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Importance of the Use of Extraterrestrial Resources to the Economy of Space Flight Beyond Near-Earth Orbit

INTRODUCTION

During the 1961-to-1966 period, the Working Group on Extraterrestrial Resources devoted its main efforts to analyzing the economy of space flight with the use of extraterrestrial resources, and during the last 2 years the American Astronautical Society as well as the Institute of Aeronautics and Astronautics have begun to devote special sessions to problems associated with the potential use of extraterrestrial resources and/or dealing directly with the subject. In October 1968, the XIXth International Congress of Astronautics will hold special sessions in New York, N.Y., which also will deal with this timely subject.

During the XVIIIth International Congress of Astronautics, Prof. Fritz Zwicky of the California Institute of Technology presented a very impressive lecture on this subject, and, more recently, Prof. Donald Menzel, Director Emeriti of the Harvard Astronomical Observatory, called the attention of the scientific community to apparently obvious indications of water action having taken place in the remote past on several locations on the Moon. These described phenomena can be clearly seen on recent lunar orbiter pictures. In a recent private communication, Prof. Harold C. Urey of the University of California at San Diego also supports this view. These interpretations can have considerable bearing on the work done by the Working Group and could be of far-reaching influence on the future course of space flight. Those who have followed the work of this group will remember the frequently stated fact that support of extraterrestrial space flight and the logistics of manned stations on the Moon or in interstellar space will require that more than 90 percent in weight of all vital logistic supplies will consist of water or its derivations, if we plan to use oxygen and hydrogen as fuels.

Another subject recently discussed more frequently in space-flight-related meetings is the quest for utilization of the extraterrestrial environment for commercial and industrial uses in addition to research objectives. Many processes performed on Earth are subject to limitations as a consequence of our particular Earth environment. To achieve particular objectives, man has artificially changed his environment, for instance, to make these commercial objectives more efficient or more economic at a cost. However, our state of technology and the celestial body we happen to live on sometimes do not permit us to duplicate environments on Earth with great economy; we could achieve them more easily in space or on the surface of celestial bodies within reach of our Earth by space flight.

A third observation I would like to make is that space flight at the present cost level will not become attractive to many of the proposed uses, particularly those which entail commercial uses, much beyond the ones recognized as economically feasible. Substantial reduction in space flight cost would attract many new uses into the "orbit" of commercial utilization of space flight. These uses in themselves would tend to reduce space-flight cost because of the increased volume of space flight and the factors involving reaction to cost as a function of volume and time.

The following remarks will be devoted to the various possibilities and factors which could involve, or result in, increased economy of space flight and the promotion of commercial ventures making industrial or other use of extraterrestrial resources and environments. These remarks are based on my own past work, on work of members of the Working Group or of contributors to it, and on more recent independent observations and contributions, which have resulted as a consequence of our growing storehouse of knowledge of the cislunar and lunar environment.

DEFINITION OF EXTRATERRESTRIAL RESOURCES

Extraterrestrial resources can be considered resources which can maintain space flight and human life in space and on extraterrestrial bodies without Earth-derived logistics. In other words, self-contained exploration, operation, and settlements, as, for example, on the Moon, and maintenance of traffic and logistics between different extraterrestrial bodies without continuing logistics from Earth, would require extraterrestrial resources. But we can define this term even more broadly. Physical phenomena can be considered extraterrestrial resources, too, if they permit us to conduct processes or operations which would be more difficult or less economical to achieve in the natural Earth and Earth atmosphere environment, such as lowered or disappearing gravity, wide spectrum of radiation level, varying degree of vacuum, extreme temperature environment, or potential or kinetic energy levels difficult to achieve from Earth.

These resources could be:

(1) Indigenous raw materials to produce fuel and life support.

(2) Indigenous raw materials to support construction and operation on the Moon.

(3) Raw materials of value and qualities to be furnished from extraterrestrial resources to the Earth.

(4) Environmental conditions difficult to achieve on Earth as, for example, lack of gravity, different radiations or lack of radiations, and degree of achievable vacuum.

(5) Natural radiation spectra and propagation phenomena not directly available on Earth.

