the footing on firmer soil, and chemical stabilization.

Waste Disposal and Storage

Because of its relatively fine gradation, the fluid conductivity of the lunar soil would be too low ($<1 \times 10^{-5}$ cm/sec) to permit its use as a drain field for liquid waste. On the other hand, because of the ease of excavation and the excellent insulating properties of the lunar soil, underground chambers for storage of cryogenic fluids should be feasible. The lining of such chambers could be accomplished using polyurethanes.

Conclusion

Much specific knowledge of lunar soils is already available relative to their use for civil engineering on the moon. A major unknown is the nature of the materials deeper than 3m. Deep drill holes will be needed in the early stages of further lunar exploration and development.

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FORMATION OF WATER AND METHANE, CATALYZED BY LUNAR DUST

A. L. Cabrera, M. B. Maple, S. K. Asunmaa and G. Arrhenius
University of California, San Diego; La Jolla, California 92037

Implanted solar wind plasma as a resource - The solar corpuscular radiation that over billions of years has been implanted and stored in the lunar surface provides an important link in the record of the evolution of the Moon. The irradiation effects also give useful indications of the surface properties of solid grains in interstellar and circumstellar space. In the present context we will also discuss some related phenomena which may potentially be of technological use. The solar plasma flowing at 10^8 particles/cm^{2}sec, penetrate a few hundred Å into the exposed lunar dust and rocks. Erosion and mixing processes expose new material and bury irradiated particles so that a stratified sequence of lunar soil is formed. This sequence, containing the implanted solar wind, extends at least to the two-meter depth that has been sampled. Dust particles of less than one mm in size from highly-irradiated Apollo 15 soils release, on the average, 40 to 70 moles of hydrogen per ton and 5 to 9 of carbon upon heating to 1200°C (1., 2.,). Hydrogen release culminates around 600°C; carbon appears mainly in the form of carbon monoxide with small amounts of methane (0.1 - 8.0 percent of the total carbon) and traces of C_2H_4 and C_2H_6.

In discussion of technological operations on the Moon the suggestion has been made that these gases be extracted from the lunar soil and used as fuels. However, there are several disadvantages to this scheme. The low density of hydrogen and carbon monoxide gases would pose problems in fuel storage and transportation, and since their boiling points are low (H_2, -252.7°C; CO, -191.5°C), storage in liquid state would require strong cooling. Catalytic conversion of hydrogen and carbon monoxide to methane and higher alkanes would be a way to avoid these disadvantages. Perhaps most importantly such a reaction would also provide a source of water from the lunar dust. For production, on the Moon, of water and hydrocarbons from stored solar plasma the reservoir material itself, the lunar dust, may possess the necessary catalytic activity. This case is of unusual interest since the reactants are embedded in the interior of the potential catalyst, which, in turn, seems to have acquired its active state from the implantation process itself.

Lunar dust as a model material for interstellar and circumsolar dust - In a more fundamental scientific application, the lunar dust and its surface properties can be used as a model system for interplanetary and interstellar dust. Although the bulk properties of some meteorite materials are probably even more representative in this respect, compaction and alteration have clearly modified the surface properties of the individual meteorite particles.

FORMATION OF WATER AND METHANE

A. L. Cabrera

ORIGINAL PAGE IS
OF POOR QUALITY

It used to be thought that interstellar dust would differ from lunar dust by lacking the effects of corpuscular irradiation. It is now known, as would be expected on the basis of hydromagnetic considerations (see e.g. 3) that dark interstellar clouds (and obviously any circumstellar medium) are magnetized (4.-6.) and characterized by interaction of accelerated charged particles (7., 8.). Consequently, corpuscular irradiation has to be considered a general phenomenon in space, with flux and energy distributions subject to large fluctuations in space and time. Hence one would expect interplanetary as well as interstellar dust to be subjected to corpuscular radiation, and therefore, lunar dust irradiated by the solar wind should be a useful model material.

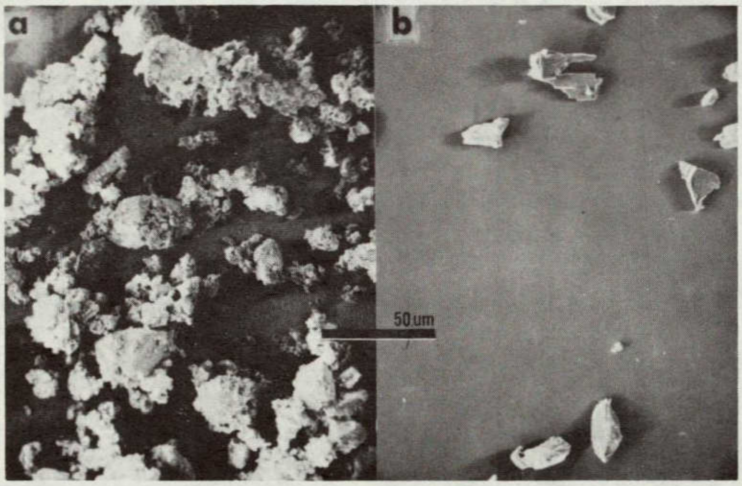

Figure 1. Comparison of the adhesion to mica cleavage surfaces of (a) space irradiated silicate grains and (b) normal silicate grains. The mica surfaces are facing down so that the adhering grains are hanging with the adhesion force exceeding their weight. Both mica sheets were originally completely covered with silicate dust. The lunar dust (a), due to its electret properties, remains extensively adhering while the majority of normal grains (b) have fallen off. The experiment illustrates that the adhesion caused by the persistent internal polarization due to irradiation exceeds the adhesion due to contact forces alone in material which has been in contact with gases for a long time. The lunar dust (a) comes from lunar sample 68501.17, and consists mainly of pyroxene, glass and feldspar. The normal dust consists of pyroxene (augite) from Danville,N.J., ground to a size distribution approximately that of the lunar sample and kept in a closed container for several years. (From 11.)

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One of the notable effects of space irradiation on lunar dust is the strong enhancement of interparticle adhesion due to persistent internal polarization (Fig. 1) (9.-12.) induced by charged-particle implantation. This radiation-induced attraction between grains is likely to be an important factor in the growth of particle aggregates in interstellar and circumstellar space.

Among other factors that would affect particle adhesion and cluster growth are unsaturated forces due to the lattice termination at the solid surface. Such forces are particularly effective between clean surfaces such as in vacuum cleaved crystals and on grains freshly condensed from high temperature vapor or plasma (Labeyrie*; 13., 14). Such forces decay as a result of absorption of polar molecules on the clean solid surface; in contrast, (Fig. 1) the polarization adhesion persists at least for times of the order of 10^7 years on the Moon, and in the terrestrial atmosphere for at least the six years that lunar samples have been kept on Earth.

In interstellar and interplanetary space, and also on the Moon, particle attraction, repulsion and acceleration must also be extensively influenced both by the photoelectric effect (15) and by ambipolar diffusion of electrons and ions (16.-19.).

Another surface property of dust in space, potentially modeled by the lunar dust is catalytic activity for molecular reactions, particularly those involving abundant, volatile species, i.e., those which contain He, H, C, O and N. Such reactions on grain surfaces immersed in dilute space plasmas become ineffective without catalytic mediation because at low grain temperature the reaction products do not easily evaporate, and at high grain temperature the reactants are not retained long enough to achieve reaction involving an activation step (20., 21.). Non-activated chemisorption on grain surfaces has consequently been suggested as a major channel for recombination of atomic hydrogen to H_2 molecules (22.) as well as for the synthesis of hydrocarbons (23.).

Catalytic properties of lunar dust - For the technological and scientific reasons outlined above, investigation of the catalytic properties of the lunar dust is of interest. High resolution studies of the extraction of Mn^{+2} from an aqueous solution in contact with lunar dust grains (24.) suggest that manganese deposits were formed and localized in discrete spots with a size of the order of 200-2000Å. These apparent absorption and oxidation centers on the lunar grain surfaces are believed to be lattice defects catalyzing the reactions.

In order to establish quantitatively the catalytic properties of the lunar dust, lunar soil sample no. 10084.30 was evaluated by a microcatalytic technique (25.) using the reaction

$$CO + 3H_2 \leftrightharpoons CH_4 + H_2O$$

* reference to early work by J. Labeyrie not at hand

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Concentrations of reactants and reaction products were measured using a Hewlett-Packard 5700A gas chromatograph with a thermal conductivity detector. A carrier gas of hydrogen, which served as one of the reactants, was flowed at a rate of 50 cc/min through the reactor over 0.417 gm of the lunar dust and into the gas chromatograph. Pulses of CO of 0.125 cc were injected into the hydrogen carrier stream by means of a Hewlett-Packard gas sampling valve. The production of methane was monitored as the temperature was increased from 52°C to 856°C, with detectable quantities of methane appearing only above 440°C.

The CO methanation data were then converted to plots of ln [B ln (1/1-x)] vs 1/T, where x is the fractional concentration of CH_4. Here, the constant B is equal to F/R T W where F is the flow rate of the reactants, R is the gas constant per mole, and W is the mass of the catalyst. For a first order reaction, the quantity B ln(/1-x) is equal to the product k K, where k is the first order rate constant of the surface reaction and K is the absorption equilibrium constant (26.). Although we do not know the order of the CO methanation reaction over the lunar soil sample, we have nonetheless identified B ln(1/1-x) with k K in order to compare its activity for CO methanation with other catalysts for this reaction. The results for CO methanation over the lunar dust sample in the form of a plot of ln k K vs 1/T are shown in Fig. 2 where it can be seen that the data follow a rate law k K=A exp(-E/RT). The pre-exponential factor A is equal to 2.01 x 10^{-2} moles CH_4/sec gm atm and the apparent activation energy E is equal to 16.5 kcal/mole°K. These results can be compared to unit surface area by noting that lunar soil is characterized by a surface mass ratio of approximately $0.5 m^2/gm$.

The activity of the lunar dust sample for CO methanation is compared to the activities of powdered Ni and Co samples for the same reaction in the ln k K vs 1/T plots of Fig.3. Although the CO methanation data for the Co and Ni catalysts were taken from a previous investigation (27.), they were obtained by means of the same procedure and with the same apparatus which was employed in the present study of the lunar soil sample. The specific surface areas of the Ni and Co samples are 0.7 and 0.3 m^2/gm, respectively.

Since these values are comparable to the specific areas of the lunar soil samples it can be inferred from the data in Fig. 3 that at least the major component of the lunar soil sample is a much less active methanation catalyst than nickel or cobalt. If, however, the assumption is correct that the catalytic activity is proportional to the radiation damage, then a higher specific activity, not only per unit mass, but also per unit surface area would be expected in the ultrafine fraction of the lunar dust. Becuase grains of small size live a more active life on the lunar surface than larger particles (28.-30.), they receive extreme radiation doses. If the observed activity in the grain fraction (<0.1 cm) resides mainly in the highly radiation damaged particles ($\leq 10^{-4}$ cm) which form a mass fraction of the order of 10^{-3} of the sample, then a catalytic activity, similar to an effective industrial catalyst (Fig. 3) would be expected in this submicron grain fraction. This possibility has not yet been explored.

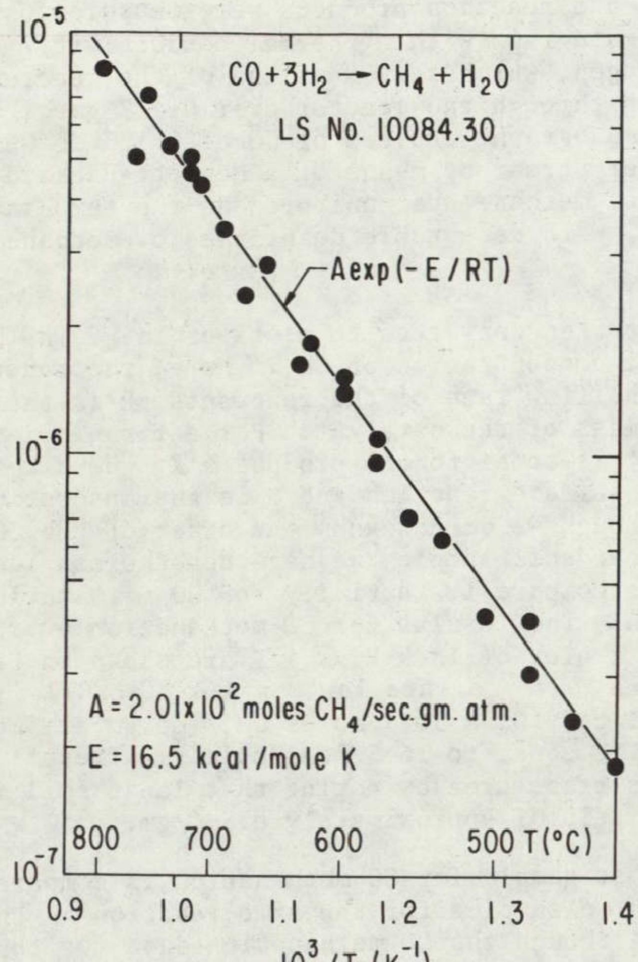

Figure 2.
Semilogarithmic plot of the reaction rate constant vs. inverse temperature for carbon monoxide methanation over lunar sample no. 10084.30.

<u>Separation and concentration of the source material</u> - If a grain size correlation of the catalytic effect can be verified experimentally, then utilization of the lunar soil for effective catalysis would require separating and concentrating the fine dust. Such a concentration would also be desirable because of the higher yield of gas from implanted solar plasma in small grains; DesMarais et al (2.) found the dust fraction with grain size less than 20 μm to contain about three times as much hydrogen and carbon as the bulk soil sample.

Laboratory scale experiments show that electrostatic separation is a promising technique for this purpose (see Fig. 4). Lunar dust particles can be accelerated in an electric field gradient because of their persistent internal polarization which is caused by the implantation of excess positive charge at depth in the grains, and by any additional surface electric charge.

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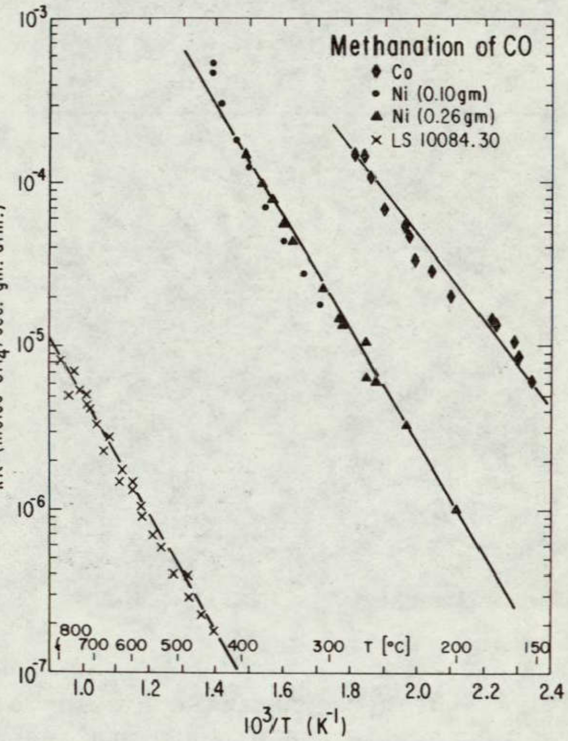

Figure 3.
Semilograithmic plots of the reaction rate constant vs. inverse temperature for carbon monoxide methanation over lunar sample no. 10084.30, nickel and cobalt. Data for nickel and cobalt are taken from a previous study by Luengo et al (27)

Reaction of implanted atoms - In the catalysis experiment described above, the reacting gases were provided from external sources rather than from the interior of the lunar grains. This procedure permitted the use of the convenient and sensitive pulse technique for precise evaluation of the reaction parameters. If instead the implanted carbon and hydrogen in the grains are used as reactants while the grains are immersed in excess hydrogen, it is possible that under appropriate conditions the equilibrium can be displaced toward the formation of higher alkanes.

Summary - The measurements of the bulk catalytic properties of the lunar dust reported here suggest that information relevant for understanding the chemical role of interstellar and circumstellar dust may be derived from investigation of the ultrafine grain component. This component may also be of technological interest for the production of water and alkanes on the lunar surface.

Acknowledgements - Research was supported by the National Aeronautics and Space Administration under Grant NGL-05-09-154 and by the National Science Foundation under Grant No. NSF DMR74-03838.

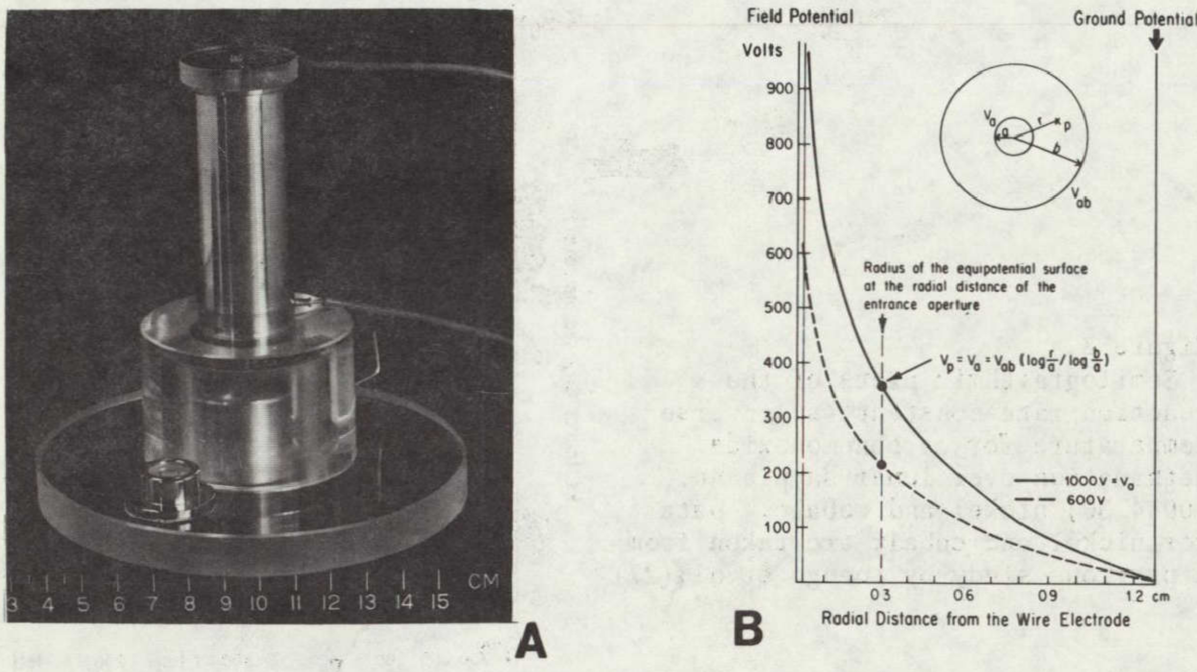

Fig. 4. Electrodynamic separation of charged and polarized components of lunar dust. In the experimental separation device (A) the verticle tube serves as ground electrode and a potential of the order of a kV is applied to a central wire coinciding with the tube axis. The lunar soil sample is introduced at the top of the device and at the radial distance a from the central electrode (B). During free fall the grains are deflected in the inhomogenous field (B). Electret grains (and grains with negative charge) are collected on the wire electrode (C) at a verticle position determined by the dipole moment and/or the magnitude of the charge. The central electrode is coated with a thin layer of a tacky resin in order to retain grains at the point of impact.

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PORTABLE LUNAR SURFACE SHELTERS OF LIQUID METAL-TEXTILE COMPOSITES;

A. J. Bauman and Fun-Dow Tsay, Jet Propulsion Laboratory, Pasadena, California.

Lunar surface exploration or manufacturing operations will require portable or temporary shelters which can easily be set up and disassembled by unmanned devices and which are adaptable to permanent use, if required. We suggest that liquid metal-textile composites (LMTC)[1] be further developed as construction materials for such shelters. LMTC consist of flexible, high strength, thermally durable, radiation-resistant metallic textiles[2] impregnated with low melting alloys, such as those of lead, tin, bismuth and indium. These composites in the liquid state are capable of being folded, packaged, and subsequently deployed by unmanned devices. They are also totally impermeable to gases[1], would self-seal to micrometeorite impact, would resist most high energy radiation and would not degrade in the vacuum and radiation lunar surface environment.

Consider as an example, an inflatable structure (Fig. 1) in the form of a Goldberg Prism[3], which has the minimal number of folds per unit volume of any polyhedron. It will have double walls comprised of two layers of LMTC sewn to a thin, thermally insulating layer of an organic elastomer, such as a silicone or fluorocarbon rubber. At the time of inflation both metal skins would be in the liquid state as delivered from the warmed interior of a lander, but after inflation (as from an integral pressurized air vessel in the base of the structure), the outer skin will solidify in the cold lunar environment and provide the structure with "sheet metal" rigidity. The inner metal skin would be kept liquid as a micrometeorite barrier through heat supplied by photovoltaic roof panels which would also provide storage energy to chemical batteries for use in heating and lighting the interior structure during the lunar night. The structure would readily refold under gravity for portability once its air was released and sufficient power supplied to "melt" the outer skin.

An equilateral Goldberg prism 9 feet on an edge would weigh about 68 lb.[4] if constructed of an alloy textile, such as Chromel R impregnated with Bi (41%), Pb (22%), Sn (11%), Cd (8%) and Ga (1%). Textiles, such as Chromel R maintain their high tensile properties through a temperature range of from -320°F to 500°F. Single small shelters of this type could be used as emergency accessories to mining or manufacturing operations on the planetary surface or they could be ganged to form a large modular colony.

It is apparent that foldable forms other than the Goldberg Prism would also be useful, as for example, large domes to be erected over craters. These structures would be man-erected and suitably braced, as major operations centers. If a crater were first smoothed mechanically and its interior sealed (as with silicone or epoxy resin) an LMTC canopy would make it habitable, without the large energy requirement needed for underground works.