Of the consumables, water and oxygen require the highest support level in weight to maintain human life in extraterrestrial space. Since oxygen is the major weight component of water (approximately 87.5 percent), availability of water alone could reduce logistic requirements to support life by almost 90 percent. Oxygen and hydrogen, a highly effective fuel and oxidizer combination for chemical rocket motors, could be supplied from water and thus this logistic percentage would be increased far above the 90-percent point.

More recently, many proposals have been made to use extraterrestrial environment for manufacture of products which would be difficult to produce on Earth because of high-gravity effects, not low enough vacuum, the need to add or remove heat at high rates economically, or the need to provide conditions of peculiar radiation or absence of it. If the product is of sufficiently high value with respect to its weight or volume when the cost of transportation is included, it may pay to have it produced outside the terrestrial environment. In turn, if transportation cost to extraterrestrial space is low enough, the candidates potentially capable of taking advantage of this environment may increase to such a magnitude that use of space for commercial purposes may become increasingly attractive and eventually self-supporting. Prof. Zwicky, in his paper given during the XVIIIth International Astronautical Congress, made an eloquent case for using the Moon as a resource for fuel and life support by using minerals of expected high abundance to produce fuel and life-supporting oxygen.

THE CASE FOR THE PRESENCE OF WATER IN THE MOON AND THE INNER PLANETS

Prior to unmanned lunar landings and lunar orbital flights, the prevailing theory of the composition of the lunar crust and the lunar interior was based mainly on the assumption that the Moon, being a part of the system of the inner planets of the solar system, would have to have a distribution of elements similar to that found on Earth. If this is true, one then could expect that water, which is not now observable on the surface of the Moon, could possibly have played a role in the lunar past or could be expected to be found in the form of water of crystallization or hydration within the rocky material of the surface and interior of the Moon and even might be found in underground lunar deposits in the form of liquid water or as permafrost particularly in areas which have surface temperatures permanently below freezing level. Presence of liquid water could be particularly expected if volcanism has been active in the lunar past or is present even at this time, or if interior temperatures, due to compression and possibly radioactivity, reach levels required to start dehydration of the rock material (300° to 1400° C).

Analysis of the alpha-scattering experiment used on Surveyor V after its lunar landings, as recently reported by Dr. Newell of NASA and his team and, particularly, by Dr. Anthony Turkevich of the University of Chicago, shows preliminary results of composition of surface rocks (table 1) similar to that observed on rock samples of the Earth. This confirms the expectation of there being approximately the same relative abundance of elements as there are on Earth. This scientific achievement can be considered as one of the greatest in human history. Even if this fundamental experiment to obtain the chemical composition of the lunar surface material reflects the composition of only a very thin surface layer and does not give insight into the composition of the rocks of the crust below, in which case much of the information might be based on meteoritic dust spread over the Moon's surface, but not originally from the Moon, this achievement loses none of its significance. Another characteristic of this experiment is that it cannot disclose or detect the presence of hydrogen, which is necessary to prove presence or certainty of water within the Moon. A determination of the relative abundance of water has to be derived by indirect means of rather high uncertainty.

TABLE 1.—*Chemical Composition of the Lunar Surface at Surveyor V and VI Sites (Preliminary Results)*

Element	Atoms, percent, found by—	
	Surveyor V	Surveyor VI
Carbon	<3	<2
Oxygen	58 ±5	57 ±5
Sodium	<2	<2
Magnesium	3 ±3	3 ±3
Aluminum	6.5±2	6.5±2
Silicon	18.5±3	22 ±4
Calcium	13 ±3	6 ±2
Iron		5 ±2

Before I come to another observation, which may point to presence of water at some point of time in the history of the Moon, I would like to present two figures originally published by NASA which compare abundances of elements represented in terrestrial rocks to that obtained on the surface of the Moon as exhibited by the alpha-scattering experiment of the Surveyor V (figs. 1 and 2). Dr. Gault's interpretation, as published in the preliminary results of the Surveyor mission, postulates that the lunar-surface material as presented by the alpha-scattering experiment is best interpreted to consist of a general basaltic composition. This confirms the prediction of Dr. Jack Green, who has been a distinguished speaker to the Working Group in the past. Proof of presence of basaltic material, confirmed in parallel to the alpha-scattering experiment by a magnetic properties test and a proton-scattering test, points to the fact that, within the interior of the Moon, rock material of ultrabasic type has reached temperatures necessary to drive water of crystallization or hydration out, but in some cases or locations the temperature was not sufficient to melt the original rock material. I would not postulate at this time whether such melting took place as a result of mechanical heat generation caused by impact of large meteors (which possibly resulted in the existing maria), whether it is a direct consequence of internal heat generation (independent of heat of impact), or whether it was a consequence of the original source of the material not being of the Moon at all.