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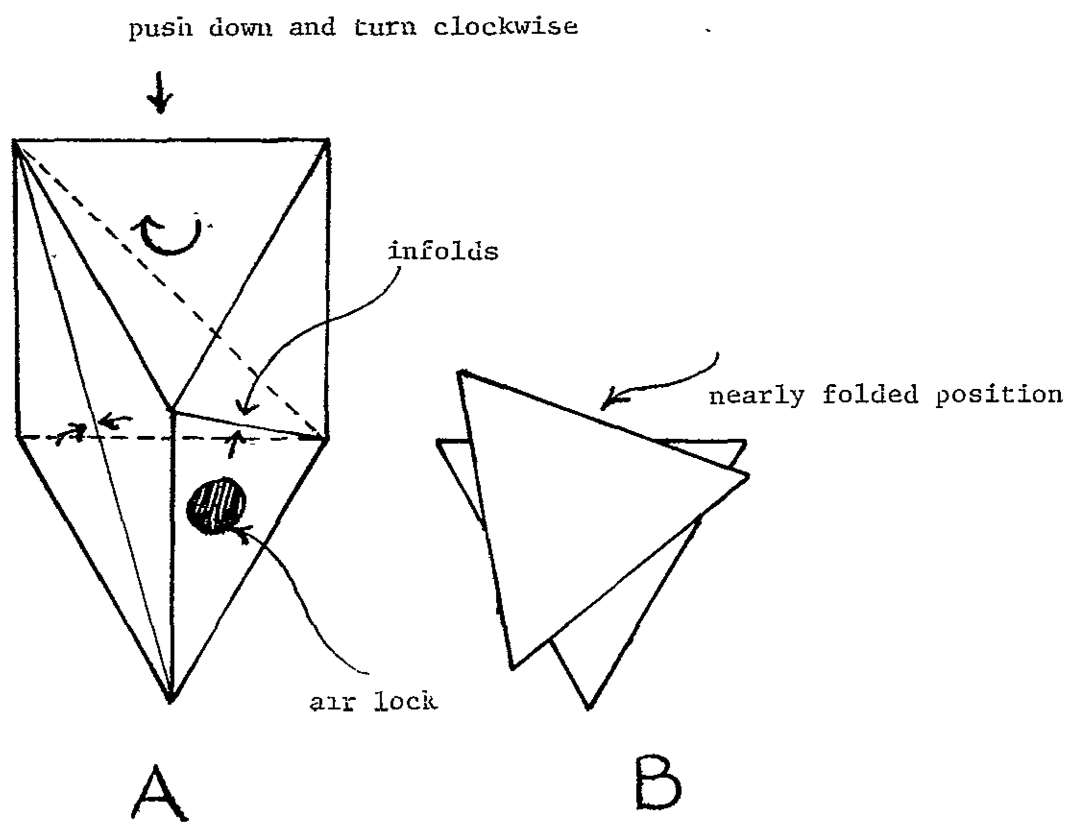
(4) Weight, approximately 12 lb. on the lunar surface.

FIGURE 1 Goldberg Prism, open (A) and folded (B)



CHEMICAL ENGINEERING ON THE MOON

Ralph H. Condit, University of California Lawrence Livermore Laboratory, Livermore, CA 94550

In discussing the possible industrialization of space it should be recognized that a major economic problem will be the difficulty of chemical process engineering. It is obvious that extracting desired elements and compounds from lunar material will present many novel challenges. However, two fundamental problems might be termed the entropy problem and that of waste heat disposal.

The entropy problem has four aspects each of which has implications for the other:

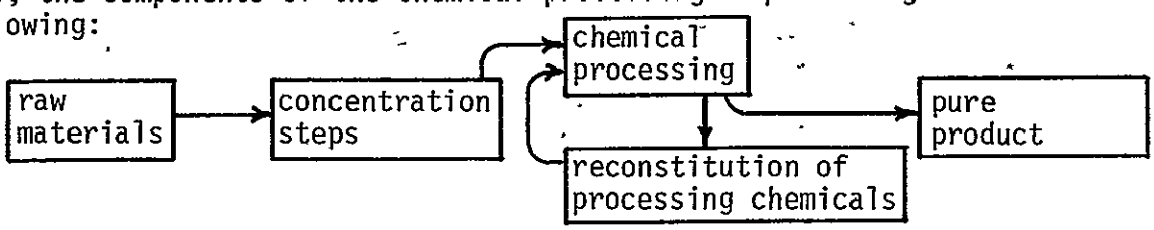
1) The relatively homogeneous nature of lunar material requires that steps be taken to concentrate species wanted for chemical processing. On the earth this has already been done by various geological processes so that enriched ores and sources for the necessary processing chemicals are available.

2) The cost of making processing chemicals from lunar materials or of importing them from the earth requires that they be re-used.

3) We will need to achieve necessary purities of the product materials without at any time being able to use large amounts of cheap, pure cleaning agent in the way that we are able to use water on earth. Purity of the product will be necessary to meet performance standards for the material and to avoid wasteful entrainment of precious processing chemicals.

4) We will need to avoid contamination of moon's atmosphere or space with gaseous or solid debris.

Thus, the components of the chemical processing sequence might be the following:



Conventional chemical engineering cycles normally include additional input and output paths such as disposable wash water. It is very hard to devise a closed cycle such as the above where the processing chemicals are reused with only slight loss. The degree of re-purification can be equated to energy by the formula, $E = -k \ln W$, where E is the energy per mole of material, k is Boltzmann's constant, and W is the fraction of the species of interest in the material. The work to increase the concentration from 9 to 90% is the same as that to decrease the impurities from 1 to 0.1% by this formula. The energy may be expended to run a distillation column, electrical energy to disassociate some compound used for cleanup, etc. The reconstitution loop would include many sub-loops for purification and in

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turn for purifying the purifying chemicals, and each would require energy input. At this stage in the study of possible space industrialization we should propose some likely production processes and examine them in detail from the foregoing point of view.

Waste heat disposal is a problem familiar to the space community but not to the chemical engineering community under the restrictions relevant to operations on the moon or in space. Radiation to space is the only method available on a long term basis. In chemical operations such as distillation, for example, it is necessary to remove thermal energy at the condensation stage. This may still be hot in which case radiation cooling is practical, but if it is too cool, it will be necessary to use refrigeration systems to pump the heat to the necessary temperature for radiation. If one takes the option of selecting chemical operations where the low temperature point is still hot enough for radiative dissipation of heat, the system tends to suffer from corrosion problems. For any scheme, large radiative surfaces will be necessary.

The entropy problem and the heat disposal problem play on each other, because each sub-loop in the reconstitution of processing chemicals consumes energy which must eventually be radiated away as heat. Also, pumping efficiencies are not typically high in moving materials or in refrigeration processes. Therefore, the total energy costs for chemical processing might be high enough to make a significant economic impact on the proposal for space industrialization.

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DESIGN OF EQUIPMENT FOR VAPOR PHASE PROCESSING OF METALS, K. Eric Drexler (MIT, Cambridge, Mass.) and H. Keith Henson (Analog Precision, Tucson, Arizona).

Introduction: Among the operations to be performed on lunar materials are metal separation and fabrication. If the metals to be separated are in reduced form, or if the object to be fabricated locally resembles a curved sheet, then candidate processes include distillation and vapor deposition. Both the separation factors per stage in the first case, and the materials properties attainable in the second are promising. The goal then is the design of a light-weight, direct solar heated metal evaporator for use in space, as this is the key technology in both systems.

Major design problems and proposed solutions: Containment of vapor to prevent deposition on sun concentrating optics; construct furnace with absorber cavity separated from vapor filled cavity by a conductive diaphragm (see fig. 1; mirror, vapor nozzle, condensation system, gas recirculation, and means for adding metal not shown). Mechanical strength of diaphragm at circa 2700°K; use pyrolytic graphite (short term strength greater than 20 kg/mm^2 (1)). Diaphragm evaporation and creep; fill outer cavity with gas to balance pressure load and retard evaporation. Gas containment; construct a dome-like fused alumina window outside aperture. Diffusion and condensation of carbon vapor on window; circulate gas through aperture into cavity. Diaphragm conductivity; machine interlocking grooves in graphite. Corrosion by molten metal; make use of zero-g and some combination of surface tension, induction, dynamic feed, and cold metal tabs to avoid contact of dissimilar materials. Metal vapor reactions with graphite; reasonable operating conditions (temperature differences, pressures) can make carbides unstable at walls and diaphragm (see fig. 2).

System Parameters and Relationships:

D = diameter of furnace (m)
D^2*A_W = area of external walls (m^2)
D^2*A_D = area of diaphragm (m^2)
D^2*A_m = area of exposed metal (m^2)
f = fract. wall area behind diaphragm
t = mirror reflectivity* window transmissivity
e_D = emissivity of diaphragm
e_m = emissivity of molten metal
C = conductivity of diaphragm (W/m^2-K)
K = quality of insulation for specified conditions (W-kg/m^4)
$\sigma = 5.67*10^{-8}$ (W/m^2K^4)
$\dot{m}$ = metal vapor mass flow (kg/s)
p_m = pressure of metal vapor (N/m^2)
ΔH = heat to vaporize metal (J/kg)
M = molecular weight of metal (kg/mole)
$P_m = \Delta H*\dot{m}$ = useful power (W)
P_w = power leaving through walls (W)
P_n = power radiated through nozzle (W)
P_a = power entering through aperture (W)
A_a = area of aperture (m^2)
A_n = area of nozzle (m^2)
T_a = av. focal temp. at aperture (K)
T_{C1} = temp. of ext. cavity rad. field (K)
T_{D1} = temp. of ext. surface of dia. (K)
T_{D2} = temp. of inner surface of dia. (K)
T_{C2} = temp of inner cav. rad. field (K)
T_m = temperature of metal (K)

Approximating (conservatively) the radiative transfer beteen two surfaces as transfer from the first surface to an isotropic radiation field, and then from the field to the second surface, the following relations describe the major thermal differences and power flows in the system:

$$T_{C2} = \left(\frac{P_m}{\sigma e_m A_m D^2} + T_m{}^4\right)^{\frac{1}{4}}; \qquad T_{D2} = \left(\frac{P_m + P_n + fP_W}{\sigma e_D A_D D^2} + T_{C2}{}^4\right)^{\frac{1}{4}}$$

$$T_{D1} = \left(T_{D2} + \frac{P_m + P_n + fP_W}{CA_D D^2}\right); \qquad T_{C1} = \left(\frac{P_m + P_n + fP_W}{\sigma e_D A_D D^2} + T_{D1}{}^4\right)^{\frac{1}{4}}$$

or:

$$T_{C1} = \left(\frac{P_m + P_n + fP_W}{\sigma e_D A_D D^2} + \left(\frac{P_m + P_n + fP_W}{CA_D D^2} + \left(\frac{P_m + P_n + fP_W}{\sigma e_D A_D D^2} + \frac{P_m}{\sigma e_m A_m D^2} + T_m{}^4\right)^{\frac{1}{4}}\right)^4\right)^{\frac{1}{4}}$$

$$P_n = \sigma T_{C2}{}^4 A_n; \qquad A_n = \frac{\hat{m}}{8.06*10^{-3} p_m (M/T_{C2})^{\frac{1}{2}}}$$

$$P_a = \left(P_m + P_n + P_w\right); \qquad A_a = \frac{P_a}{\sigma (T_a{}^4 - T_{C1}{}^4)}$$

$$\text{mirror area} = \frac{P_a T_a{}^4}{1350*t(T_a{}^4 - T_{C1}{}^4)}$$

<u>System productivity</u>: K = $9.5*10^5$ for carbon black at 2600°K (3); insulation thickness must be optimised with respect to mirror specific mass. Fused alumina should give t = 0.75 with a mass of $2.5*10^{-5}$ kg/W if operated at 1400°K (3,4). In the following, pressure vessel mass is taken as 1 kg/m^3, mirror as 0.5 kg/m^2 (5), diaphragm as 20 kg/m^2, furnace lining as 5 kg/m^2, and the metal as iron. For a system of D = 15 m, Tm = 2400°K, and $\hat{m}$ = 10 kg/s, maximum temperature in the system is 2700°K, with mirror mass of 190 tons, insulation of 33 tons, window of 10 tons, and a total mass (including other components) of 250 tons. Such a system processes its own mass in under 8 hrs., and over 1000 times its mass in a year, with mass scaling closely with throughput. The most sensitive parameter of uncertainty is mirror specific mass; a factor of four variation varies optimised system mass by a factor of two.

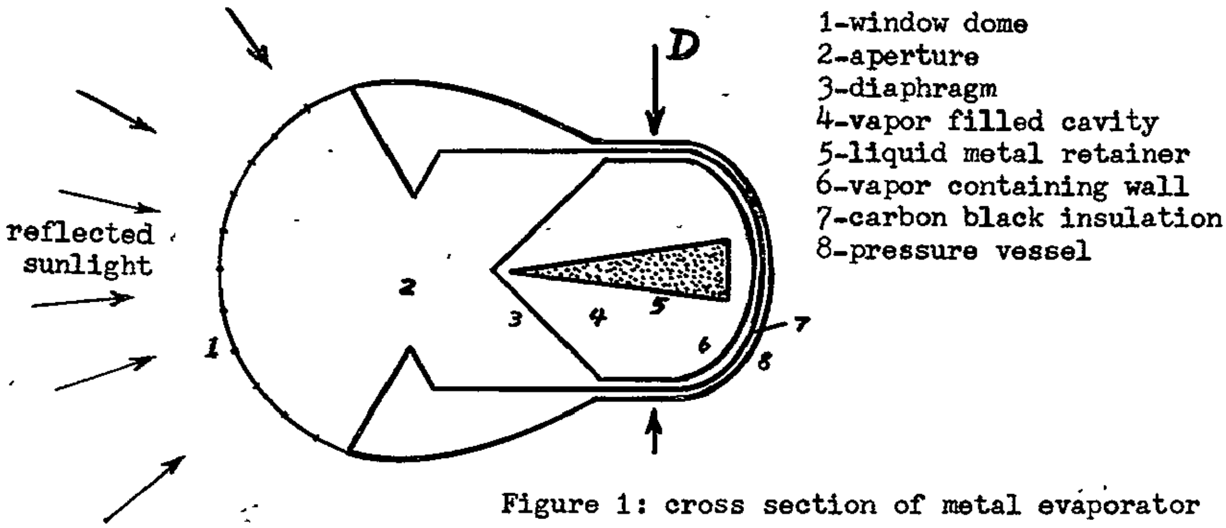

Figure 1: cross section of metal evaporator

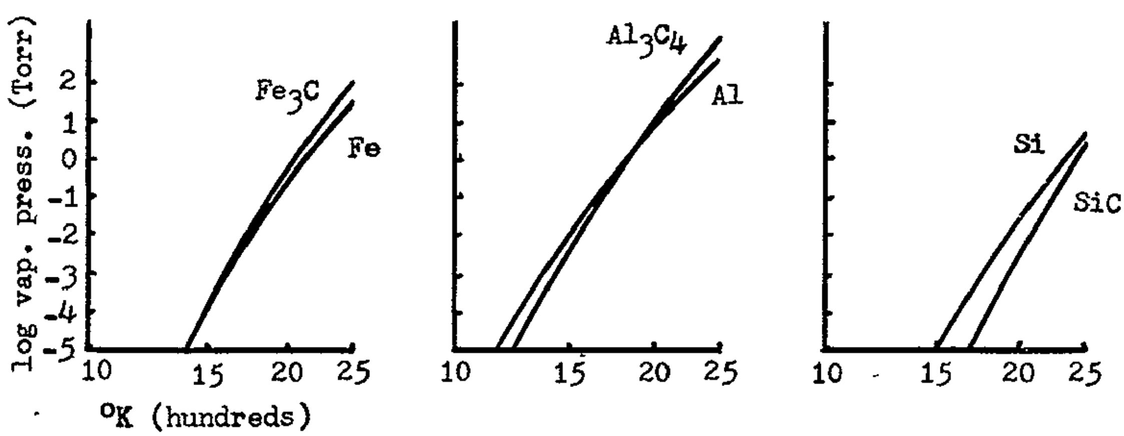

Figure 2: vapor pressures of metals and carbides(2). If the metal vapor pressure at equilibrium over a carbide is greater than ambient, the carbide will not form. In most systems, the carbide pressure will be elevated by greater temperature, while the ambient will be reduced by vapor leaving the system, hence graphite should remain the stable phase where used.

Conclusion: Distillation and vapor deposition are promising means of refining and fabricating lunar materials in space. The design of equipment to accomplish this has been considered from the standpoints of system mass, energy flows, short term materials strengths, evaporation kinetics, and gross materials compatibility. While preliminaries look promising, work remains to be done on the design of metal retention systems, component joining techniques, residual loads due to operational fluctuations and flows, and lifetime from creep and local evaporation-deposition mechanisms. If these are solved properly, such equipment should find wide application in lunar utilization.

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PROCESSING LUNAR SOIL FOR STRUCTURAL MATERIALS; Philomena Grodzka, Lockheed Missiles and Space Company, P. O. Box 1103, Huntsville, Alabama 35807.

Since a previous assessment of the prospects of processing lunar soil for structural materials (1), more information has been gathered on the subject. The new information is indicated under the following material categories.

Metals: Numerous articles and patents continue to appear on methods of extracting aluminum or titanium from earth materials similar to those that are present on the moon, i.e., anorthosite for aluminum and ilmenite for titanium. Reported work, however, is aimed at developing earth based technologies for the lower grade ores. As a result, most of the methods utilize alkali or acid bleach processes which involve copious amounts of water and complex processing operations. Although it is understood that a study conducted by a group at Ames in the summer of 1975 recommended an acid bleach process for the extraction of aluminum on the moon, it is still the opinion of others that more direct routes must be sought for moon based extractive technologies. Electrolysis of molten silicate melts was one means suggested earlier (1). Since then a couple of other possible approaches suggested themselves. One possibility might be to explore further the chemistry of molten silicate melts. For example, it is reported (2) that when an aluminosilicate is fused with cryolite or fluorspar and sodium chloride, the mass forms two layers. The upper layer contains sodium chloride and aluminum fluoride, and the lower layer sodium and calcium aluminosilicate. Theoretically, the upper layer could be electrolyzed to give aluminum.

An intriguing thought is what would be the result of adding magnesium to a molten aluminosilicate mass. Magnesium oxide has a larger standard free energy of formation than does aluminum oxide (3). Magnesium, therefore, should reduce aluminum oxide at temperatures below about 1500°C. The free energy relationships, however, are such that magnesium can also reduce silicon dioxide. It would thus be interesting to see if any aluminum could be produced by adding magnesium to aluminosilicate melt. Such an approach is attractive because magnesium can probably be readily produced on the moon by some variant of the following vacuum retort reaction (4):

$$2\,CaO + MgO + Fe_xSi \rightarrow 2\,Mg(g) + (CaO)_2\,SiO_2 + x\,Fe$$

The reaction goes to the right because the pressure of magnesium gas at 1200°C is only about 34 mm Hg, i.e., a vacuum drives the reaction to the right. Magnesium gas is subsequently condensed to give a metal product that is purer than ordinary electrolytic magnesium. Magnesium production on the moon may also be desirable as a step in the production of titanium. The Kroll process for titanium production is based on the following reaction:

$$TiCl_4(g) + 2\ Mg(l) \rightarrow Ti(c) + 2\ MgCl_2(l)$$

Glasses and Ceramics: The relatively large number of recent papers on the production of glasses and ceramics from anorthosite, anorthite, various feldspars, and basalt indicate that such raw materials will soon be routinely used in many glass and ceramic industries. It is interesting to note that the Europeans and the Russians appear to be particularly active in this area. Interesting highlights from these papers are the following:

- Cylinders of basalt/sulfur concrete exhibited average strengths of 3,348 psi to 10,398 psi in compression (5).

- Basalt fibers have high thermal and electrical insulation properties and are extremely strong (6).

- Glass fiber reinforced cement make possible lightweight cement based sheets for cladding of large buildings. The composite has a high impact strength together with an associated pseudoductility during the early part of its life. More research is indicated, however, before the composite is considered for load bearing purposes. Wet conditions seem to hasten the aging (7).

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A WAY TO COMPARE COSTS OF BUILDING ROTATING STRUCTURES IN SPACE

C. H. Holbrow Colgate University

In order to compare the costs of constructing in space large rotating shells of different shapes containing atmosphere, surrounded by a layer of non-rotating radiation shield, and suitable for habitation, quantitative parameters are defined for two of the most useful shapes and a simple cost model is set up. Formulas are presented for structural mass, shielding mass, atmospheric mass, projected area, and cost of construction of a sphere and a torus (ring shape) in such a way as to permit comparison of the merits of the two geometries under various conditions. For simplicity only stressed skin structures and tensile stresses are considered.

Size of a Rotating Structure

Rotation with angular velocity ω of a shell of radius R about an axis of symmetry produces a pseudogravitational acceleration $g = R\omega^2$. This parameter g and the rotation rate ω are basic design choices. Their selection determines R and thus the overall size of the structure.

Projected Area

Structures are built to provide area on which people may live. In an environment where there are forces such as gravity, houses and buildings must align with them. This fact means that the useful area is a surface perpendicular to g in the structure. Building on curved surfaces by terracing will not make available any more surface than is contained in the surface perpendicular to g. The area of this surface available in a given structure is called the projected area A. Its location and size depend upon the magnitude and location of the maximum value of g in the structure and in what range of variation of g habitation is acceptable.

For simplicity, however, let us take for A the largest surface perpendicular to g in the structure. Then for a torus with major radius R and minor radius ηR (where η is an aspect parameter), $A_t = 4\pi\eta R^2$ the area of a belt of width $2\eta R$ passing through the middle of the tube of the torus around the axis of rotation at radius R. For a sphere $A_S = 2\pi R^2$ which is the area of a belt of width $\sqrt{2}\,R$ passing around the axis of rotation at a radius $R/\sqrt{2}$.

If R is fixed, specification of A as a design parameter determines how many structures of a given shape will be required to provide the desired amount of projected area. Obvious difficulties arise if a fraction of a structure is called for. In practice a complete structure must be built producing excess capacity. The economics of the problem of excess capacity must be considered as a problem separate from the construction cost of a unit of projected area.

A WAY TO COMPARE COSTS

C. H. Holbrow

Structural Mass

A torus of major radius R and minor radius ηR, built with a stressed skin of a material of density ρ, and containing a gas at a pressure P_A will need a thickness of wall $t = \dfrac{P_A R \eta}{\sigma - \rho g R}$ where σ is the working stress of the structural material. Assuming the wall thickness is small compared to ηR, the structural mass will be the product of the surface area of the torus, the density of the structural material and the wall thickness $m_t = \dfrac{4\pi^2 \rho P_A \eta^2 R^3}{\sigma - \rho g R}$

The wall thickness and related structural mass of a sphere can be found to be

$$t_{sp} = \frac{P_A R}{2\sigma - \rho g R} \qquad \text{and} \qquad m_{sp} = \frac{4\pi P_A R^3 \rho}{2\sigma - \rho g R}$$

It is useful to note that if $R \ll \sigma/\rho g$

$$m_t \approx 4\pi^2 \rho P_A \eta^2 R^3 / \sigma \quad \text{and} \quad m_{sp} \approx 2\pi \rho P_A R^3 / \sigma$$

This approximation neglects the effects of rotation. Its use in what follows introduces errors of < 11% as long as $R\rho g/\sigma < .1$. The approximation also makes evident the functional dependence of cost on various quantities as will be seen below.

Shielding Mass

The mass of a radiation shield of thickness t_s and density ρ_s surrounding a torus of major radius R and minor radius ηR is for $t_s \ll \eta R$

$\bar{m}_t = \rho_s t_s 4\pi^2 \eta R^2$. For a sphere it is $\bar{m}_{sp} = \rho_s t_s 4\pi R^2$.

Atmospheric Mass

An atmosphere of density ρ_A will correspond in a torus to a total mass $\rho_A 2\pi^2 \eta^2 R^3$; in a sphere the mass will be $\rho_A 4\pi R^3/3$.

Cost

Projected area is the end product sought. Structural mass, shielding mass and mass of atmosphere are the main resources paid to obtain a given projected area. The cost of these expenditures can be measured in man-hours or dollars or whatever units seem suitable. Let P_1 be the cost of a unit of structural mass; let P_2 be the cost of a unit of shielding mass; let P_3 be the cost of a unit of mass of atmosphere. The cost of a unit of projected area for a torus is then $C_t = \dfrac{P_1 \rho \pi P_A \eta R}{2\sigma} + P_2 \rho_s t_s + \dfrac{P_3 \eta \pi R \rho_A}{2}$ and for a sphere

$$C_s = \frac{P_1 \rho P_A R}{\sigma} + 2P_2 \rho_s t_s + \frac{P_3 2R \rho_A}{3}$$

A WAY TO COMPARE COSTS
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Comparative Analysis

Construction costs are the same for the two shapes when $C_t = C_s$. Defining $y = \frac{P_2\ \rho_s t_s \sigma}{P_1\ \rho P_A\ R}$ and $x = \frac{P_3 \sigma\ \rho_A}{P_1\ P_A \rho}$ we can rewrite $C_t = C_s$ as

$y = \frac{2 - \pi\eta}{\pi - 2} + \frac{4 - 3\pi\eta}{6(\pi-2)} x$. For a given choice of η, the equation divides the x-y plane into two regions: $C_t > C_s$ and $C_t < C_s$. A plot of the x-y equation for a given value of η gives a convenient way to determine the relative costs of the two kinds of construction. After calculating the values of x and y for a given configuration, we can read off the graph which mode is the more expensive way to provide a unit of projected area.

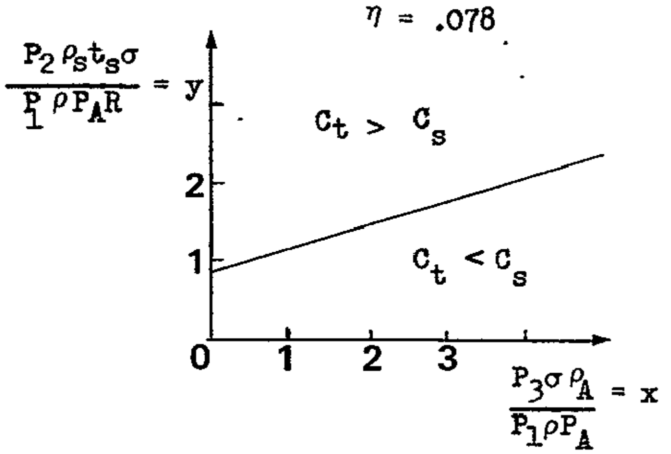
Within the limits of the approximation under which the equation was derived the graph also makes evident the dependence of cost on the various parameters of the structures. From the definitions of x and y we see that changes in P_2, ρ_s, t_s, or R will displace a point describing the difference in

cost parallel to the y axis. Similarly, changes in P_3 will result in displacements along the x axis. Changes of ρ, σ, or P_1 will produce displacements along a line of unit slope through the point. (The ratio ρ_A/P_A appearing in the definition of x can be replaced by $M/R_g T$ where M is the molecular weight of the gas, R_g is the gas constant, and T is the absolute temperature. Consequently, varying P_A or ρ_A does not affect x; only changes in T or M will affect x.)

Example

Consider the Stanford Torus (1) for which $\eta = .078$ and R = 830 m. Then with P_A = 50 kPa, σ = 200 MPa (29 000 psi), $\rho_s = 2.65\ g/cm^3$, $\rho = 2.7\ g/cm^3$, and t_s = 4.5 m the x-y equation can be written $21.3\ P_2/P_1 = .768 + .436\ P_3/P_1$.

If $P_3 = 0$, i.e. if the atmospheric mass costs nothing, then only if P_2/P_1 is less than .036 will toruses be cheaper to build than a sphere. Otherwise, although the structural mass required for the toruses sufficient to produce a desired projected area A will be much less than for a sphere, this benefit will be offset by the extra shielding which a torus requires in the ratio of π:2 for each unit of A.



On the other hand, if the atmosphere contains an appreciable amount of nitrogen which will have to be brought from Earth, P_3 will not be zero. In fact P_3/P_1 will be somewhere between 10 and 100. (1,2) If, for example, $P_3/P_1 = 10$, then $C_t < C_s$ for $P_2/P_1 < .24$.

A WAY TO COMPARE COSTS

C. H. Holbrow

Summary

A discussion of the costs of construction in terms of the masses required per unit of projected area leads to a description which makes evident the dependence of the difference in cost of construction of toroidal and spherical shapes upon their respective structural parameters. The formulation permits a simple graphical representation which further facilitates interpretation.

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POWDER METALLURGICAL COMPONENTS FROM LUNAR METAL

A. D. Romig, Jr. and J. I. Goldstein Dept. of Met.-Mats. Sci.,
Lehigh University, Bethlehem, PA 18015

INTRODUCTION

Assuming the eventual establishment of high technology colonies on the moon, one may wonder what possible industrial goods can be produced at these colonies using lunar resources. It is proposed that in such a colony, with adequate but limited energy resources already developed, industrial powder metallurgy components can be fabricated from native iron alloys.

Free iron is readily available on the lunar surface, making up approximately 0.045 st% of the regolith [2] (Fe, <.02-23 wt% Ni, <0.02-3.1 wt% Co, < 0.02-11.5 wt%P, ≤ 0.02-1.6 wt% S, and ≤ 0.02-0.1 wt% Cr) [3]. Using a regolith density of 0.9-1.1 g/cc [4], one can calculate that 3.9×10^{10} metric tons of Fe alloy are available in the top five cm. of the regolith. The quantity would be even larger if one considers greater depth and the possibility of crushing larger rocks.

With the raw material available the appropriate manufacturing techniques must be selected. Traditional processes such as casting, rolling, forging, etc. are rejected because they are all very energy intensive procedures. One viable alternative is powder metallurgical fabrication. It is a well suited option since its energy requirements are not extravagant, iron metal is readily available and a natural vacuum (2.7×10^{14} atm) [4] is already present.

The components considered for fabrication will be smaller than 100 kg., probably less than 10 kg. It is not suggested that large structural components can be fabricated in this manner. Proposed components cover a broad spectrum of uses. Machine parts such as gears and cams are distinct possibilities and are currently two powder metallurgy parts widely produced on earth. Other possibilities include nuts, bolts, screws, connecting rods, bearings, and electrical contacts. One distinct advantage of a powder process is that the final product can be essentially fabricated in one step. For example, a gear can be directly fabricated without subsequent machining.

Despite the cost required to develop a powder metallurgy facility, it is thought that it is a better alternative than transporting all these components from earth. The first technological problem is the collection of the "ore." It may easily be collected by lunar roving vehicles with magnetic skimming devices, and then transported to a central production facility. By controlling the magnetic field strength of the skimming magnet and the skimmer distance from the surface, one can restrict the gathered material to highly magnetic metal and avoid collection of weakly magnetic minerals.

Metal Preparation and Part Fabrication - (see Figure 1 for a flow sheet.)

Initially the material will be mechanically sieved into various size distributions. Following, it will be sent to a vibratory device to separate the metal particles from any adjoining silicate. It is hoped that the low temperature in the lunar shadows (-173° C) will somewhat embrittle the material and assist in metal/gangue separation. The precise configuration of such a separating device has yet to be determined. The retained gangue must be kept at a minimum, since it will adversely influence the properties of the finished component. A magnetic separator will then serve to differentiate the metals from the gangue.

With powdered metal stock available, production may begin. One earth proven powder process is hot compacting, where compacting and sintering are done simultaneously. Dies of air or oil hardened tool steel will be used, and suitable production parameters would be T-800°C (>0.5 mp) (electrical resistance heating), P-6.89 x 10^7 Pa (10,000 psi), and time-20 min.[5,6]. Another possibility, yet to be thoroughly investigated in the laboratory, is to compact the powder in the ultrahigh lunar vacuum (ion-pump range). It is possible that under these conditions, and with no oxide present on the surface of the metal, the green compact will auto-sinter. The 100°C lunar daytime temperature may assist this reaction. Various subsequent heat treatments could be used to vary the components mechanical properties with design requirements. For reference, Table 1 summarizes the mechanical properties of pure Fe and a possible lunar alloy (both annealed) [7]. Realize that the remaining traces of silicate will somewhat deteriorate the mechanical properties of the lunar component, especially impact resistance. Fortunately, Ni is a toughener when added to Fe, and one may still expect a suitable finished product.

Following the basic production of the part, many subsequent procedures are possible, including machining and welding.

Conclusions -

Once a high level colony has been established on the lunar surface, lunar resources of free iron could be used to produce industrial components. The raw material is plentiful and the quality of the finished goods should be excellent. Proposed components would find uses in lunar machine manufacture and maintenance. The production of large structural components (>100 kg.) is not feasible with a lunar powder metallurgical process. If one wishes to allow his mind to wonder, even the production of components for orbital assembly of interplanetary spacecraft and orbital stations is technically feasible.

POWDER METALLURGICAL COMPONENTS FROM LUNAR METAL

A. D. Romig, Jr.

Figure 1

Production Flow Sheet

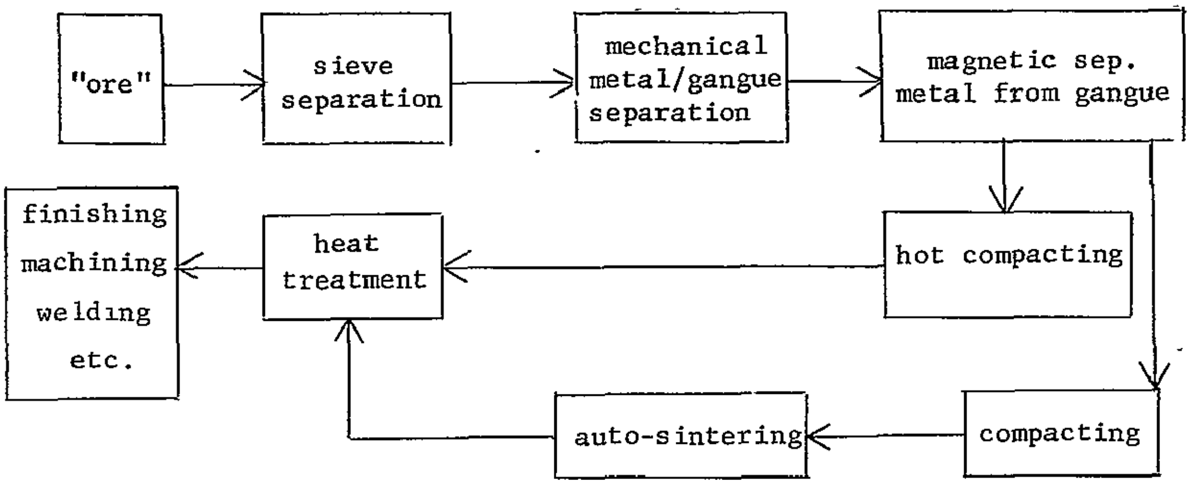

Table 1

Mechanical Properties of Lunar Alloys (annealed) [9]

Property	Pure Fe	Fe-5.Ni-0.5 C
theoretical density	> 95%	> 95%
tensile strength	90×10^6 Pa (13,000 psi)	420×10^6 Pa (61,000 psi)
elongation	1.7%	5%
hardness	-	Rb 50

Note: The other elements present, especially Ni, will significantly increase the properties listed above.

POWDER METALLURGICAL COMPONENTS FROM LUNAR METAL

A. D. Romig, Jr.

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THE MOON BASE POWER SATELLITE: A PRELIMINARY ANALYSIS

B. R. Sperber, M. I. T., Dept. of Aeronautics and Astronautics

In a recent study on space colonization[1] a nuclear power plant was used to power an electromagnetic mass launcher and a moon base. The base-lined specific mass of the nuclear power plant was 45 kg $(kw)^{-1}$. There is probably no alternative to using a nuclear power plant for the first mass launcher.

However, an economically viable space colonization system is probably a fast-growing one, with power requirements on the order of those put out by power satellites. These requirements are taken to be .75 to 2 Gw_e approximately 10 years after establishment of the moon base. A power satellite might be actively stationed at Lagrange point L-1, transmitting microwave power to the lunar surface for subsequent mass launchers. A procedure for estimation of power satellite system mass as a function of microwave transmission wavelength has been developed.

The acquisition cost of a power satellite with receiving array may be described by the equation

$$K = \gamma \, (T_A A_T + T_M P \eta_T^{-1} \eta_R^{-1} + C P \eta_G^{-1} \eta_T^{-1} \eta_R^{-1} + \beta R A_R)$$

where

γ = lift cost to satellite site per unit mass material

β = rectenna site/satellite site lift cost ratio

A_T = microwave transmitting array area

A_R = microwave receiving array area

P = system power output to load at rectenna

T_A = mass per unit area of microwave transmitting antenna

T_M = specific mass of microwave generation equipment

C = specific mass of solar to D.C. electric conversion system

R = mass per unit area of rectenna

η_G = D.C. to microwave generation efficiency

η_T = geometric beam transmission efficiency

η_R = microwave to D.C. conversion (rectenna) efficiency

THE MOON BASE POWER SATELLITE: A PRELIMINARY ANALYSIS

B. R. Sperber

Factoring out lift cost γ leaves an equation for the power satellite system's location-referred mass $M = K\gamma^{-1}$. This simply means that the portion of the system mass on the lunar surface is multiplied by the factor of increased transportation cost to the lunar surface with respect to L-1. This number will be taken to be $\beta = 3/2$ here.

With the substitution $\alpha = T_A A_T + \beta R A_R$, M may be written as a function of λ, the microwave transmission wavelength:

$$M = \alpha(\lambda) + T_M(\eta_G(\lambda)) P \eta_T^{-1} \eta_R(\lambda)^{-1} + C P \eta_G(\lambda)^{-1} \eta_T^{-1} \eta_R(\lambda)^{-1}.$$

$T_M(\eta_G)$, $\eta_G(\lambda)$ and $\eta_R(\lambda)$ are shown on Figures 1-3. α can be minimized by using the antenna relation

$A_R A_T = \pi^2 k^{-2} \lambda^2 H^2 \eta_T^2$, where k is a dimensionless constant.

The antenna relation says that for a given configuration and λ, $A_R A_T$ is constant. This allows α to be written as

$\alpha = T_A (A_R A_T) A_R^{-1} + \beta R A_R$. Differentiating w.r.t. A_R,

$d\alpha/dA_R = -T_A (A_R A_T) A_R^{-2} + \beta R$. Rearranging terms at the minimum

yields $A_T = \beta A_R R T_A^{-1}$. Plugging this result into the antenna relation

yields $A_R = \pi k^{-1} \lambda H \eta_T (\beta^{-1} R^{-1} T_A)^{\frac{1}{2}}$. Furthermore,

$\alpha = 2\beta R A_R = 2\pi k^{-1} \lambda H \eta_T \beta^{\frac{1}{2}} R^{\frac{1}{2}} T_A^{\frac{1}{2}}$.

For a constant amplitude transmitting aperture illumination with $H = 6.4 \times 107$ m and $\eta_T = .8$, k was found to be $1.93 \simeq 2$. It is likely that only a fraction of the rectenna area would be installed to begin with, so that no matter how tight the antenna pattern, most of the power is wasted anyway. The constant amplitude illumination was chosen because it is likely to be the easiest to build.

Shown on Figure 4 are $T = T_M P \eta_R^{-1} \eta_T^{-1}$ and two cases of solar-electric conversion mass fraction $c = CP_G^{-1} \eta_T^{-1} R^{-1}$ as functions of λ for P = 2Gw. The difference in the two cases of c is that for a typical photovoltaic satellite design C = 1.5 kg $(kw)^{-1}$(Ref.2) whereas for a thermal conversion design

$C = 4.6$ kg $(kw)^{-1}$. (Ref. 3).

On Figures 5 and 6 M is plotted for the cases of photovoltaic and thermal solar-electric moon base power satellites, respectively, for different values of R, assuming $T_A = 4.3$ kgm^{-2}. Each curve is a factor of 4 in R different from adjacent curves and also represents satellite mass alone for the curve above it.

Since the fits to Figs. 1-3 are crude, the results in Figs. 4-6 are purely demonstrative, especially at shorter wavelengths. However, carrying out such plots allows an appropriate microwave wavelength to be selected in a rational manner. The selected wavelength will vary according to the criterion used, i.e., is M or the satellite mass minimized?

Thanks to Prof. R. Miller, W. C. Brown and an unnamed host of proof readers for their help.

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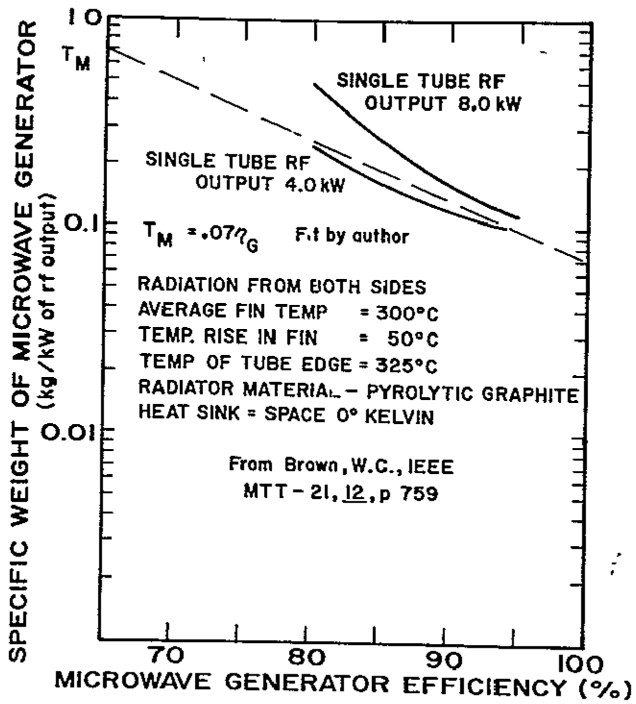


FIGURE 1.

FIGURE 2.

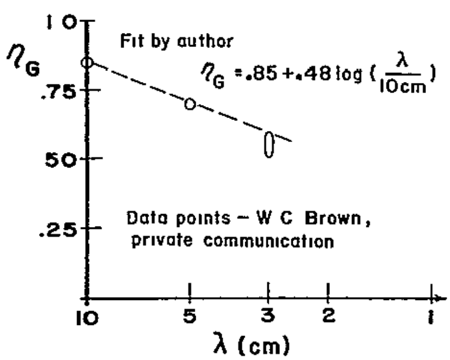


FIGURE 3.

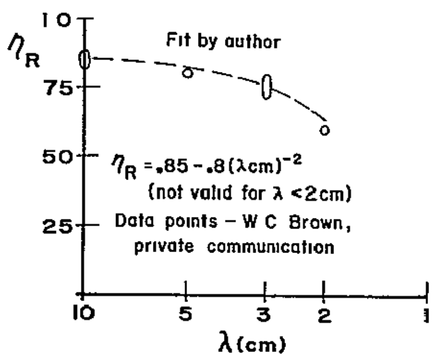


FIGURE 4.

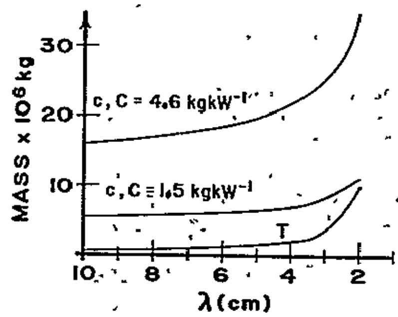


FIGURE 5.

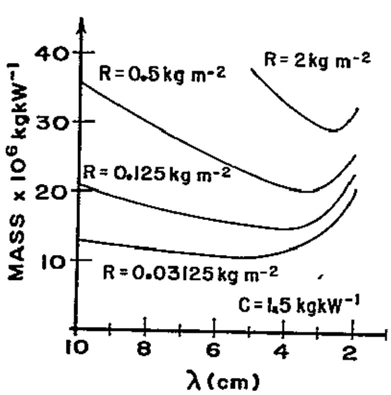
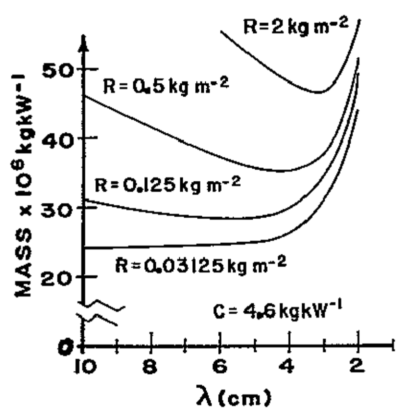


FIGURE 6.