Prof. Donald Menzel, in his paper presented to the last technical conference of the AIAA at Anaheim, Calif., in October 1967, showed a number of specific surface features of the Moon, which, according to his interpretation, can only be caused by liquid erosion by water

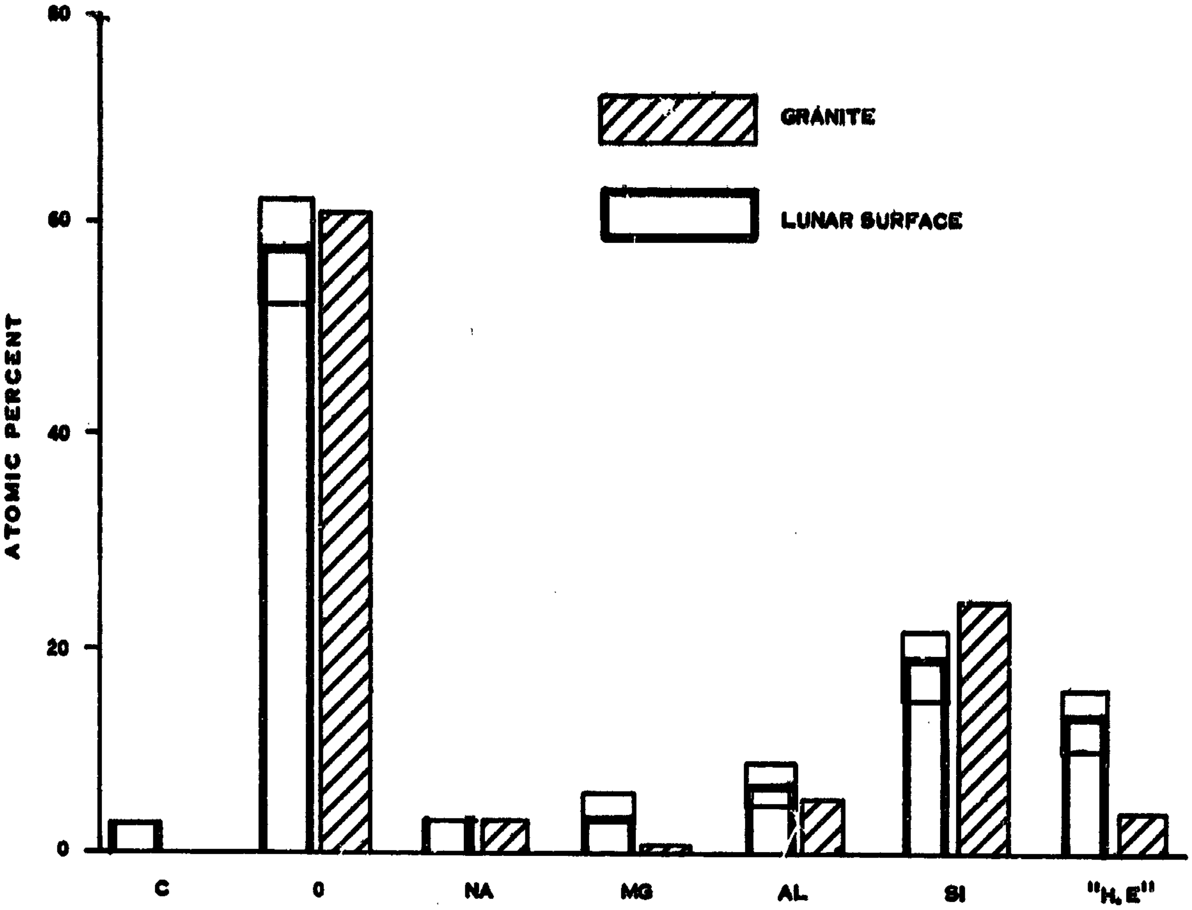

FIGURE 1.—Abundance of elements found in terrestrial granite and that of elements found on lunar surface by alpha-scattering experiment of Surveyor 5.