LIGHTWEIGHT MOBILITY SYSTEMS FOR LUNAR OPERATIONS UTILIZING ELASTIC LOOP SUSPENSIONS; Wolfgang Trautwein, Lockheed Missiles and Space Company, P. O. Box 1103, Huntsville, Ala. 35807 and Nicholas C. Costes, National Aeronautics and Space Administration, Marshall Space Flight Center, Alabama.

Effective utilization of lunar resources has been identified as the key to reduce the cost of constructing large scale solar power satellites. All phases of erecting and operating a lunar base including site surveying, shelter construction, exploratory and production mining, hauling, processing and launch of lunar materials will require highly reliable surface transportation equipment.

The enormous cost to transport equipment from the earth to the moon places a high incentive on lightweight and low power consumption.

The four-wheeled lunar roving vehicle (LRV) used very successfully by the Apollo 15, 16 and 17 astronauts and the eight-wheeled remotely controlled Lunokhod I and II vehicles demonstrated that wire mesh wheels can perform light to moderate lunar logistics functions.

Additional traction as required in more adverse terrain and for digging, loading and hauling of ore and overburden would call for much larger and heavier wheels.

An alternate mobility concept has been under development at Lockheed Missiles and Space Company's Huntsville Research and Engineering Center for the last five years. The loopwheel or elastic loop, is a one-piece continuous band providing a large track-like footprint and spring suspension in a simple and lightweight design.

NASA's Marshall Space Flight Center recognized the attractive features of the loopwheel, such as high performance in marginal terrain, lightweight and low part count, and has supported the exploratory development for low-gravity extraterrestrial applications through several prototype and test programs. Tests of a second generation loopwheel conducted for NASA-MSFC by the U. S. Army Engineers Waterway's Experiment Station (WES) have shown that the loopwheel provides an 85 to 100% improvement in soft soil mobility over the Lunar Roving Vehicle at a lower power requirement (refs. 2, 3, and 4). An early test model is shown in Fig. 1.

The loopwheel's low weight and potential for high reliability has prompted the U. S. Marine Corps to support a loopwheel development program at Lockheed-Huntsville (Ref. 5) which is now being joined by the Army Tank Automotive Command. Weight savings of over 40% and an 80% reduction in the number of major moving parts over track suspensions in high-performance off-road vehicles appear feasible.

Early lunar operations call for a multi-purpose vehicle with maximum mobility to minimize the risk of getting immobilized in adverse terrain. An articulated three-loop vehicle with yaw steering between the dual-loop and the single-loop module was found to provide the best pay-off in mobility per unit cost.

A front-loader version is shown in Fig. 2. The front bucket could be removed for personnel transportation or replaced by a drilling or scientific unit for surveying sorties.

The spring suspension inherent in each elastic loop enhances ride qualities and reduces shocks and vibration levels for onboard instruments, antennas and imagery in both manned or remote control operation. Shocks and vibration levels could be limiting factors in efforts to adapt conventional unsprung earth-moving equipment to lunar operations which must relay on heavy instrumentation, a factor not addressed in earlier vehicle surveys for lunar mining operations (Refs. 6 and 7).

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FIG. 1: Sub-scale functional test vehicle with titanium loops, electric drive and remote control demonstrated high degree of rough-terrain mobility and maneuverability under NASA-MSFC sponsored test program (Refs. 1 & 2).

FIG. 2: Multi-purpose articulated three-loop vehicle concept for lunar operations.

Figure 1

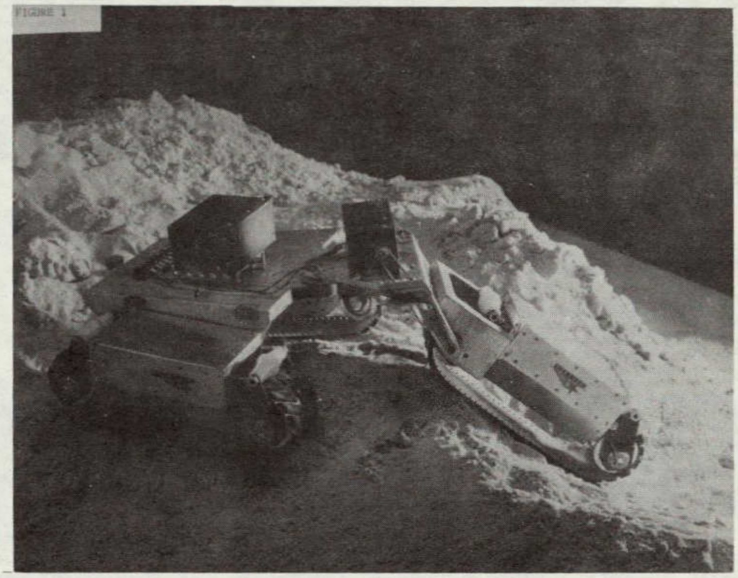

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Figure 2

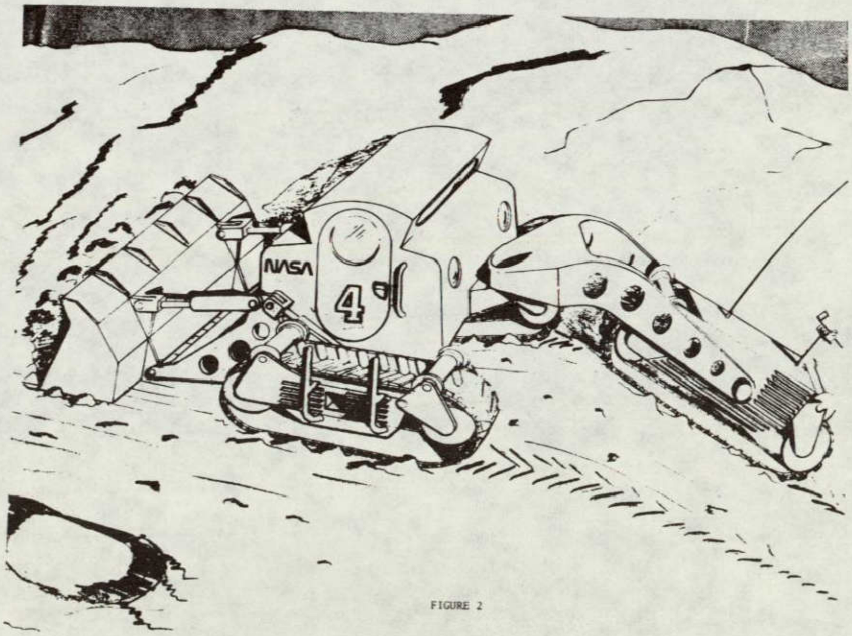


FIGURE 2

FUTURE EXPLORATION

FUTURE GEOPHYSICAL TECHNIQUES FOR PROBING BENEATH THE REGOLITH - PROSPECTING OBJECTIVES David W. Strangway University of Toronto

After the presentation by H. Davis, when it was pointed out that Canada and Trudeau had cut the U.S. off their oil supplies, I'm not sure that I should really stand up here and talk about things from a Canadian point of view, but nevertheless I'm here and will say something about geophysical methods of exploring the Moon. I'm going to say a little bit about magnetic and electromagnetic methods as they might be applied to understanding the nature of the near surface of lunar materials. It's obvious from many of the previous discussions that the use of lunar materials is going to require us to understand something about how they are distributed. This is where geophysical methods can play a role. It is rather interesting that in the lunar environment I believe that it is possible to do much more, more effectively, in terms of geophysical techniques than it is in terrestrial problems. This is largely because in the terrestrial environment, we have water which causes rocks to be conductive. The dry nature of the lunar surface means that electromagnetically we can penetrate to very significant depths in the surface and we can do a high-resolution mapping of a kind that we are unable to do in the terrestrial environment.

I want to refer to just two methods although there are many others that could be used. I actually should perhaps qualify this discussion by saying that about 3 or 4 years ago, about a year and a half before Apollo 17 went, I remember going through a very similar kind of discussion with Chris Kraft and a number of high-level managers at the center because there was a move at one point to try to automate the rover on Apollo 17 and to leave it behind to traverse several hundred kilometers across the lunar surface and do some of the things that I'm going to talk about now. Naturally, too late, and too expensive and it would have introduced many complexities into the mission at that point.

Figure 1 illustrates the distribution of metallic iron among different materials on the surface. Of course, the soils or the regolith is the material that people are most interested in. And, as you can see, there's something like 0.5 weight percent metallic iron distributed through the lunar regolith materials. If we were going to run magnetometer surveys or traverses across the lunar surface, there would be significant anomalies due to the remnant magnetic fields. This would be a noise problem from the point of view of trying to map the distribution of iron because you would have to worry about eliminating them. In terrestrial exlploration, you always have a magnetic field present -

FUTURE GEOPHYSICAL TECHNIQUES

David W. Strangway

a very significant magnetic field - and this permits you to map the induced fields with a small component of remanent field. The induced fields can then be interpreted in terms of the magnetite content or the magnetic minerals that are present. On the lunar surface, there is essentially no field and therefore essentially no induced magnetization and therefore you would not be able, with a simple magnetometer system as such, to map the distribution of metallic iron. You would not be able to map the distribution of iron on the lunar surface without doing something a little more clever than just taking a magnetometer around. A magnetometer would find you anomalies, but they would have no particular relationship to the amount of metallic iron present. You would have to use an artificial source. You could lay a large coil out on the surface that could be used to generate a static dc field. This would magnetize the surface. You would then traverse with a system which would map the magnetic field both in the presence and in the absence of this artificial source located at a lunar base or at a base station. From the differences between these two, you could then map the susceptibility distribution, which would then be directly interpretable in terms of the metallic iron distribution in the upper part of the surface.

I have to mention that there would be a complexity to this; perhaps it's a detail. In figure 2 it can be seen that the magnetic properties of the lunar materials are, in fact, very complex. After you turn off a static dc source, the magnetization continues to decay for a considerable length of time. So, by looking at the way in which this magnetization decays as a function of time and by looking at the strength of the mangetic field that would be created due to your artificial source, you would be able to say something about the distribution of the grain size of the iron as well as about the amount of the material. So fundamentally then you would have to use an artificial-source technique which could map the susceptibility variation. This could be interpreted in terms of the metallic iron present. By looking at the time dependence, you could also determine something about the distribution of the grain sizes of this metallic iron.

Now let me turn to the next set of methods. These are the electromagnetic methods. Conventionally the Earth contains very conductive materials. This means that when we put a transient or a pulse of electromagnetic energy out, that the eddy currents generated will simply circulate through the materials. One then attempts to measure these eddy currents as a result of the applied transient. These are very well known techniques. There are airborne systems flying all over the world in the exploration for mineral deposits and they're all dependent on the fact that there are eddy currents being generated. The thing you would map in an electromagnetic experiment on the moon would, in fact, be dielectric constant and as figure 3 is attempting to illustrate, the dielectric constant of the returned lunar soils is almost entirely a function of the density. You could then map the thickness of the regolith in very considerable detail.

In figure 4, we show the loss tangent or the losses associated with lunar samples. The ones with open symbols are measurements that may have been

David W. Strangway

contaminated during the lab processes by small amounts of moisture and the set that do not have the squares on them represent good, high-quality, high vacuum measurements made of the loss tangent. We have indicated that the losses seem to be very much controlled by the ilmenite content. So the dielectric constant itself is largely controlled by the fact of whether the material is soil or solid and the loss tangent is controlled in part by the density and in part by the amount of ilmenite that's present in the material. Now if you were to attempt to build a system which you could be put on a roving vehicle which would be a time-domain system, where you'd send up pulses and watch them reflect, you would be able to map the lunar regolith. You would undoubtedly pick a frequency less than about 30 megahertz. It turns out that at higher frequencies there are enough boulders and they are large enough that the Moon is good scatterer. In fact, at radar frequencies, it's a very good scattering object, but at around 30 megacycles and from there on down we know that the Moon is a very smooth object. There are not very many large boulders that would cause scattering. Basically this means, then at 30 megacycles, the Moon is a poor scatterer, and this means that it is highly transparent. It means that you can do very high resolution mapping of stratigraphy in the top kilometer of the lunar surface, giving you a good measure of the thickness and the nature of the regolith as you traversed across the surface. Finally, of course, because of the ilmenite content, if there were massive concentrations of ilmenite, these would be very good reflectors. I remind you that the ilmenite on the lunar surface is completely nonmagnetic, so you would not look for ilmenite with any of the magnetic methods, but high concentrations of this material would cause the surface to behave as good reflectors. So electromagnetic exploration on the Moon could be done quite effectively, it could be done with high resolution and it could be done to considerable depth. It would detect not only the stratigraphy just as one does in ice sounding - but it would also be a way of mapping the ilmenite content distribution.

I believe these techniques could become very effective for great depth penetration, for high-resolution mapping, and for mapping very carefully and in much detail the distribution of metallic iron and the distribution of any metallic conductors or good reflectors. So geophysical mapping on the lunar surface, in fact, could be a very useful method of prospecting or exploring for these kinds of materials. I suppose I should finish off by pointing out that there have been a number of papers mentioning water. Of course, everybody would like to use electromagnetic methods to find water. They are not going to do you very much good, I believe, in the lunar environment. First of all, water molecules can stick themselves onto surfaces. Because of the large surface area associated with lunar samples, you can probably stick up to almost 0.1 percent of water, as a monolayer , which gets very tightly bound onto the surfaces and does not then affect the electrical properties very significantly. That amount of water is kind of a threshold level for detection. If there was any more than that, you would probably detect it. Any less than that and it is so tightly bound that it does not respond and cannot be detected. Water might be present in the form of ice in the polar regions. Again this would be a problem. If you freeze

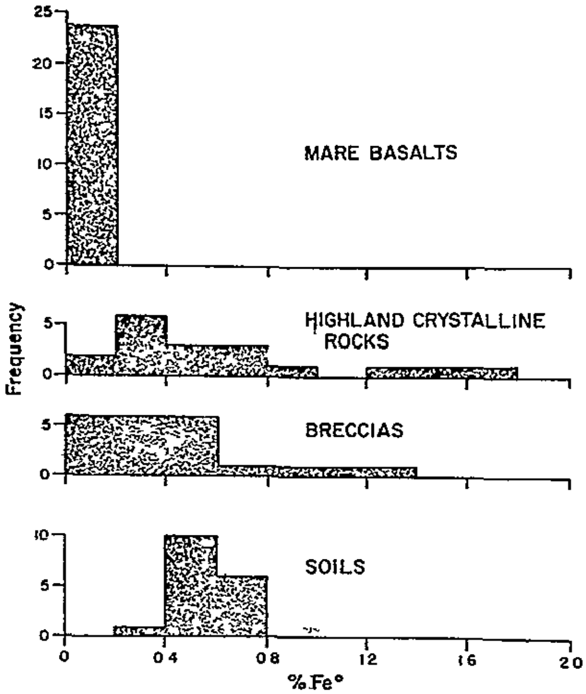


FIGURE 1:

Distribution of metallic iron in various types of lunar materials.

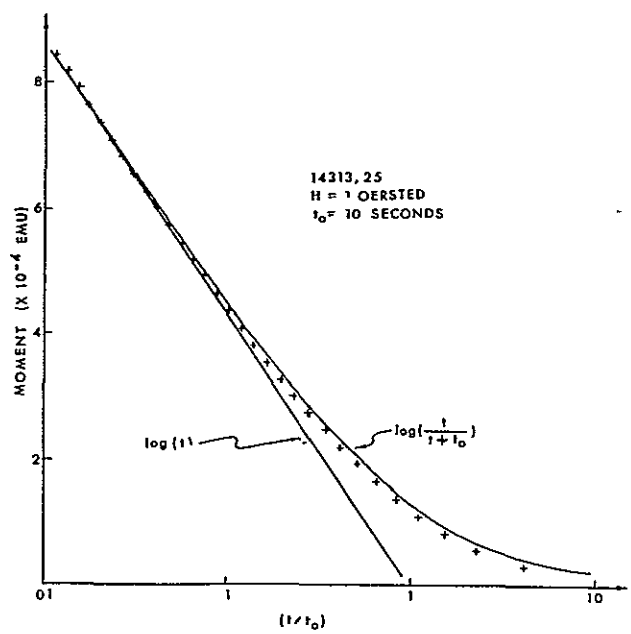


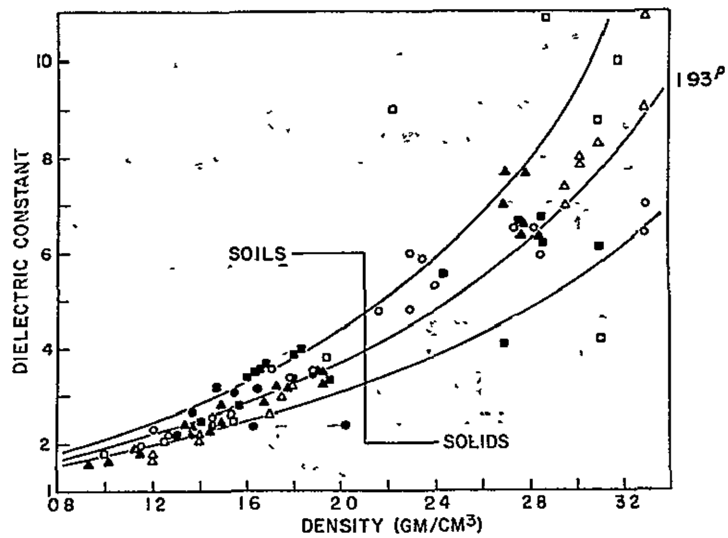
FIGURE 2:

Decay of magnetization in a soil breccia after magnetic field is turned off - x are experimental points and show the so-called magnetic aftereffect which lasts for longer than the time of application of the field.

the water, it also becomes a very poor conductor and the molecules are not able to respond to the electromagnetic fields. Therefore, whether there is less than 0.1 percent or whether there is a lot of it present in the form of very hard forzen ice, you would not really be able to detect the water. Either of those two cases would be transparent essentially to the electrical methods.

FIGURE 3:

Dielectric constant of lunar samples as a function of density - open symbols for Apollo 11,12, 14 where moisture not carefully controlled.



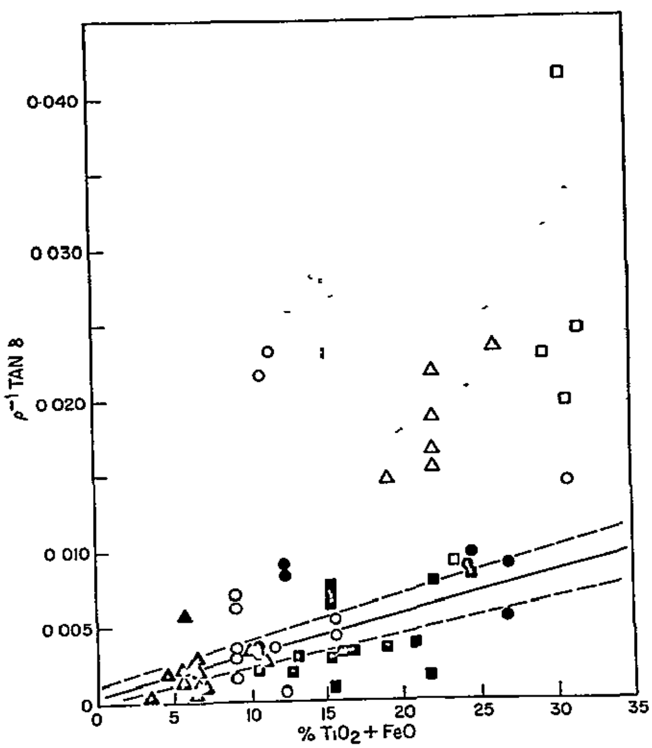


FIGURE 4:

Density normalized loss tangent versus chemical analysis of titanium and iron (approximately ilmenite content). Open symbols are for early measurements where moisture was not well controlled.

DISCUSSION (Strangway Paper)

SPEAKER 1: You mentioned this prospecting was considered on Apollo 17. Do you have any idea of what the mass would be of a device - not the traversing device, but just the prospecting device that you'd need. Is this a very big thing or a small thing?

STRANGWAY: No, these devices I'm sure can be packaged into 5-, 10-, 15-pound type of units. If you're going to put it on an automated vehicle that would obviously be much the controlling factor. There were experiments of this general nature that were carried. You wouldn't carry those same experiments in the same form. You know, you would take the knowledge that you now have and do the thing rather differently, but I'm sure the basic packaging and electronics and all the rest of it could easily be put into 15- or 20-pound packages quite readily.

SPEAKER 2: Dave, I know the purpose of our geophysical surveys is to find concentrations of economic value so we can pay the geophysicist for his Jeep and his axe and his beer and the other things he needs to go do these good things. And I understood that the regolith is, by comparison to the Earth's crust, an undifferentiated source. Could you give any quantification at all of the relative merits of doing these geophysical surveys in the context of this session this afternoon of an economic type of thing?

STRANGWAY: I can't really give you an answer to that. These would be largely tools that would map the geometry of this material. If you picked your frequencies right, you probably also could set it up so that you could get a distribution of the particle sizes. And if it was important in the manufacturing process that you don't pick up areas and sample areas with lots of big boulders and things in them, you might first pick an area in which there is a fairly thick amount of fairly fine grained material and then that would become your base of operations. So I would think of these as sort of presurveys, if you like, for looking for these particular kinds of conditions. If ilmenite was important to you and you were wanting to extract that, you would obviously again want to pick the area where there was the greatest amount of that material present. It's not an easy question for me to answer in terms of tradeoffs, but if you found variations from place to place of factors of 2 or 3 in some of these things, I would assume that that would make a fair amount of difference in the manufacturing or the extraction/ mining process itself.

SPEAKER 2: Is that order of differentiation you're looking for, factors of 2 or 3 rather than thousands as we have on the Earth's crust?

DISCUSSION (Strangway Paper)

STRANGWAY: I think probably that's right. I think the soil tends to have a sort of a homogeneity to it. That's right.

SPEAKER 3: Just a bit in response to that last question. We've looked a little bit at this problem. If you look at the analog of Meteor Crater in Arizona, although most of the impacting projectile is destroyed or disrupted during the impacting, a small fraction is injected as lenses in the wall rock. In other words, in Meteor Crater you have lenses of mixed nickel-iron with the bedrock. These type of things might be locatable in the walls of the small impact crater.

STRANGWAY: If we open that door, you know, we can get ourselves into long discussions as to the amount of material that is present in the soils of meteorite contamination in general. And certainly there is some, but I think many people now agree that percentagewise, in terms of the metallic iron that's being found in these areas, very little of it is probably of extralunar origin. Some of it, certainly, and I think there's no question that some of it is, but the bulk of what we're talking about in here is very fine grained and it's processed or it's developed in situ as a result of these impacting processes. So I guess in principle, while I would have to say it sounds reasonable, there is really very little evidence that there's very much of this kind fo stuff to be found.

POLAR LUNAR EXPLORATION AS A PRELUDE TO LARGE-SCALE OPERATIONS

James D. Burke - Jet Propulsion Laboratory, Pasadena, CA.

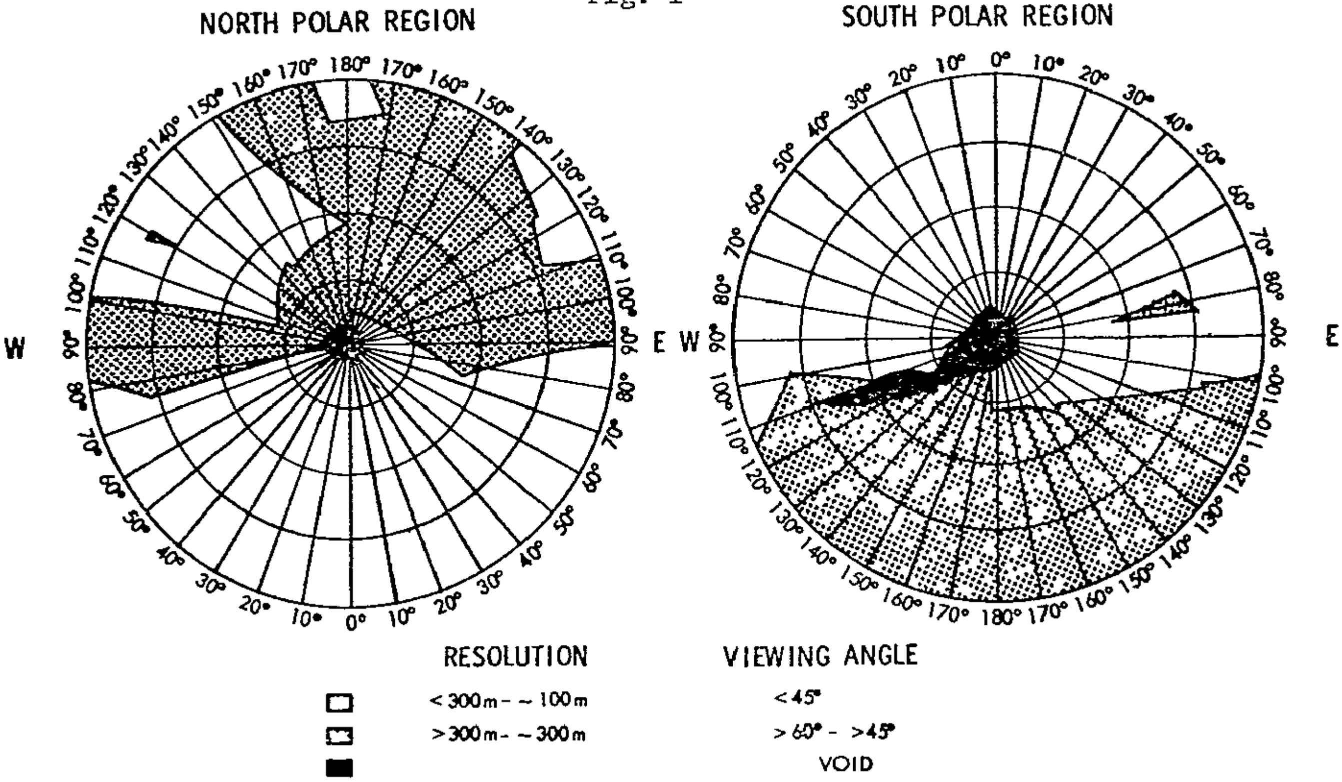
1. Introduction

Before planning large-scale ventures on the Moon it will be logical and prudent to learn more about lunar properties at high latitudes. Some of the needed knowledge can be supplied by an automated polar orbiting mission. Depending on the findings of the orbiter, it may also prove worthwhile to explore the polar regions by means of automated surface rovers. While much of the technology for such missions already exists, we have yet to go through a complete analysis of the objectives, methods, and problems of polar surface missions. Therefore this discussion is mainly about orbiters.

2. Lunar Polar Environments

Lunar Orbiters IV and V photographed the Moon's polar regions (Ref. 1). Figure 1 summarizes the extent and approximate resolution of polar photo coverage by the Lunar Orbiters.

Fig. 1



POLAR LUNAR EXPLORATION

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At the scale of this imagery the Moon's polar surface morphology is grossly similar to that at lower latitudes. There is, for example, no evidence of large-scale surface collapse due to sapping, or removal of subsurface ices, as has apparently happened on Mars in response to major climatic changes. This can mean either that no great amount of ice has accumulated beneath the lunar polar surface or that it has accumulated and not been removed. Of course, the orbiter photos do not show the permanently-shaded regions, which may be cold traps for lunar atmospheric volatiles (Ref. 2).

Lunar polar subsurface temperatures are quite low, as can be seen by extrapolating Earth-based microwave and infrared observations made at lower latitudes. Figure 2 shows the results of observations at 3 mm wavelength (Ref. 3).

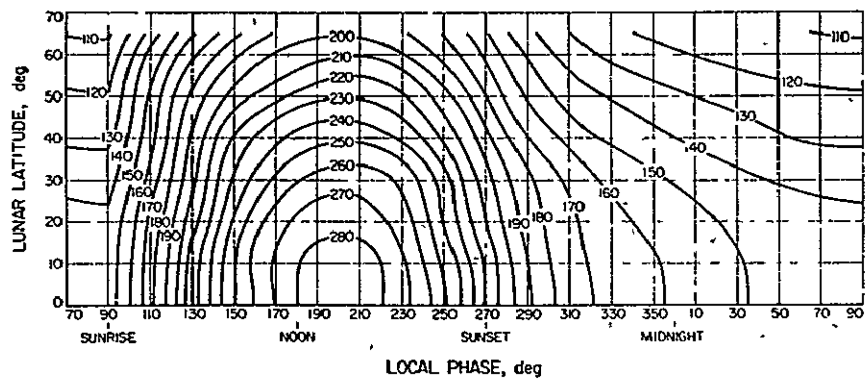

FIG. 2 —An empirical model showing the dependence of brightness temperature (° K) on lunar latitude and local phase. No corrections have been made for effects related to emissivity or depth of emission This plot may be used in comparing the observed brightness temperature of a particular region with the average observed brightness temperature of all other regions at the same lunar latitude and condition of solar illumination

Clearly there is the potential for trapping volatiles at the poles, if any volatiles have been available in the Moon.

Other environmental effects that may differ at the poles are (a) solar particle implantation in soils and (b) electrostatic levitation transport of particles near the terminator. Both of these effects could result in altered lunar soil chemistry at the poles; the effect, if any, on large-scale operations is unknown.

3. Significance of Polar Environments to Large-Scale Operations.

Any man-made subsurface structures in the polar regions will be surrounded by very cold material. This can be either a benefit or a problem depending on the application. Continuous access to the sun, which may be possible from some near-polar locations, offers the prospect of simpler and more efficient energy management for a habitat. Also, a polar location permits ready access to orbital services (communications, resupply, rescue) because of the frequent

POLAR LUNAR EXPLORATION

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passages of a polar orbiter over the poles. Disadvantages are that less of the sky is visible for astronomy, and the Earth is always close to the horizon. Though previous lunar base studies have treated these tradeoffs, many of the assumptions are now obsolete and it will be wise to re-examine the question once more is known about (a) lunar polar characteristics and (b) the nature and purposes of planned lunar habitats. Should available volatiles, especially water, be found only at the poles, this would dominate the choice of sites.

4. Contributions of a Lunar Polar Orbiter

At JPL a study is now in progress to define a Lunar Polar Orbiter project for continuing the scientific exploration of the Moon. Characteristics of the mission are listed in Table 1.

Lunar Polar Orbiter

Mission Summary

1. Measurements for geochemistry, gravity, topography, magnetism and heat flow.
2. Data system correlates multidimensional data from all experiments.
3. 290 Kg orbiter in 100 km polar orbit.
4. 65 kg of instruments continuously pointed to nadir.
5. 32 kg relay in high orbit, and/or gravity gradiometer.
6. One year operation.
7. 4000 bps data continuous when orbiter in view.
8. 250 ksps tape dumps when orbiter near poles.
9. DSN 26m stations + possibly STDN 26m.
10. Opns. mostly routine; command updates approx. weekly; data received in blocks, most off-line opns. one shift.
11. Extended mission depends on fuel (orbiter) and orbit evolution (relay).

The main mission objectives are to measure from orbit all lunar properties that can be so measured and that are relevant to understanding the present state and past history of the Moon.

POLAR LUNAR EXPLORATION

James D. Burke

Examples of these properties and the planned means for measuring them are:

Gravity	Doppler tracking, including far-side Doppler via a radio relay
Surface composition	IR reflectance spectrometry X-ray spectrometry Gamma-ray spectrometry UV spectrometry
Figure, topography	Radar altimetry
Electromagnetic properties	Magnetometry Electron reflection
Heat flow	Passive microwave radiometry, IR photometry

In the process of meeting its scientific objectives the Lunar Polar Orbiter will produce information of value to planning large-scale operations. For example the orbiting gamma-ray spectrometer can detect subsurface hydrogen, and hence can tell whether or not the single most important polar resource (water ice) is likely to be recoverable (Ref. 3). The orbiting microwave-infrared heat flow experiment effectively measures brightness temperature at various depths, and hence yields information useful for designing subsurface lunar base elements. The gravity and topography measurements are essential for planning orbital tranfers and polar landings. The compositional and magnetic experiments will map available mineral resources.

In the aggregate, by providing information to constrain models of the Moon's history and interior composition, the Lunar Polar Orbiter mission has the potential of helping to guide farther-future large-scale operations such as the creation of artificial lunar atmospheres. Thus in carrying out this relatively modest mission we may once more be actively enroute to the vistas of the future for human activities on the Moon.

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ASTEROIDS: A SOURCE OF NATURAL RESOURCES FOR TERRESTRIAL AND EXTRA-TERRESTRIAL APPLICATIONS. Michael J. Gaffey and Thomas B. McCord, Remote Sensing Laboratory, Room 24-413, Dept. of Earth and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Mass. 02139

The visible and near infrared (0.32-1.6μm) reflectance spectra of about 100 asteroids are available in the literature (1). These spectra can be interpreted utilizing diognostic mineral absorption features and spectral parameters to determine the mineralogy and petrology of their surface materials (2). Assemblages of minerals typically found in meteorites (Ni-Fe, pyroxene, olivine, feldspar, carbonaceous materials) dominate as asteroid surface materials. The surfaces of Asteroid Belt bodies (≈2.2-3.6AU) are primarily materials similar to carbonaceous chondrites and iron and stony-iron meteorites. The Apollo and Amor (perihelion < 1.0 and 1.5 AU respectively) seem to be of ordinary chondritic materials (Px,01,Ni-Fe,Fd) (3). The abundance of native metal phases in the surface materials of these objects raised the obvious question of the feasibility of acquisition and utilization of these materials either in space or on the Earth. We have completed a preliminary qualitative and quantitative investigation of this concept. We have evaluated in at least a general way, the physical, social and economic problems and/or benefits resulting from such access to extra-terrestrial sources of the Ni-Fe metals.

In terms of supplying materials for large-scale operations in near-earth space, asteroidal sources appear to be competitive with lunar or terrestrial sources. The direct energy requirement for delivering materials to near-earth space (eg. 5-60 Earth radii) are: Earth's surface ≃ 40-65 x 10^6 joules/kg; Lunar surface ≃ 3-15 x 10^6 joules/kg; Belt asteroids ≃ 30-80 x 10^6 joules/kg and Apollo and Amor asteroids ≃ 3-100 x 10^6 joules/kg. It is probable that some or all of the Apollo group objects are extinct cometary nuclei and thus should contain the volatile hydrogen, carbon and nitrogen phases beneath a layer of insulating overburden (4). Since these vital materials are rare or absent on the lunar surface, the Apollo objects provide a significantly cheaper alternative than a terrestrial source.

The main thrust of our effort has been concerned with acquisition and delivery of the Ni-Fe group metals to the Earth's surface for terrestrial applications. There appears to be strong economic and environmental incentives to undertake such a program. Utilizing realistic and conservative assumptions concerning terrestrial demand, prices and delivery rates for these metals at some point in the relatively near future (eg. 30 to 40 years), it should be possible to realize an annual gross return of $100-200 billion (in 1975 dollars), for an investment comparable to the presently projected capitaliza-

ASTEROIDS: A SOURCE OF NATURAL RESOURCES

M. J. Gaffey

tion program of the Western iron industry over the same interval. The direct energy cost of producing raw iron from high-grade iron ore (iron oxide) is about 17 x 10^6 joules/kg and will continue to increase as the grade of terrestrial ores and fuel sources continue to decrease. Thus even at the present time, certain asteroidal bodies could supply iron to the Earth's surface at a lower energy cost than terrestrial sources, and this balance will shift more strongly in favor of the asteroidal sources in the future. In addition, the increasing terrestrial dependence on lower and lower grade ores will result in an increased environmental impact as more raw ore and fuel must be mined, more terrain disrupted and more waste products disposed of to obtain the same amount of metal (5). Access to extra-terrestrial sources of these metals would remove this environmental damage and the decline in quality of life and/or increase in cost of materials which results. In effect, the mines and factories no longer need be anybodys backyard. This proposal should not be viewed as displacing the terrestrial iron industry and its' labor pool, since the decline in grade of ore will require an increase per unit of metal in both the plant and labor required for terrestrial processing.

Technically, the proposal appears to be quite feasible as outlined in the following scenario. The Ni-Fe metal is brought into near-earth space either by moving a small asteroid ($\approx$ 1 km) by means of nuclear pulse propulsion (6) on a near-term basis or from an independent, self-sufficient mining colony situated on an appropriate asteroid on a longer-term basis. In a large factory/colony near 60 Earth radii, the metal is melted and refined in solar furnaces, a volatile phase injected into the melt to produce a metal foam ($\rho \approx 0.5$ gm/cm^3) and fabricated into a large-scale (10,000 to 100,000 tons) lifting-body with a low mass/cross-section ratio (100 to 1000 gm/cm^2). The orbit of this body is perturbed to arrange a close encounter with the Moon and thus convert an essentially circular geocentric orbit into an extremely eccentric orbit with perigee near the Earth's surface. (Such gravitational modification of orbital parameters requires precision guidence but little direct energy input.) After the Lunar encounter, the orbit is refined to achieve a tangetial atmospheric graze at about 80 kilometers altitude with a lift/drag ratio of 0.1 to 1.0. Such conditions permit the atmospheric entry and decleration of the body without the surface of the body reaching the melting point of Ni-Fe metal, so that ablation is minimal and no problem of particulate pollution of the upper atmosphere is introduced. The low density of the body permits landing to take place in the oceans where it will float for subsequant recovery. Terminal velocity in the lower atmosphere is approximately 60 meters per second so that no large impacts will occur.

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DISCUSSION (Gaffey and McCord Paper)

SPEAKER 1: One now uses spectrophotometry and similar astronomical methods to infer the surface composition of observed asteroids. I'd like to ask this. Can we look at a specific asteroid, such as Vesta or 1976 AA or what will, and in the surface spectra see actual evidence for native metals, for reduced metals or is it simply by analogy with meteoroids that you are arguing that these metals exist?

GAFFEY: We can look at any asteroid that's bright enough - and if you look at Vesta you aren't going to see any metal because there isn't any metal there. Vesta is a very nice spectrum and indeed it's a nice clean silicate that's rather well characterized at this point in time. A lot of work has been done. You can look at a fairly large number of objects; roughly a third of all of the asteroids we looked at appear to have surface compositions ranging from 25 to 100 percent metallic nickel-iron.

SPEAKER 1: On what do you base that?

GAFFEY: On the behavior of the spectral characteristics. Nickel-iron has a characteristic spectral signature.

SPEAKER 1: So then you actually do see a signature of nickel-iron in some asteroids. Could you name a few asteroids which show very high abundnace?

GAFFEY: Three Juno, 15 Eunomia, 39 Lutetia, 40 Harmonia, 354 Elinora -- how far do you want me to go up in numbers?

SPEAKER 2: What about evidence for water ices or asteroids that might have a lot of water content to them? Can you tell that from ground-based observations?

GAFFEY: You won't see any stable water ices in the inner solar system because literally they're not stable. Inside the orbit of Jupiter, ices exposed to the solar radiation do not last for reasonably long periods of time. What you do see is objects, for example - I can't pronounce the name, it's Indian I believe it is, which was originally identified as a comet; it had a transient feature. Penogium, I believe, is the name. In subsequent passes, it is classified as an asteroid. It shows no transient phenomena. This is direct evidence that that object has volatile phases buried in the surface. The other example is things of carbonaceous chondritic composition range in the low metamorphic grades from 20 percent water, bound water, down to in the high grades 1 or 2 percent bound water. In this case we see a large number of low-grade carbonaceous chondritic material. We do not see the water directly; we see the assemblage that's tied up.

COMETARY CAPTURE MISSIONS: BENEFITS FOR HABITATION AND MATERIALS PROCESSING ON THE LUNAR SURFACE; A. J. Bauman and Fun-Dow Tsay, Jet Propulsion Laboratory, Pasadena, California.

The lunar surface appears to be a poor source of metallic materials of construction, except for the 0.5% submicron free iron of soils[1] which might be recovered electromagnetically. The chief obstacle to preparing aluminum or titanium from lunar soils and rocks lies in the insignificant levels of chemical reducing agents, such as carbon and hydrogen present in surface soils only to about 50 and 10 ppm,[2] respectively. Large-scale high-temperature metals recovery processes[3] on the moon will thus require the uneconomical transportation of carbon or hydrogen from earth. Within this context, a recovery mission to land a portion of a cometary nucleus (CN) as a carbon source on the moon merits first priority consideration in the establishment of a Lunar Manufacturing Base (LMB). The CN would provide sufficient water, carbon dioxide, nitrogen compounds (such as hydrazine), hydrocarbons and C-1 chondritic carbon[4,5] to operate a base completely autonomous even to the synthesis of food from CO_2 and water[6]. Aluminum and titanium for deep space construction would be made from lunar soils using the CN carbon, (probably) halogens[3] and high solar energy temperatures. Silicon for photovoltaic devices would also be a major product. The initial base would be most effective underground for air-tightness and meteorite protection; it would adjoin a large enclosed, insulated crater which would hold the CN at a convenient pressure. The LMB should be regarded as a first and significant testing ground for the development of advanced technology to support large space colonies, such as the L-5 orbiters suggested by O'Neill.[7,8] It should be more economical to build than the "Orbiters", although its gravity well would be larger, because the underground bulk of it would consist of fused or sealed lunar material.

Is it feasible to capture, transport and soft-land cometary nuclei and, later, asteroids, on the regolith? Cometary nuclei appear to be fragile "dusty snowballs" comprised of frozen gases which readily ionize in the solar wind to yield the visible coma and tail. Typical nuclei weigh about 10^{12} - 10^{13} kg, have a diameter of a few Km or less, and include solids of indeterminate composition, such as carbonaceous chondrites.[4] It should be entirely possible to plug large numbers of very light reinforced plastic or paper rocket nozzle-"firing chamber" assemblies into the soft "snow" of the nucleus, probably by unmanned means. The nozzles, in arrays clustered at opposite ends of an axis through the nuclear center, would have gimbal-mounts and could be directed (by computer) in any direction. "Firing" and propulsion would occur when a focussing mirror directed sunlight into the "firing chamber" which would immediately cause gases to issue from the nozzle. The system as a whole would consist of a number of such assemblies plugged on opposite sides of the spherical nucleus along an axis such that the whole could be accelerated or decelerated on computer demand. If necessary, it should be easy to cut or shape very large nuclei into smaller units by means of powerful lasers. This approach is conceptually simpler than that of the "transport linear accelerator" (TLA) machine suggested by O'Neill,[7] but that device would probably be quite effective in transporting metallic asteroids from the belt with its adequate supply of "fuel". It should, of course, be feasible to transport an asteroid by carrying it "piggyback" on a cometary nuclear "engine" to lunar orbit for soft landing by means of chemical rockets.

A flyby to Comet Encke in 1980 and an encounter in 1984 have been suggested as scientific goals; we strongly support those missions in terms of their pragmatic value to the LMB concept. Comet Encke, and Comets Arend-Rigaux and Neujmin I, as well as asteroids - 1936 Adonis and 1566 Icarus may consist of carbonaceous residues and thus would be other suitable candidates. The "fast-moving object Helin" 1976 AA has an orbit between 0.79 and 1.14 au, appears to be a large carbonaceous planetesimal, and will approach to within close proximity to earth in 1996.[9] It appears to be about 1 Km in diameter and is typical of the Apollo asteroids also of interest for the LMB. An LMB based on these concepts would in the long term be a good prototype for an autonomous Martian colony which, in that case, would already have adequate amounts of CO_2.

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REMOTE-CONTROLLED STUDY OF THE HISTORY OF LUNAR VOLATILES; J. H. Fremlin, Department of Physics, University of Birmingham, England.