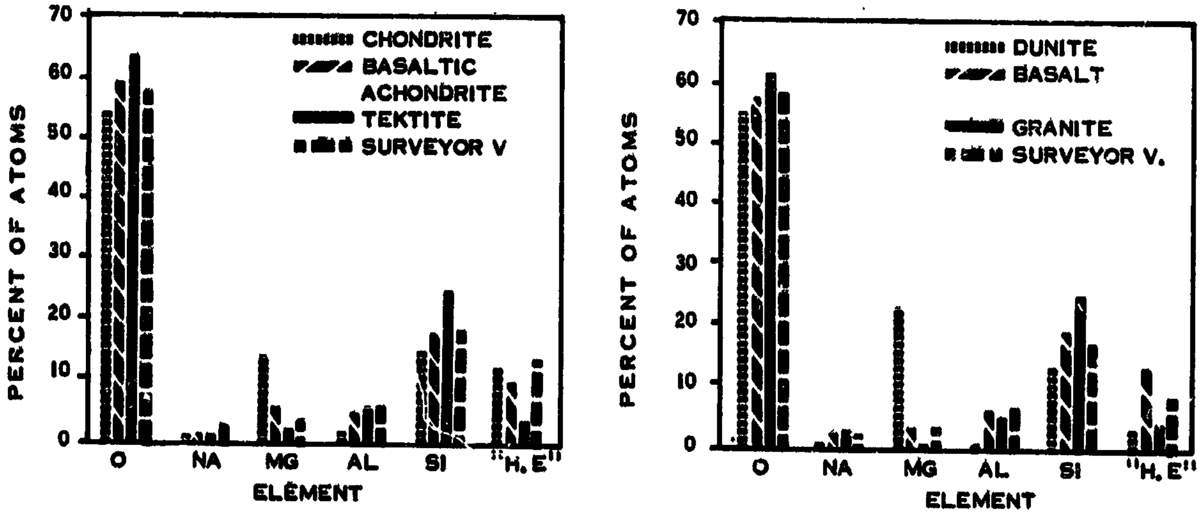

FIGURE 2.—Abundance of elements found in various terrestrial rocks and that of elements found on the lunar surface by alpha-scattering experiment of Surveyor 5.

or by a medium having similar properties. These erosion features are distinguished by their meandering tracks, which begin mostly near a crater's fractured wall and continue toward lower territory as they gradually fade out. Figure 3 is a picture of such a case taken by Lunar Orbiter V. Pictures obtained from Gemini missions show similar erosion features on the surface of the Earth caused by water erosion in desert areas (fig. 4). Both Dr. Urey and Dr. Menzel agree that these features point toward active water erosion sometime in past lunar history and to the distinct possibility that, in spite of the apparent barrenness of the surface, underground liquid water storage exists. Dr. Menzel goes even further in his conclusions and postulates that, under the assumption of relative abundances of cosmic elements on the Moon, the Moon ought to have had an atmosphere in its distant past and evidence of this should turn up in future observations on the Moon itself. These

FIGURE 3.—Lunar Orbiter V picture showing erosion on surface of the Moon.

FIGURE 4.—Gemini picture showing erosion on surface of the Earth.

thoughts and conclusions are not too much different from those presented in the past years by Dr. H. Strughold and this author.

EFFECT OF INDIGENOUS FUEL SOURCES ON SPACE TRANSPORTATION

The problem of producing fuel and oxidizer on the lunar surface or on a planetary surface from the indigenous raw materials has been studied in the past, and a number of processes have been developed or proposed as conceptional approaches, which are derivatives of industrially known processes, but take into account the particular operational and environmental peculiarities of extraterrestrial application.

Since transportation costs to a lunar or planetary location are very high as compared with the specific cost of establishment, operation, and maintenance of an industrial chemical plant and its manpower for conventional Earth use, the design has to reflect extremely low-weight construction, long life, minimum-type preventive maintenance, resistance to wear, and a very high degree of automation to save operating manpower. Installation and assembly are other areas requiring a very high degree of sophisticated engineering, so that final assembly can be accomplished at the extraterrestrial destination with a minimum of manpower and equipment. Use of construction materials with properties now on the fringes of our technology may be cheaper in total cost, including transportation, emplacement, and long-term operation, than those that current chemical-plant construction technology and practices may be able to provide; therefore, a considerable amount of advanced engineering and fabrication research will be required. Waste disposal from the manufacturing site may also cause problems which in the case of fabrication on the Earth are easily surmountable although frequently bothersome, but under extraterrestrial environment and extreme shortage of manpower may become important factors to deal with. Here, the magnitude of the problem is directly proportional to the yield of waste as compared with the useful yield and, in the case of fuel, to the inverse specific impulse produced per pound of fuel.

If pure water is the raw material, the case of no waste would be the optimum case, while for a raw material of 1 percent extractable water content, the waste would have 100 times the weight of the product and possibly between 30 and 100 times the volume of the useful yield. This ratio can become a problem as to waste disposal, difficult to handle with a minimum of physical labor, and requiring considerable analysis of engineering solutions and many other aspects, as, for example, the cost per construction man-hour or assembly man-hour involved to complete the plant to turnkey conditions. A value of $15,000 per man-hour was arrived at from studies of one such example. Depending on the details of the assembly and duration of the job, this number may fluctuate in a wide range around this value. Studies done in my office by members of my staff indicate that, given a lunar source for fuel, the amount of fuel needed to maintain a certain level of space-flight activity between Earth orbit and lunar surface, broken down into two traffic sections (Earth orbit to lunar orbit and lunar orbit to lunar surface), shows advantages for lunar-based systems (fig. 5). One can see immediately that a substantial advantage for the lunar-based system extends in the case of the round-trip-payload mode to between 1000 and 2000 nautical miles above the Earth, and in the case of the one-way-payload empty-return mode down to 300 nautical miles. In this mode, it appears that Earth-launch payload fractions never show an advantage. For example, assume that 1-million-pound vehicles are launched from the surface of the Earth and from the lunar surface. The Earth-based system will deliver approximately 3.9 percent of its launch weight as payload, or 39 000 pounds. Using the same level of technology, the lunar-based system on the other hand will deliver 6.5 percent, or 65 000 pounds, to the 300-nautical-mile Earth orbit.

While fuel per pound produced on the Moon will be more expensive than that produced on the Earth, the implication of the lunar supply permits one to break down operations into individual traffic sections and achieve an optimum traffic pattern so that the space-