Since the formation of the moon, very large quantities of volatile materials must have been evolved from the interior. If the moon was originally formed nearer the sun as its high refractory content would suggest, most of these must be permanently lost. This could also be true if it formed in association with the earth, but had for a long time a high surface temperature internally generated. For most of the time since it was established in its present orbit, however, it must have had a surface temperature determined as now by the dynamic equilibrium between the input of energy from sunlight and the loss from thermal radiation. During this period some further loss of volatiles, including small quantities of water derived from interaction between solar wind protons and surface oxides must have continued.

It is well known that the gravitational field of the moon is inadequate to hold an atmosphere at its average surface temperature of around 250°K, but if areas exist on the moon sufficiently cold to freeze out volatiles, some of these may still persist. Such areas may exist near the poles. If the moon were perfectly smooth an area near one of its poles would be calculably cooler than the equator, but not cool enough. The axis of the moon's orbit and of its rotation is inclined at just over 5° to the axis of the earth's orbit round the sun and hence in the polar 'summer' there will be six months insolation rising to a maximum with the sun just over 5° above the horizon.

The rate of input of solar energy will then be reduced to about 1/11 of that at midday at the equator and, since thermal radiation varies as T^4 the maximum temperature reached will be only about 210°K. At this temperature the vapour pressure of water is still high enough for it to be lost quite quickly but 210°K is the temperature that would be reached if the moon were perfectly smooth. It is not in fact perfectly smooth. Even a micro-roughness in which some dust particles projected to reach near-equatorial temperatures and hence lost thermal radiation at eleven times the local average rate would enable temperatures well below 210°K to be permanently maintained by much of the surface, although estimation of the magnitude of the effect would be difficult. The moon's surface, however, is rough on a major as well as on a minor scale. A range of hills at a latitude just under 85° (5° from the pole) and with a poleward slope of over 10° would leave an area in permanent shadow; hills of only 200 metres high would shadow a strip a kilometre wide. Near the pole craters or parallel ranges of hills with internal slopes over 5° will give permanently shaded areas. Thermal conduction from the sunlit areas, themselves having average round-the-year temperatures of only 170°K or so, would be negligible over even a few hundred metres - much less than

REMOTE-CONTROLLED STUDY: HISTORY OF LUNAR VOLATILES

Fremlin, J. H.

the thickness of the hills or crater walls.

We can, therefore, confidently expect that there will be areas of significant size near the lunar poles in which the surface temperature has for extended periods been almost entirely determined by the amount of heat from the interior reaching the lunar surface. This has been found from Apollo studies to be 2×10^{-6} watts/cm^2. At the equator we have a daytime absolute temperature of about 390°K with a solar heat input of 1.4 kw/m^2. The equilibrium temperature on a dark area near the pole should then be in the region of $390 \div (0.14/2 \times 10^{-6})^{0.25}$ or 26° K.

This would be low enough to hold water, ammonia or carbon dioxide indefinitely, probably together with oxygen and nitrogen. Only a fraction of volatile gases evolved from the interior would, of course, reach such areas; most on the day side may be ionised at once and swept away by the solar wind, but any large emissions, especially on the dark side, should have left frozen layers in the polar craters. In the long term it is even possible that there could be enough water ice to be of practical value to a lunar colony, but my present concern is with the possible scientific value of the "sedimentary" layers in offering us a record of volatile emissions over a very long period of lunar history. Careful analysis of a core from such sediments, on the lines of the examination of deep ocean cores, should enable us to reconstruct this history.

My specific proposal is that a mobile unmanned remote-controlled unit should be landed at a suitable point at polar midsummer when the permanently dark areas could readily be identified. The unit would carry a core-digger, an evaporator and a recording or on-line mass spectrograph which could transmit results periodically to a lunar satellite in polar orbit. The unit should have sensors capable of measuring surface temperatures so that it could first survey the surface temperature distribution in the chosen area and then be directed to the coldest point for its analysis of volatiles as a function of depth. If more convenient, the motion of the unit could be self-controlled to follow surface temperature gradients downwards until it reached a minimum.

If the results were interesting, a later version of the unit could include a recoverable module either to return a complete core suitably cooled or at least a sample of the underlying rock which might be dated by fission-track analysis to determine the time at which the crater itself was formed and hence the length of time over which the sediments were collected.

FAR-ULTRAVIOLET PROSPECTING OF THE ENTIRE LUNAR REGOLITH; Richard C. Henry, W. G. Fastie, and R. L. Lucke, Physics Department, Johns Hopkins University, Baltimore, MD 21218; B. W. Hapke, Earth and Planetary Sciences Department, University of Pittsburgh, Pittsburgh, PA 15260, and W. R. Hunter, Naval Research Laborabory, Washington, DC 20375.

The mining of large quantities of industrial materials from the surface of the moon requires meticulous care in the selection of mining locations. Identification from lunar orbit of regions that differ in composition or in physical state is an economic imperative. Only a limited number of physical or compositional parameters are accessible from orbit, however. We propose that a generally useful parameter is the index of refraction of the regolith, and we propose that it be measured for the entire lunar regolith by survey of the far-ultraviolet reflectivity of the moon.

The far-ultraviolet reflectivity of the moon depends strictly on the lunar index of refraction, in a way that the visible-light reflectivity does not. In the visible, considerable penetration by light into the particles that make up the lunar surface occurs. This light is absorbed selectively by wavelength, and is scattered, a good amount of it leaving the particle and becoming part of the reflected beam. Thus, minor impurities in the interior of the surface particles can have a profound effect on the optical reflectivity. In the far ultraviolet, in contrast, this effect is negligible, as ultraviolet photons will not significantly penetrate the grains. The reflectivity coefficient will be determined virtually entirely by the index of refraction of the grain as a whole.

Data obtained with the Far-Ultraviolet Spectrometer Experiment (1,2) carried on Apollo 17 have been analysed (3,4,5) and show that substantial index-of-refraction differences do occur from place to place on the lunar regolith. The Apollo 17 spectrometer had a 1000 km^2 field-of-view, and therefore no fine-scale compositional/physical state survey was possible, even for the 3% of the moon that was observed; but a multi-channel orbital far-ultraviolet photometer has been described (5) which is capable of mapping the entire regolith with 1 km^2 resolution. This photometer has been proposed for the Lunar Polar Orbiter mission. The ground resolution it will provide is probably adequate for large-scale surface mining operations.

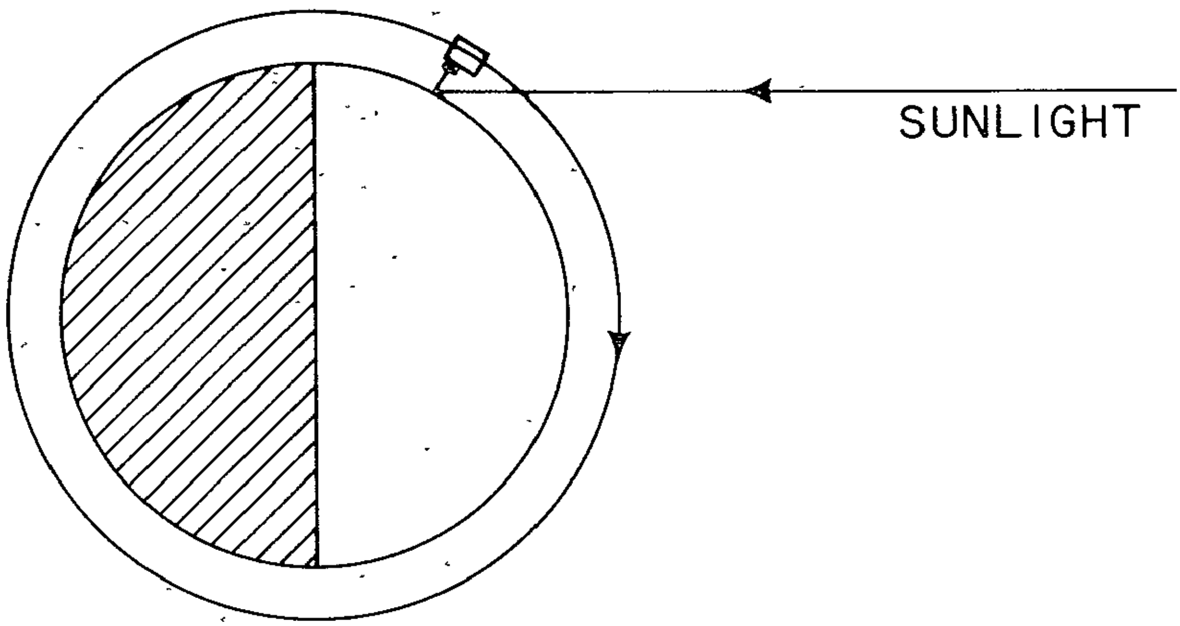

Figure 1 shows schematically the method of acquisition of data. The photometer is a three-channel device, which allows verification of the absence of any influence of body scattering on the reflectivity observed. The angle of incidence of the sunlight must be taken into account in computing the index of refraction, but techniques for doing this are well developed (4,6).

FAR-ULTRAVIOLET PROSPECTING

Henry, Richard C., et al

The result of these measurements will be a refractive index map of the moon. The refractive index is determined by the composition and the physical state of the material. Measurement of the refractive index does not, of course, determine the composition. However, differences in refractive index from place to place certainly indicate differences in composition or in physical state. If detailed measurements in the laboratory of the composition of samples taken at a certain site on the moon have been made, then the lunar refractive index map can be used to safely infer that the composition of contiguous regions containing the sample site and differing negligibly in refractive index is substantially the same. Also, one of us (B.W.H.) is currently carrying out NASA-supported laboratory research to determine, among other things, the effect of composition on refractive index. The refractive index map, used in close conjunction with optical photographs and other orbitally-obtained composition-dependent parameters, will be a powerful tool in the selection of lunar mining sites. The choice of sites is critical: for example (7), the Apollo 11 and Apollo 12 sites differ by a factor 3 in their titanium abundance. With 1 km^2 resolution, the refractive index maps might reveal comparatively small, highly anomalous regions, which could prove exceptionally rich in desirable minerals.

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UTILIZATION OF UNIQUE MARE STRATIGRAPHY FOR DETERMINATION OF LUNAR SURFACE MATERIAL PROPERTIES AND LOCATION OF SUBSURFACE OPERATIONS FACILITIES;
R. A. Young, Department of Geological Sciences, SUNY, Geneseo, N. Y. 14454.

Detailed studies of mare crater size-frequency distributions in the diameter range from 100m to 600m have demonstrated a distinct inverse relation between total numbers of craters and surface ages in the diameter interval below 300m (1). This relationship indicates that caution must be exercised in any theoretical calculations of the particle size distributions of regolith fragments based on models using measured crater size distributions. Because the disappearance of small craters in this size interval (<300m) is considered to be caused by the cumulative effects of seismic vibrations, as well as impact gardening in the thickening regolith, further studies are needed to estimate the effect of prolonged impact gardening on the physical nature of the regolith. The buffering effect of the growth-regulated regolith has been discussed by Quaide and Oberbeck (2), but additional factors may be of importance. For example, the subsurface stratigraphy of Mare Serenitatis (3,4) has produced a conspicuous increase in the size and number of ejecta fragments around small craters. Additional studies (5) have shown that both crater-size frequency distributions and crater morphology for craters up to 700m in diameter are measurably affected by the magnitude of impact gardening and the nature of subsurface discontinuities in individual mare regions.

It would be advantageous to attempt calculations of probable regolith fragment size distributions for a number of theoretical ages and simple layered models to explore the economics of various surface mining, stripping, construction, or processing operations. In this regard, each mare basin or subregion is probably unique.

Southern Mare Serenitatis (inside the dark annulus) is the most obvious of those regions where a number of orbital and remote sensing experiments indicate an older regolith in a widespread subsurface layer that is probably 100 to 200m beneath relatively coherent surface lavas (4,5). The evidence for this buried zone can be seen in crater-size frequency distributions, the morphology of craters ≤700m in diameter, infrared spectral reflectance data(6), Lunar Sounder data (7), the ejecta of large craters such as Bessel (4), and rim height/diameter ratios of partially flooded craters (Fig. 1).

The presence of this buried zone of regolith and dark mantle (?) material provides a unique situation for combined subsurface construction, natural shielding, and access to large quantities of fragmental lunar materials. In addition, it is possible that the voids in the buried regolith contain mineral-ized zones, intrusive veins, or vapor phase mineral deposits from events associated with the emplacement of the younger surface flows and intrusive mare ridges.

Access to this buried regolith zone is readily provided by fresh craters less than one km in diameter (Fig. 1). The mineralogy of ejecta from these craters can be studied by remote spectral reflectance from earth or lunar orbit (6,8). Fresh craters with progressively larger diameters could be examined by infrared reflectance to explore below the surface and detect mineralogical differences, regolith, or dark mantle zones.

Mare Serenitatis has the additional advantage of containing some of the youngest intrusive mare ridges (4) as demonstrated by flow into numerous postmare impact craters. These ridges are probably the most coherent surface exposures of lunar bedrock with a minimum of regolith cover and could provide solid foundations on the surface for related engineering, scientific, or launch facilities. The ridges may also represent late-stage differentiation of magmas injected as residual melts from the earlier widespread mare flooding. For this reason, they might be the best candidates in the maria for mineral "prospecting".

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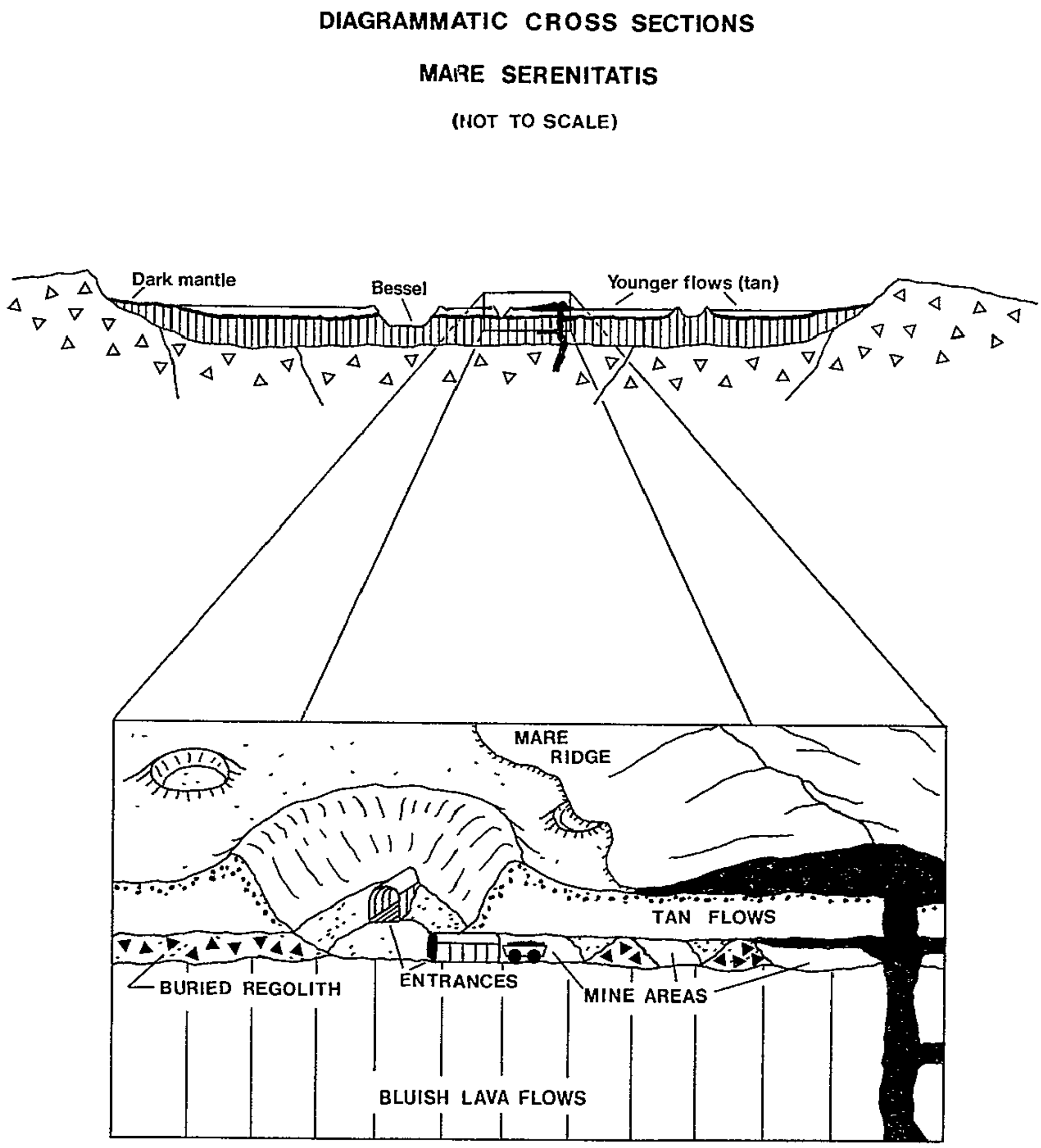
DIAGRAMMATIC CROSS SECTIONS
MARE SERENITATIS
(NOT TO SCALE)
Dark mantle
Bessel
Younger flows (tan)
MARE RIDGE
TAN FLOWS
BURIED REGOLITH
ENTRANCES
MINE AREAS
BLUISH LAVA FLOWS

FIGURE 1

TRANSPORTATION

FREE-FALL TRAJECTORIES FROM THE MOON TO THE LAGRANGIAN EQUILIBRIUM POINTS;. R. A. Broucke, Jet Propulsion Laboratory, Pasadena, California 91103.

In the last two years some interest has developed in the construction of large manned space stations. These stations would be orbiting in the Earth-Moon system and would be constructed and assembled in space from materials taken partly from the Earth, but mostly from the Moon. Several transportation systems could be considered. They range from magnetic accelerators located on the Moon to space-shuttle type vehicles traveling back and forth. Several possible locations for the large manned station have also been proposed, and the equilibrium points (Lagrange Points) are favorite candidates, especially the triangular points L_4 (60 degrees ahead of the Moon) and L_5 (60 degrees behind the Moon), or even the collinear points L_1 (in front of the Moon) or L_2 (behind the Moon).

We have thus undertaken a systematic study of the possible free-fall trajectories connecting the Moon with any of the equilibrium points L_1, L_2, L_3 and L_4. We only consider here those free-fall trajectories which are of enough practical value: the trajects should be as direct as possible, with short transit times and with small velocity at the arrival at the Lagrangian point. As a model, we have taken, for the present initial exploration, the well known circular restricted three-body problem in two dimensions. The Earth and the Moon are the only two acting bodies; they are point-masses in circular orbits around each other. The true radius of the Moon does not enter the problem. A Levi-Civita regularization was used for the numerical integration of trajectories in proximity of the Moon.

We have used the symmetry properties (mirror image theorem) of the restricted problem in order to reduce the exploratory work: to each trajectory corresponds a mirror image on the other side of the Earth-Moon line (Syzygy-axis). For instance, to each Moon-to-L_4 trajectory corresponds a symmetric L_5-to-Moon trajectory (traveled in the same time).

In the examples that are given below, we specify the trajectories by their final condition at L_1, L_2, L_3, or L_4 rather than the initial conditions at the Moon. This can be reduced to a set of initial conditions at the Moon by integrating backwards or more simply by using the mirror image theorem. The parameters which are used to specify a given trajectory are the 2 coordinates of the libration point together with the velocity and flight path angle at the point. The flight path angle is measured with respect to the Earth-Moon line and is zero in the Earth-to-Moon direction (180 degrees in the Moon-to-Earth direction). These angles (and also the velocities) are relative quantities measured in the rotating Earth-Moon system.

FREE-FALL TRAJECTORIES FROM MOON

Broucke, R. A.

An example of the trajectory from L_5 to the Moon (or from the Moon to L_4) has been computed with a velocity of 90m/sec, a flight path angle of 205 degrees and a transit time of 15 days. This trajectory is mostly inside the Moon's orbit and is faster than the trajectories from L_4 to the Moon (or from the Moon to L_5) which are retrograde and mostly outside the Moon's circular orbit. Two such trajectories were found with a velocity of 90m/sec at L_4. In the first one the transit time is 19 days and the angle at L_4 is 96 degrees, while for the second one these numbers are 206 degrees and 25 days.

Several similar trajectories have also been computed for the Lagrange points L_1 and L_2. The point L_1 can be reached via a fairly direct path. The hidden point L_2 can be reached with a residual velocity of 230m/sec in 2.8 days. The flight-path angle at arrival at L_2 is 70 degrees.

Because so much work has been done on the study and classification of periodic orbits in the restricted three-body problem it is of interest to relate these trajectories to some of the known classical families of periodic orbits. It is found, for instance, that the above-mentioned trajectory from the moon to L_4 is very nearly the known periodic collision orbit of the retrograde family around the equilibrium point L_2.

Inspection of the complete trajectory shows that it would be possible to take off from the Moon at the sub-Earth point, travel to L_4, keep on going behind the Moon (intersect the syzygy-axis at the right angle at an apogee about 200,000 km behind the Moon) and then travel on to L_5 and finally return to the Moon and land at the departure point. Let us also mention that all the members of this family of periodic orbits have unstable characteristic components. Also, that this family corresponds to class a of Stromgren's early investigations.

The examples that we have elected to describe here seem to be some of the best compromises between fuel consumption and time of flight, but we intend to study more in detail the possibilities of other practical trajectories in the Earth-Moon system. Also, the different approach and landing paths on the Moon should be studied, as well as the sensitivities of the different trajectories.

GAS GUN FOR LAUNCHING RAW MATERIALS FROM THE LUNAR SURFACE; Allan M. Russell, Hobart and William Smith Colleges, Geneva, New York 14456.

A number of space manufacturing programs that have been suggested require transportation of large amounts of raw materials from the lunar surface to a processing or fabrication site in free space. While rockets could, of course, be used for this purpose they require the consumption of large amounts of fuel which must be supplied from earth, a requirement that is prohibitively expensive.