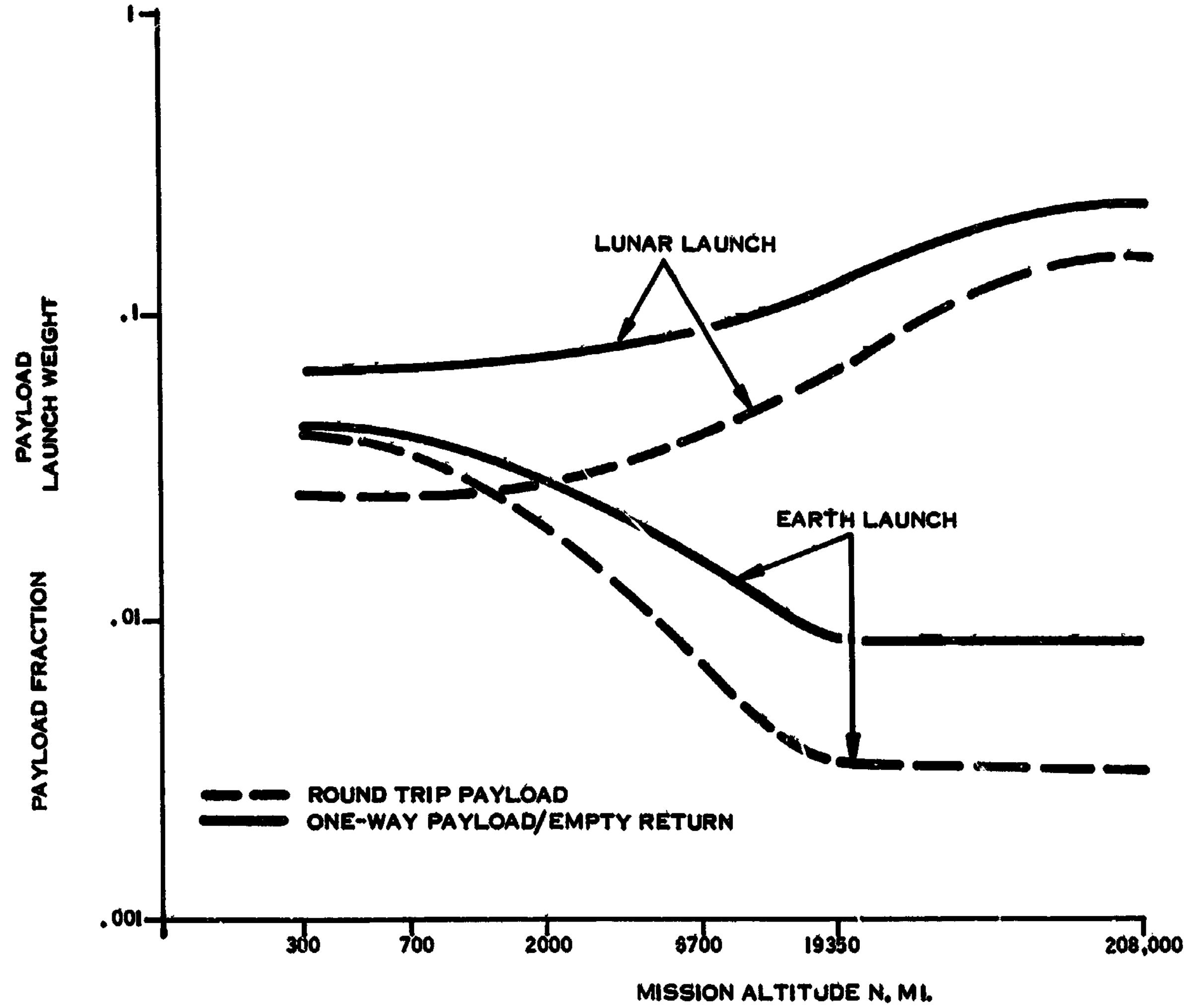

FIGURE 5.—Earth-surface and lunar-surface launch payload fractions against mission altitude.

flight system can be designed as a fully reusable system permitting hundreds or thousands of round trips with little cost of maintenance and spare parts, as soon as the used powerplants are designed for a high reuse level. In such a use pattern, currently employed stages, as, for example, the Saturn S-IVB and S-II, show spectacular payload weight fractions, even unmodified from their standard configuration. Since thrust-to-weight fractions for the Earth-orbit-to-lunar-orbit shuttle can be considerably smaller than 1 and, meantime, the failure caused by reduced power setting can already provide considerable extension of lifetime without major engine redesign, an approach to using already existing hardware, modified in orbit, may be the easiest way to convert space-flight operations using fully expendable components gradually to a pattern of increasing reuse of components.

Such a space-flight pattern, when introduced, could be supplied with fuel from lunar resources and could provide an extraterrestrial transportation system of potential economic superiority as a function of productive plant sophistication. When such a system is analyzed, the yield of the extraterrestrial raw material and plant operating cost associated with this yield become tradeoff factors. To obtain a complete Earth surface to lunar surface round-trip system, the transportation system's final link from Earth surface to Earth orbit and return to Earth surface has to be considered and its operating cost determined. If the Earth-lunar section cost level is low as compared with the per pound cost of transportation from Earth surface to Earth orbit, design and development of a reusable link between Earth surface and Earth orbit terminal system of improved economy may eventually lead to a trend of increasing space-flight economy and would eventually result in an increased use of space traffic to Earth orbit and to the Moon for research, industrial, and commercial reasons. Although achievement of space operations for commercial purposes beyond the current practical cases (Comsat, Intelsat, weather satellites, possibly navigation satellite use for commercial air and ship traffic use, conventional TV satellites, and near-future educational satellites for transcontinental TV transmission) may take decades, introduction and increased use of more economic reusable sections in our space traffic pattern may accelerate commercial uses to less than a decade if systematically made the objective of our military and civilian space plans.