Various transportation systems have been suggested that minimize the amount of mass that must be used for propulsion, by converting available energy directly into motive power. An electrical catapult or transport linear accelerator (TLA) was proposed by Clarke (1) and later by O'Neill (2). This would accelerate small payloads to lunar escape velocity by means of electrical energy. Another electrical launching device called an Electropult was developed by Westinghouse Corporation during the second world war for the purpose of launching planes from ships (3). The main difficulty with such devices is their inherent low efficiency and low power to mass ratio. O'Neill has considerably improved recent designs through the use of superconducting technology. However, electrical catapults continue to have large mass requirements and suffer from losses due to a need to decelerate sophisticated conveyer buckets. This paper describes an alternative system that uses gas propulsion.

The lunar escape velocity of 2370 ms^{-1} can be attained by a single stage light gas gun that operates with hydrogen gas. Light gas guns have been used on ballistic ranges for a number of years and have launched projectiles at speeds of up to 11,000 ms^{-1}, almost five times the lunar escape velocity (4).

Application of the equations governing the behavior of hypersonic projectiles in uniform cylindrical barrels leads to one equation relating the mass of the barrel to the barrel material and the speed and mass of the projectile, and another equation relating the length of the barrel to the bore radius, the gas pressure, and the mass of the projectile.

$$M = 5.22 \frac{\rho}{\sigma} V^2 m \qquad \text{and} \qquad L = 4.67\times10^6 \frac{m}{R^2 P}$$

GAS GUN FOR LAUNCHING RAW MATERIALS

Russell, Allan M.

where M is the mass of the barrel in tonnes
V is the muzzle velocity in ms^{-1}
ρ is the density of the barrel material kg m^{-3}
σ is the tensile strength of the barrel material in N m^{-2}
L is the length of the barrel in m
R is the bore radius in m
P is the gas pressure in the reservoir in N m^{-2}
m is the projectile mass in kg.
The constants are for hydrogen gas at 200°C

For a high strength composite material, i.e. a boron or graphite epoxy such as PRD-49 with $\rho = 1.38 \times 10^3$ and $\sigma = 1.65 \times 10^9$

$$M = 24.5 \text{ m. (at lunar escape velocity)}$$

One could imagine, therefore, a 245 tonne gas gun of barrel diameter 2 meters and length 234 meters, launching a 10 tonne projectile using hydrogen gas in a reservoir at 2×10^8 N m^{-2} (2 k bar). The gas would not be allowed to escape, but would be recompressed and stored at high pressure. If a nuclear reactor were the energy source, it could be used to drive the compressor directly without the need to generate electrical energy, a considerable saving in mass.

A nuclear power source (without shielding) and compressor that would be required to operate such a gun every half hour are estimated to have a mass of about 600 tonnes. With 10% of the mass of the system budgeted for auxiliary equipment, and if it is assumed that the gas is stored at high pressure below the lunar surface, the total mass approaches 1000 tonnes. Estimates of the mass of an electrical launching system of the same capacity run as high as three times this.

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THE CAPTURE OF LUNAR MATERIALS EJECTED INTO DEEP SPACE; Dr. Mamdouh Abo-El-Ata, San Francisco State University, San Francisco, California.

This abstract describes the concepts of two devices that can be used to capture payloads of materials ejected from the moon into space. The first device is a passive catcher which stays almost stationary in space and captures only payloads targeted to its cross-section. The second device is an active catcher that could track and move to intercept payloads over a considerably larger area than the passive catcher.

The analyses and designs have been made assuming payloads which are solid spheres 0.20 m in diameter, made of compacted and sintered lunar soil. Each payload has a mass of 10 kg and arrives at the catcher with a speed of 200 m/s. The frequency of arrival is one payload per second.

A. Passive Catcher

A passive catcher could be a bag with a one way door to prevent rebound, a bag filled with low density glass wool, or a rigid foam disc. Only the last passive catcher, the rigid cellular foam disc, is analyzed herein.

As the payload impacts rigid cellular foam, it has to shear the foam, crush it and carry the crushed foam in front of it. The payload will come to a stop when the work done against the three resistances mentioned above equals its initial kinetic energy. A theoretical analysis of the dynamics of the payload as it penetrates the foam is given in reference (1). As an example, the analysis showed that a typical payload would penetrate FR type polystyrene foam (density = 28.4 Kg/m^3) a distance equal to 1.3 m. For a circular disc 10^4 m^2 in area, the mass of the catcher is approximately 500 tons.

The foam catcher could be foamed in place. After collecting for a period of time (a lunar day, for example), it could be melted down with solar furnaces, the desired material extracted and the catcher refoamed in space. It also has the advantage of being very simple in conception with essentially no moving parts. Its 500 tons mass for a catch area of 10^4 m^2 is a disadvantage. Like other passive catchers, the foam catcher requires very high precision in launching payloads from the moon surface.

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B. Active Catcher

If an extremely high precision of launching payloads from the lunar surface could not be attained, catch areas of the order of 10^6 m^2 or higher would be required. In this case, passive catchers become too massive to be practical and an active catcher becomes a necessity.

The catcher is in the form of a thin light net, 10m^2 in area, which is manipulated by three strings to position the net anywhere within an equilateral triangle abc as shown in the Figure. The strings are wound on motorized reels which move on three closed loop tracks. The equilateral triangle is 1000 m on the side, providing 0.43 X 10^6 m^2 catch area.

By using a perimeter acquisition radar system, the catcher could track and move the net to intercept payloads. Having captured the payload, the net and reels assembly (rig) act to decelerate it from its incoming velocity of 200 m/s to 20 m/s. The payload is then released into a storage depot and the rig returns to its initial position by means of the closed loop tracks. The estimated circulation time is 60 sec/rig and therefore 60 such rigs are required.

A detailed kinematic, force and stress analysis is given in Reference 1. The length of the active part of the track is about 1000 m The forces involved are less than 1000 N. For a catcher frame made of 2024 Aluminum alloy, the weight of the entire catcher is a little over 200 tons. Contrasting the weight of catcher per unit catch area gives the active catcher a 100:1 advantage over the passive catcher described in A above. On the other hand, the active catcher requires many moving parts, synchronized motions and thus considerable developmental work is need before this concept is realized.

Acknowledgement

The work summarized in this abstract has been carried out by the author during the 1975 summer study on Space Colonization at NASA-Ames Research Center. The author wishes to thank Professor Gerard O'Neill for his help and encouragement in developing the active catcher concept.

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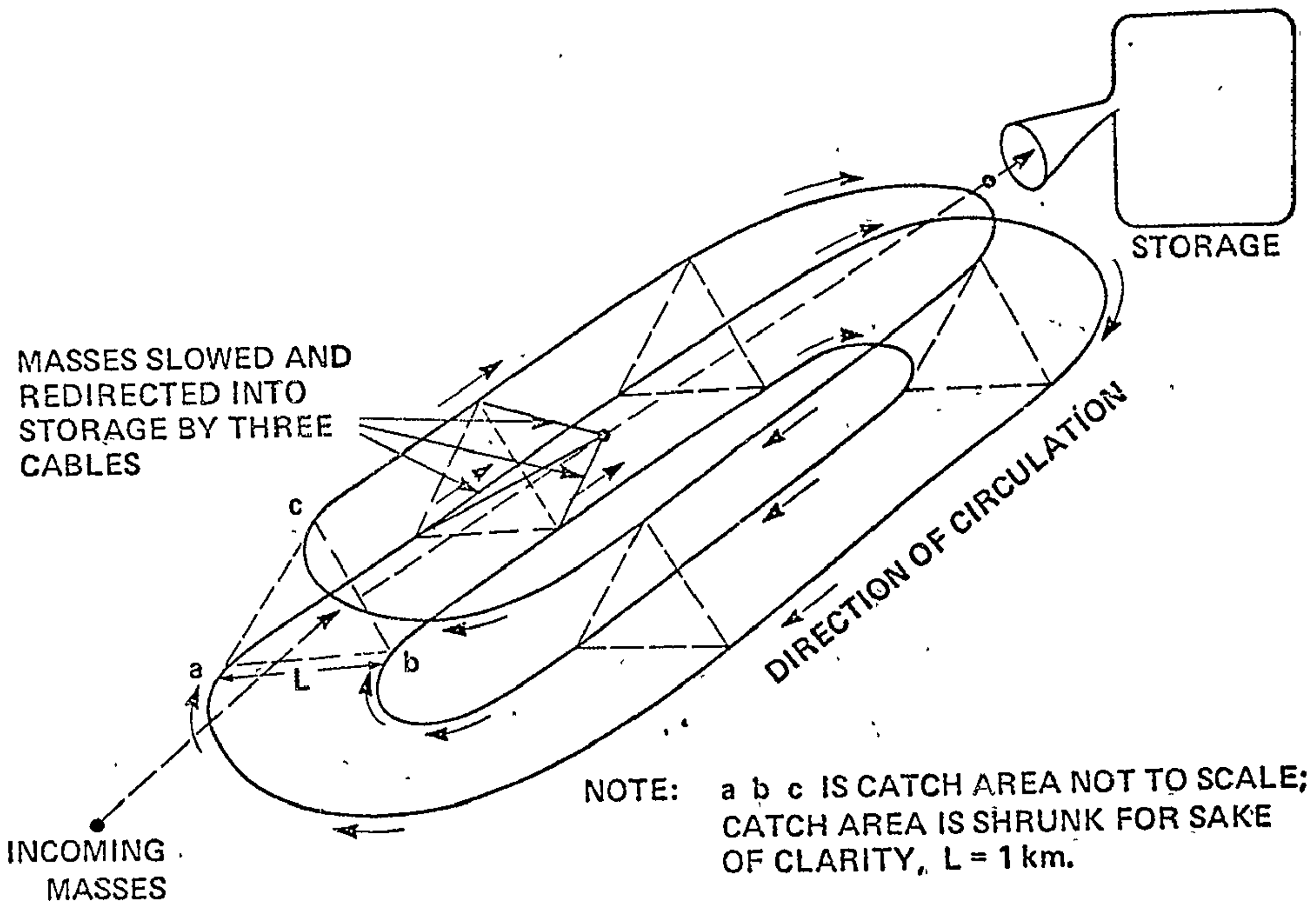
THE MASS CATCHER: SCHEMATIC REPRESENTATION OF CATCHER TRACKS



A SCHEME FOR TRANSPORT OF LUNAR MATERIALS TO UTILIZATION SITES IN EARTH ORBIT; Gerald W. Driggers, Southern Research Institute, Birmingham, Alabama.

Use of lunar resources at some earth orbit location implies transportation by some means of raw or processed materials. Large scale use of such materials will dictate an inexpensive operation in order to minimize overall cost. One method to accomplish this has been proposed by O'Neill wherein small masses would be ejected in large numbers from the moon and collected in space (1,2). Electromagnetic fields would be used to accelerate "buckets" to near lunar escape velocity where the material would be released and the buckets "recycled" for new payloads. This paper is not intended as a review of pros and cons for this proposal, but as a medium for presentation of an alternate technique. Each approach has particular advantages and other competitive possibilities certainly exist.

Briefly, the scheme presented here uses a pressurized "gas gun" called a Large Pneumatic Accelerator (LPA) to eject material from the moon and a small Rendezvous and Retrieval Vehicle (RRV) to capture the ejecta and locate it as required. Individual large payloads (say,100,000 pounds or greater) would be launched as opposed to several launches of smaller masses. The LPA would eject the material with velocity (speed and direction) conditions that have a known statistical distribution. Tracking would be accomplished for a period after launch to establish an ephemeris allowing state vector prediction in time and ultimate RRV rendezvous. The speed imparted to the mass could be controlled such that a two or three standard deviation high dispersion would be the exact required velocity. Thus, 95 percent plus of the masses would require velocity makeup within known bounds. Payloads outside established bounds (velocity, path) would simply be neglected.

The parameters of the LPA have been looked at in a cursory fashion to establish preliminary estimates of size and weight. Simplifying assumptions such as constant pressure and no frictional forces are inherent to the analysis. A blow-down tank system was assumed with multiple injection ports along the LPA tube (termed the booster). The gas dynamics of accelerating the projectile to about 7800 ft/sec in a tube were not addressed. The capability to accelerate small masses to hypersonic velocity in tubes has been demonstrated.

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The effect of payload average acceleration on booster tube length is shown in Figure 1. If extended on to 1000 g's (not an unreasonable number), the tube length is reduced to about 945 feet. For an average acceleration of 500 g's and a booster tube diameter of 240 inches, an average pressure of less than 1500 psi will accelerate 130,000 pounds to escape velocity. The relationship of pressure and payload mass is shown in Figure 2 for those parameters. If a smaller diameter tube is desirable, the operating pressure can be increased accordingly or the tube lengthened. The governing equation is

$$P_b = 2\, m_{PL}\, V^2/\pi l_b d_b{}^2 \tag{1}$$

where

P_b = booster tube pressure
m_{PL} = payload mass
V = desired exit velocity of payload
l_b = booster tube length
d_b = booster tube diameter

An interesting consequence of Equation (1) is that the product $P_b l_b d_b{}^2$ is a direct function of payload mass. These parameters, coupled with simple membrane theory for pressurized tubes, lead to the following result

$$m_b = \frac{\rho}{\sigma} V^2 m_{PL} \tag{2}$$

where

m_b = booster tube mass
ρ = tube material density
σ = working stress of tube material
V = desired exit velocity of payload
m_{PL} = payload mass

For a 130,000 pound payload, a moderate strength-to-density material (say 50,000 psi/1.40 gm/cm^3) will yield a tube weight of about 3,000,000 pounds and a wall thickness of 3.4 inches. Advanced composites in use today for pressure vessels and solid rocket motors can cut this weight and thickness by a factor of two.

Holding tank requirements were explored in an idealized parametric sense. Scavenging a substantial percentage of the gas looks feasible with some careful design work near the tube exit. Ideally, 100 percent of the working gas could be contained and reused. The holding tank parameters are not very sensitive to such design details considering the total volume of the booster tube. The tank weight is determined by length (l_t) and wall thickness (t_t) which are functions of holding pressure (P_t), booster tube final volume, booster tube pressure, tank mean radius (r_t) and tank material working stress (σ). The variation of l_t and t_t as a function of holding pressure is shown in Figure 3. As a first approximation, adiabatic flow and a perfect gas are assumed.

The weight of the tank is directly proportional to the product of its length and wall thickness. The net variation of tank weight with holding pressure is shown in Figure 4. A composite with the same strength/density ratio called out earlier for the booster tube is assumed. The effect of increased pressure is dramatic particularly up to 5000 psi. At 5000 psi the approximate weight would be 5,000,000 pounds with end caps and miscellaneous. Again, advanced composites in use today could cut that weight by half or more.

Allowing 500,000 pounds for ancillary equipment, an LPA facility should weigh between 4.5 and 8.5 million pounds. It appears that no technology barriers would preclude an even lower minimum. A detailed design effort will be required to better establish weight and performance. Use of processed in-situ material (aluminum, titanium, steel, etc.) on the Moon to build the device should also be considered. For present purposes of preliminary system studies, an Earth-weight equivalent of 5,000,000 pounds transported to the Lunar surface appears reasonable to establish the facility.

An average launch rate of three per day, 257 days per year would yield a total throughput of 1.00×10^8 pounds (45,450 metric tons) per year. Fleet size for the RRV's has not been established, but one mission every other day will only require six vehicles plus backups. Further analysis is anticipated in this area.

SCHEME FOR TRANSPORT OF LUNAR MATERIALS

Gerald W. Driggers

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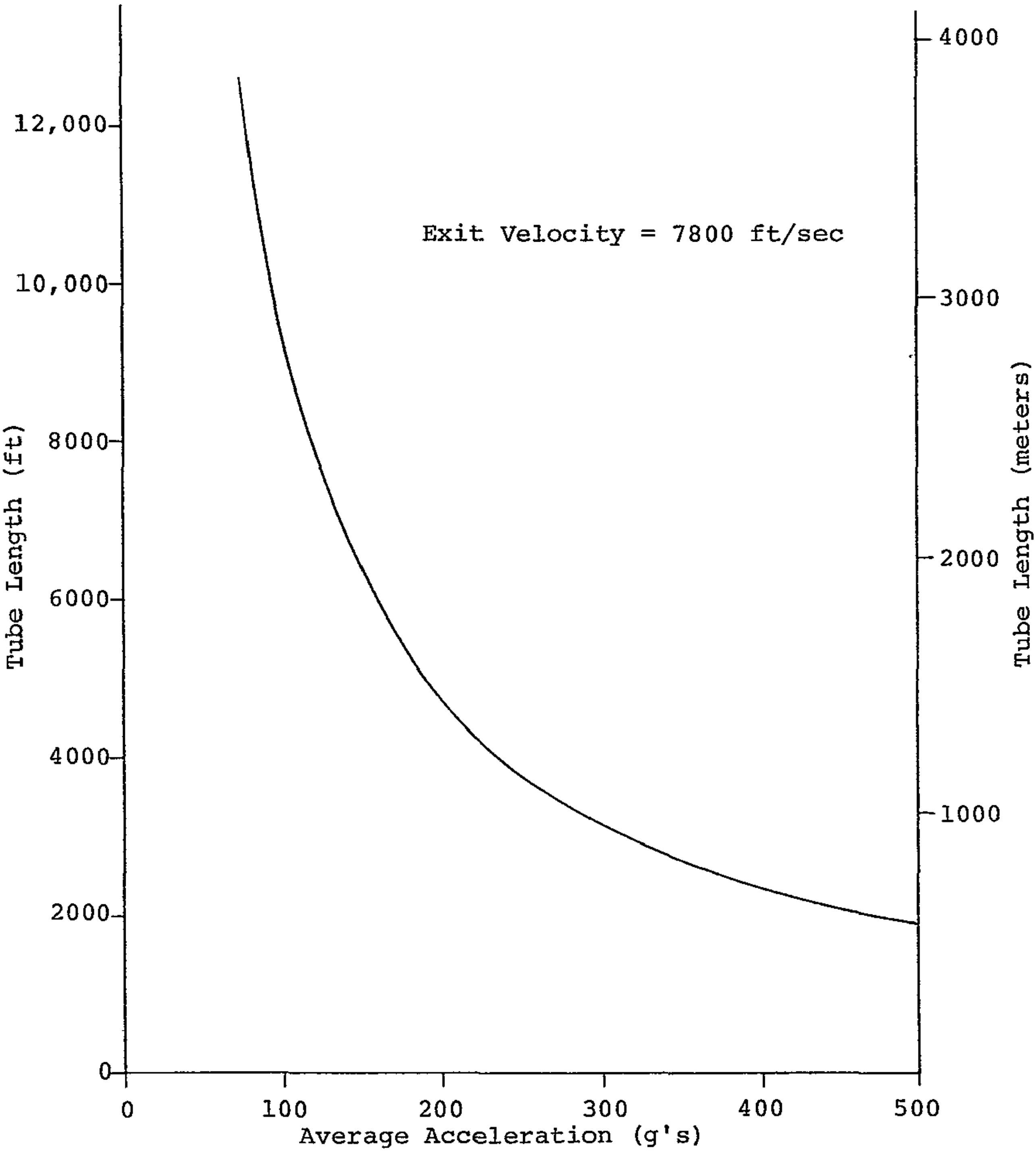

Figure 1. Required Tube Length to Allow Projectile to Reach Lunar Escape Velocity at a Specified Average Acceleration

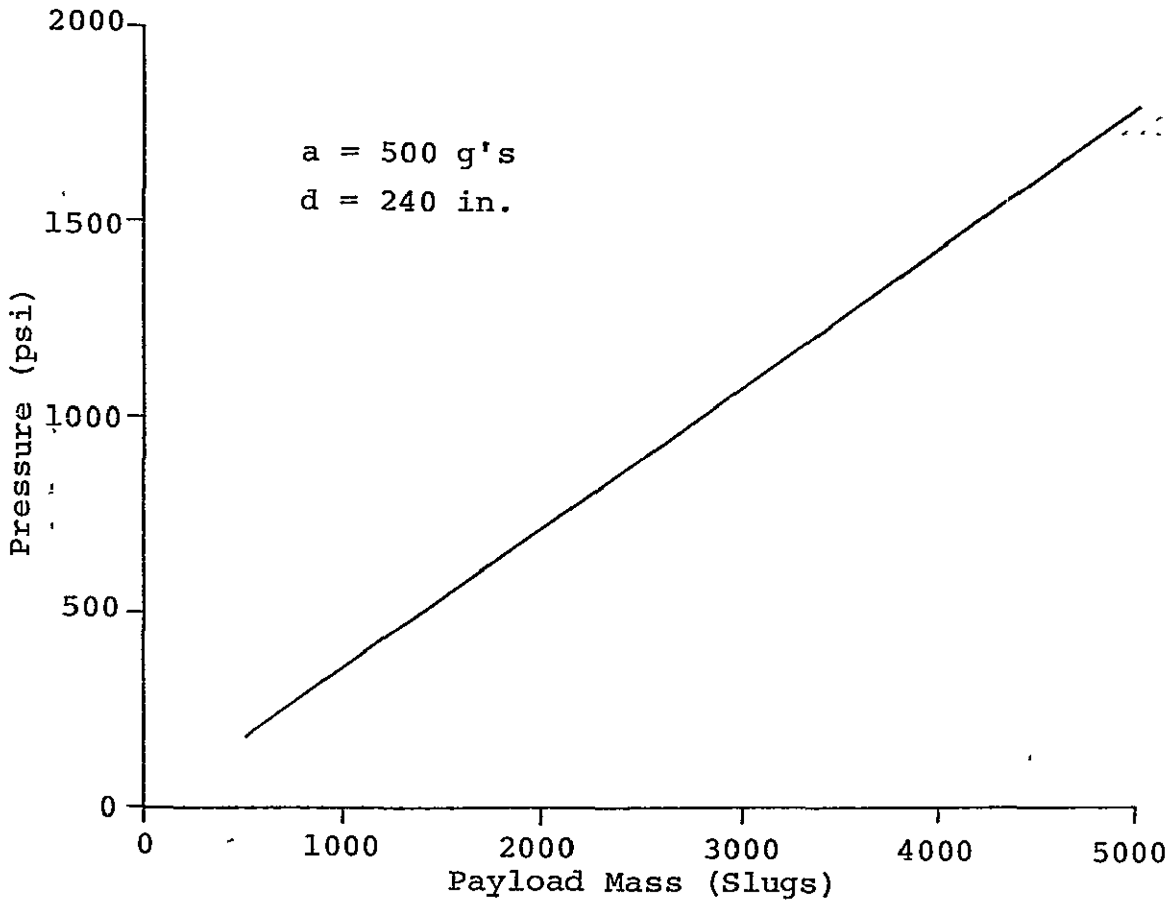

Figure 2. Booster Tube Pressure as a Function of Payload (Projectile) Mass

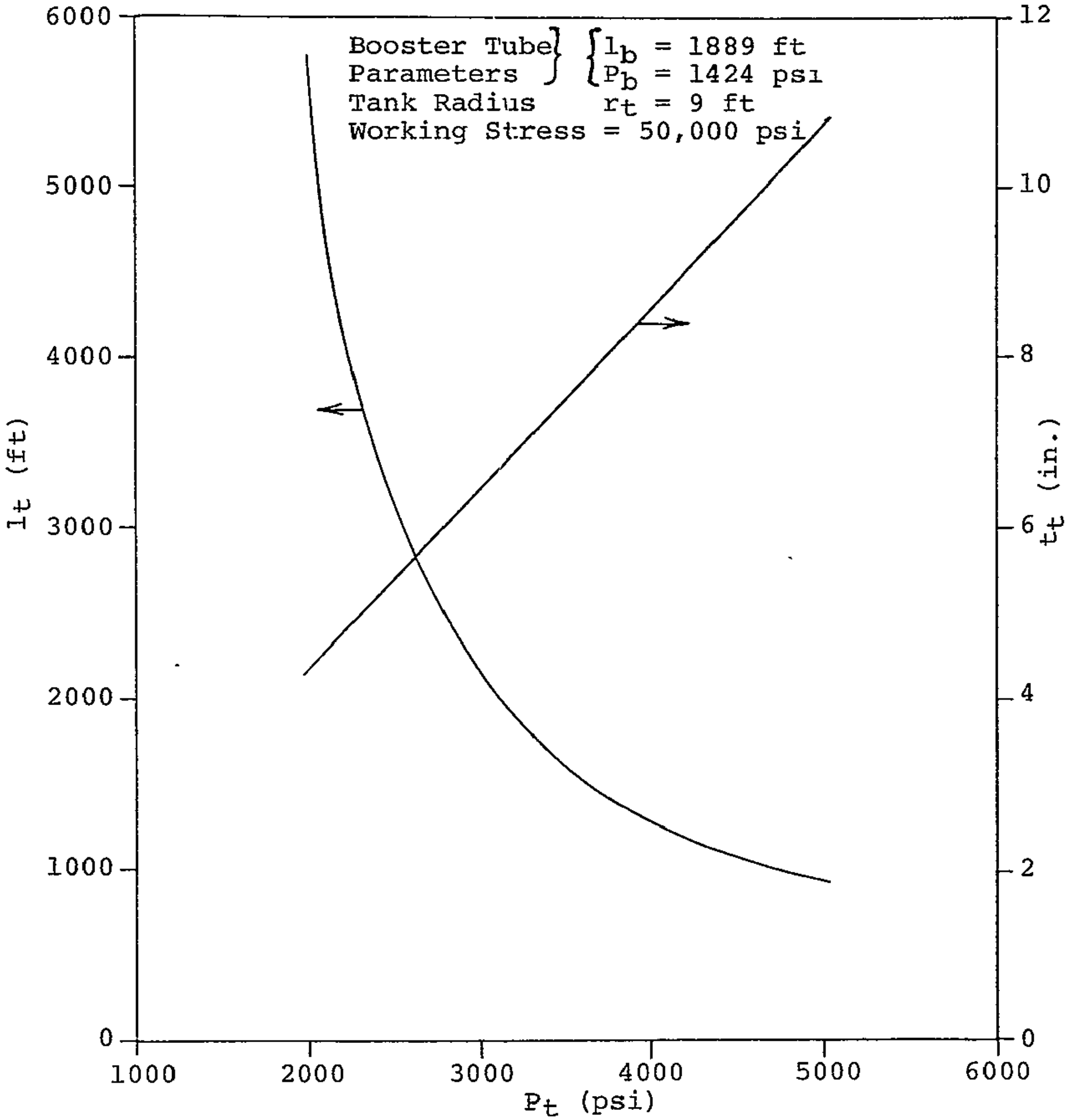

Figure 3. Length and Thickness of Blow-Down Tank as a Function of Holding Pressure

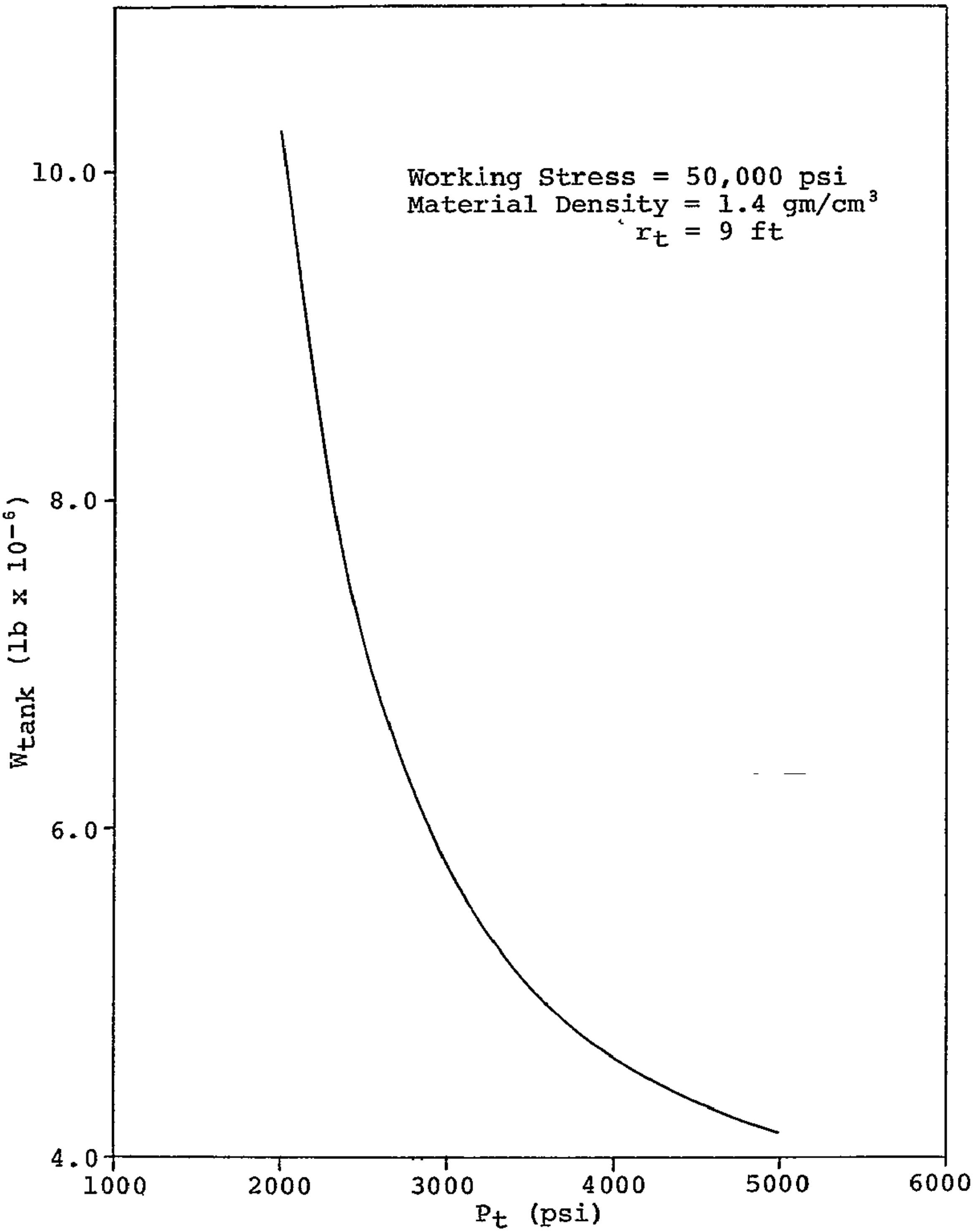

Figure 4. Weight of Blow-Down Tank as Function of Holding Pressure

A LUNAR MASS TRANSPORTATION SYSTEM; T. A. Heppenheimer, Center for Space Science, Fountain Valley, California.

In 1950, Clarke (1) suggested the use of electromagnetic accelerators in space transportation. In 1974, O'Neill (2) proposed that such accelerators be used for large-scale lunar material transport. Since then, further work has aimed at a preliminary engineering specification of such a system. The present abstract reports results which are to be published in greater detail elsewhere (3).

Requirements: The proposed approach envisions the establishment on the lunar surface of an electromagnetic accelerator or mass-driver, which operates using electricity from a nuclear or power-satellite source, thus avoiding the use of rockets. Throughput is some 10^6 tons/year. Individual packets of material are accelerated to lunar escape, 2400 m/sec, with launch accuracy of 10^{-3} m/sec or better. Payloads' flight is entirely ballistic, without midcourse guidance; they arrive at a catcher vehicle with dispersion of 100 meters or less.

Approach: The selected accelerator concept involves tracked, magnetically-levitated payload carriers ("buckets"), accelerated by linear synchronous motor. (Fig. 1). Cross-track velocity is controlled by providing an accurately aligned section of track prior to payload release, along which cross-track bucket motions damp out via a passive bucket suspension. Along-track velocity is controlled using laser doppler. Payload release occurs by withdrawal of a restraining support. The catcher is a large rotating bag of Kevlar fabric, located at the L2 libration point. When the catcher is full, onboard propulsion systems permit it to carry the payload to the delivery site. These systems involve the Rotary Pellet Launcher (RPL), also proposed by O'Neill (2): a rapidly-rotating tube, ejecting pellets of rock at high velocity.

Magnetic Levitation: The buckets are suspended by paired superconducting coils, which straddle aluminum flanges along the length of the track. The coils are of opposite polarity, so the suspension is of the "null-flux" design (4). The coils are cooled by liquid helium fed from a dewar; cold-gas boiloff is regeneratively circulated within the coils, then stored in an accumulator. Typical parameters: coil diameter, 15 cm; coil-track separation, 2 cm; current, 6200 amp-turns. For the track flanges, typical dimensions are 20 cm wide, 0.5 cm thick.

LUNAR MASS TRANSPORTATION SYSTEM

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Bucket: The bucket proper contains a main superconducting magnet (30,000 gauss), a dewar and accumulator, and payload supports. Mass, approx. 10 kg exclusive of payload and suspension coils. Payloads are 10-20 kg lumps of lightly sintered soil and rocks. Prior to launch, each bucket undergoes a servicing operation, consisting of a dewar refill, accumulator tapoff, and the placement of a payload into the support.

Tracks: The track is E-shaped in cross section, 70 x 35 cm, of aluminum, with mass 27 kg/meter (under 1000 tons for 30 km total length). The first 10 km is the main acceleration section, where the bucket is accelerated at 300 m/sec^2. The next 1 km is a fine-adjust section where accelerations of 1 m/sec^2 are applied. The next 1 km is a drift section, where the bucket decelerates at under 10^{-2} m/sec^2 due to electromagnetic drag. Release of payload occurs within the drift section. Then there is a section of 3 km in which the bucket is decelerated, again by linear synchronous motor; and finally a 15-km return section. The bucket is suspended or levitated by electromagnetic lift, once it reaches a velocity of a few tens of meters per second. Thus, for initial acceleration it must be supported by a wheeled dolly, until it gets up to flying speed.

Laser Doppler: The proposed system has (integration time) (measurement accuracy) = 10^{-6} meters. For example, integration time of 10^{-3} sec permits velocity determination to an accuracy of 10^{-3} m/sec.

Bucket Frequency Response: The supporting null-flux coils are attached to the bucket with support arms which provide a mechanical spring-dashpot coupling. Parameters of the suspension and coils are chosen to provide good frequency response so that the cross-track motions are damped within the 1 km drift section. The bucket proper has characteristic frequency approx. 10 radian/sec; the coils, 100 rad/sec. Damping is near the critical value.

Track Alignment: Required track alignment is found by Bode-plot analysis, under the condition, max. crosswise velocity at release = 10^{-3} m/sec. Then, over track lengths of 24 to 240 meters, allowable misalignment (in the fine-adjust and drift sections) is 10^{-4} meters. This may be achieved using an optical alignment system similar to that employed at Stanford Linear Accelerator Center (5). In that system, track-mounted Fresnel zone plates focus a laser beam to a point; photodetectors locate the point and scan across it. The center of the point is found automatically and reproducibly, to an accuracy of 25 microns. Hence, the displacement of a track location is found to this accuracy. The track is to be mounted upon piles driven into the regolith, spaced every 10 meters, and supported at each pile by a screw-jack mount driven by a worm-wheel actuator. (See Figure 2).

Away from these critical sections, track alignment is associated with use of standard alignment systems used in civil engineering. A misalignment of several times 10^{-3} meters is permissible. The criterion is that the ride be not too rough.

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Payload Restraint: During the initial acceleration, the payload is rigidly supported by metal plates. Upon entering the fine-adjust section, these plates are pulled away by springs, and the payload is restrained only by a mechanical "finger" which presses it down from above. The spring-actuated withdrawal of the finger constitutes the event of launch. The bucket follows the lunar surface curvature so the payload accelerates upward at one lunar g, 1.5 m/sec^2.

Other Mass-Driver Characteristics: Cycle rate is 3 to 4 launches per second. Linear synchronous motor parameters are as in (2). The track is housed within a lightweight aluminum tunnel, to aid in thermal control. Power required is some 200 megawatts, initially supplied by nuclear plant. The first solar power satellite built in space then is maneuvered to the lunar L1 libration point, 60,000 km Earthward of the lunar nearside, to provide gigawatts of power and allow a major expansion in system throughput. It is kept at L1 as a libration-point satellite (6), beaming its power to a lunar-surface rectenna.

Payload Trajectory: The payloads fly ballistically to the catcher, located at the L2 libration point, 60,000 km behind the lunar farside. There are three reasons for selecting L2: The mass-driver can be sited on the lunar nearside. Also, use of L2 allows the most liberal launch-accuracy requirements consistent with catching in deep space, away from lunar gravity. Also, the payload stream is directed away from space traffic and is not a hazard to navigation. The payloads arrive at L2 at approx. 200 m/sec. It is not possible for a payload launched from the lunar surface to arrive at L2 with near-zero velocity (7).

Catcher: A variety of active catcher concepts have been proposed, wherein incoming payloads are automatically tracked and small catching modules are opened or maneuvered to receive them. Such concepts appear open to challenge, on grounds of mechanical complexity, lack of reliability, lack of fail-safe operation, or susceptibility to damage from payloads. The preferred concept is a passive catcher, designed as a mechanical analog of the radiation black-body cavity: payloads can enter, but material once caught cannot escape.

The principal element is a bag of 10-ply Kevlar fabric. (9-ply Kevlar stops a .44 magnum bullet fired point-blank.) The bag is approx. 100 meters diam. by several hundred meters long; mass, 2 kg/m^2. The mouth of the bag is supported by a rim which mounts a grid of cables. The payloads break up on striking the grid, thus protecting the bag. The bag rotates, holding caught material by centrifugal force. The rim contains crew quarters, a nuclear power plant and its radiator, and Rotary Pellet Launcher (RPL) thrustors.

RPL: The RPL provides both stationkeeping against the payloads' momentum and propulsion to transport the filled catcher. Typical parameters: rotation rate, 2500 rpm; tube length (axis to tip), 50 ft.; material, Kevlar; thickness, 4" tube OD at tip, tapering exponentially to 40" OD at axis; mass, 38,000 lbs;

A LUNAR MASS TRANSPORTATION SYSTEM

T. A. Heppenheimer

Figure 1

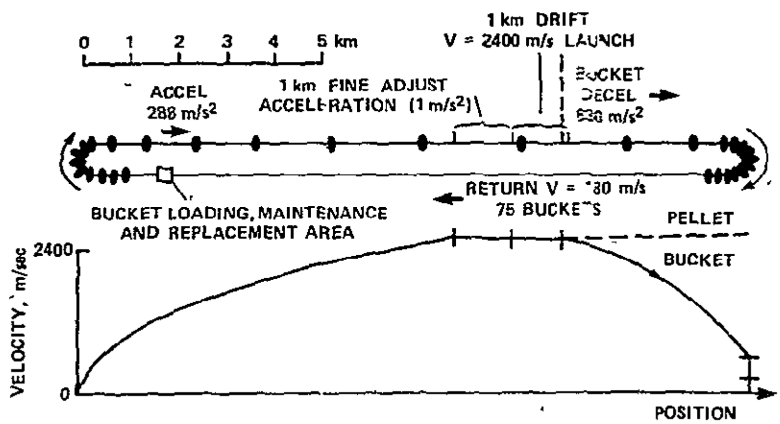
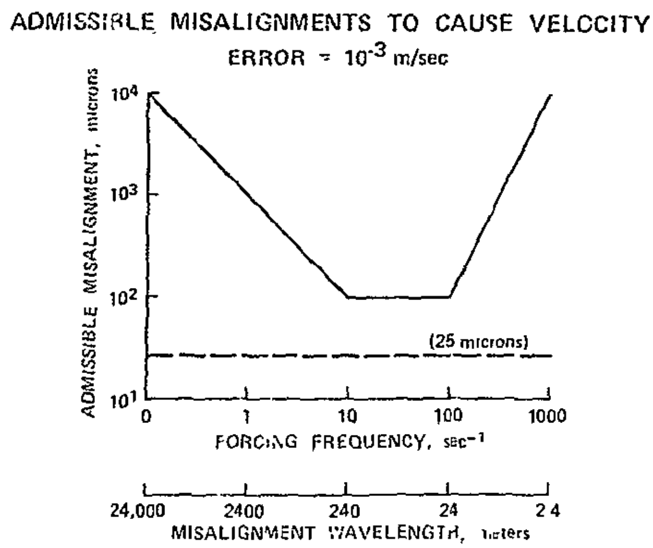


Figure 2



pellet mass, 10g; specific impulse, 405 sec.; thrust, 369 lbs.; power, 7.2 megawatts. In this design we work at 60% of the yield strength of Kevlar; max stress due to acceleration of pellet is under 7% of yield stress. Three RPL's are required per catcher.

RPL Injector: The injector admits pellets to the tube in such a manner to produce a collimated exhaust stream. Pellets are fed axially into a feed tube, which points outward and rotates with the RPL tube. A cam-driven gate ensures only one pellet is at the end of the feed tube. This pellet presses and rubs against a fixed circumferential restraint; but there is a hole in the restraint through which the pellet is admitted into the RPL tube. The restraint is concentric with the RPL rotation axis. By turning the restraint, one controls the direction of the RPL exhaust. A diagram of the injector is in reference (3).

Environmental Hazard: The RPL pellets represent artificial meteoroids. It is expected we could eject 5×10^{15} pellets (5×10^{9} tons) before the hazard from these pellets exceeds one impact per square kilometer every ten years.

General Comment: The RPL concept opens up the possibility of a solar-powered deep space transporter which uses as propellant, not hydrogen from the sea or cesium from the earth, but ordinary dust and rock from the bodies of the Solar System. The mass-driver also may have application as a reaction device. These systems may go far to overcome the limitations attendant upon any proposal to open up the Solar System using rockets.

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SUSPENSION INSTABILITIES IN AN ELECTROMAGNETICALLY LEVITATED LUNAR MASS LAUNCHER Mont Hubbard, James R. Hogan, University of California, Davis

The use of lunar derived material for the fabrication of large-scale space structures such as satellite solar power stations requires some scheme for launching the material from the surface of the moon. One such scheme [1] involves magnetically levitated vehicles (buckets) accelerated by means of a linear synchronous motor to lunar escape velocity (2400 m/sec). To allow for the use of a reasonably sized (< 100 m) passive collector, launch velocity error must be less than 10^{-3} m/sec in all three axes. These extreme accuracy requirements, a keystone of the success of such a project, may be difficult to achieve. So critical is this issue that it motivates a much closer study of the details of competing electromagnetic suspension possibilities.

The above study suggested the use of a repulsive, null-flux magnetic levitation scheme for the lunar base mass launcher [1]. Null-flux schemes are preferred over conventional normal-flux repulsive systems because they provide improved lift-to-drag ratios, greater suspension stiffness (which also increases with velocity), zero-pitch equilibrium positions and the potential for greater stability [2,3].

Unfortunately, at high speeds the electromagnetic skin depth drops below the guideway thickness effectively decoupling the induced eddy currents. As a result the null-flux system reduces to a pair of normal-flux systems opposing each other [4]. Stability analyses of normal-flux systems indicate unstable equilibrium positions of the levitation magnets for a given velocity, current and weight. The primary manifestation of this instability appears to be a runaway in velocity coupled with oscillations in height and pitch angle [5]. It is argued that the equilibrium positions are unstable with regard to small changes in coordinates and velocity as a result of the $\frac{1}{V}$ dependence of the drag force. Consequently, high spring constants alone (10^4 Nt/m, as suggested by [1]) may be insufficient to insure small velocity errors.*

A previous study of electromagnetically levitated transportation vehicles [6] determined that, even at relatively low speeds (V<200 m/sec), passive control schemes alone were not sufficient to provide the ride quality desired. In the lunar mass launcher application referred to above, with much more stringent system ride quality specifications, final trim using active control techniques will almost certainly be required. In addition, active control during the initial rough acceleration phase may be needed to overcome the instabilities inherent in the electromagnetic suspension system.

These inherent stability problems of the magnetic leviation system motivate further analysis of null-flux stability. A simplified suspension dynamics and control study including three degrees of freedom (pitch, suspension height and forward velocity) could provide valuable information. Investigation presently underway indicate that velocity independent pitch angles may be possible using certain null-flux systems.

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* Editorial Comment - "Stiffness" control alone is not adequate to provide stability in magnetic levitation systems. Considerable research indicates that active control systems are possible which can adequately stabilize magnetically levitated vehicles. References to this research are:

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