If one, for instance, would salvage S–II and S–IVB stages in orbit and perform overhaul and preventive maintenance on these from an orbital space station, these stages could be refueled in Earth orbit and lunar orbit and fly back and forth between these two terminals. The lunar-orbit terminal (a second orbital space station such as these have been proposed for the Apollo Applications Program) could be established and serve as a support base for vehicles returning from the Moon. These could be parked on the lunar-orbit terminal, receive preventive maintenance, and be reused; this would obviate the need to bring in new ones from Earth for every lunar landing. In this case, only the lunar landing module would need to be brought from Earth.

With the establishment of a small fuel-generation plant, supplied with electric energy from nuclear electric plants, as, for example, SNAP–50, fuel could be produced first for the sole purpose of returning lunar excursion modules (LEM's) to lunar orbit, and obviate the need to bring new LEM's from the Earth to the Moon. Since the LEM has a greater payload capability than has the lunar return vehicle, a new capability of return payloads begins to take shape. Increasing the fuel-plant capacity further could then lead it to provide an increasing percentage of the return fuel for S–II and S–IVB stages from lunar orbit to Earth orbit. Excess fuel arriving from the Moon in Earth orbit could be stored at the Earth-orbit terminal and be used to refuel outbound trips whenever possible; the need to bring fuel to Earth orbit from the Earth itself would be further reduced and the payload capability of the Earth surface to Earth orbit transportation system would be further increased.

Before this stage of operation is achieved, there could be an interim case in which instead of fuel and oxidizer, only water would be brought from Earth to the Earth orbit terminal, and there the water would be dissociated and liquefied for use as fuel by using spent S–II stages attached to the Earth orbit terminal as fuel storage tanks. Only a minimum of conversion equipment, including a space nuclear electric plant, would be required. The lunar orbit terminal could be similarly equipped, thus the operation could first start with water brought in from Earth and later, with water extracted or mined from the Moon. The next step would be to dissociate water directly on the Moon and thereby supply the fuel for the return to orbit of LEM's and lunar return vehicles. Payload of the LEM's could be lunar water to be converted to fuel in lunar orbit. Those familiar with the components of the Apollo system will agree that such a bootstrap-type expansion of our space-flight capability would considerably widen our space-flight horizon.

Work done by and for the NASA Marshall Space Flight Center under the Mimosa Study and work done by Dr. Howard Segal deals with the use of Apollo components beyond that of the original Apollo concept and is extremely promising as to increasing economy of space flight. Some of the thinking of Dr. Segal should be reviewed here. In the lunar orbit rendezvous mode, this combination can deliver 5750 pounds of return fuel and 2410 pounds of cargo to the lunar surface from lunar orbit. If fuel were available from sources on the Moon, the 5750 pounds of fuel could be replaced by payload (total payload, 8160 pounds). One could return not only the ascent portion of the LEM to lunar orbit, but also the complete original landing vehicle, which carried the LEM; it would carry not only payload on its return flight, but also fuel for the next landing on the Moon. Dr. Segal has investigated the possibility of returning it to Earth orbit along with the command module. With these two vehicles, one could maintain two levels of shuttle operation between lunar surface and orbit. Figures 6 and 7, which describe the Segal case, show a 2- to 3-man-crew rotation case and a 5- to 6-man-crew rotation case, respectively, with the associated objectives of a return to lunar orbit or to Earth orbit.

One interim approach which could be expected to reduce Earth logistics by a factor of approximately 2.3 would be an approach which would use lunar rocks which were recently proven to exist on the Moon by Surveyor V. Dr. Rosenberg in 1964 investigated the use of silicate rocks, which are rich in oxygen (e.g., $MgSiO_3$) and which were expected to be abundant on the Moon, to provide oxygen for life support and as oxidizer for use in rocket and extraterrestrial surface vehicle propulsion. Figures 8 to 10 describe the process he used, which is within the state of the art of chemical manufacturing. In order to get the process started, an initial supply of methane is needed, which is recycled in the process. The product is water, but this water needs to be dissociated to recycle the hydrogen into the process. If methane, hydrogen, acetylene, ammonia, or other fuels could be found on the Moon and can be easily collected, dissociated to H_2, and liquefied, no further resupply from Earth would be needed.

As an insight into the yield of the process, it takes 29 pounds of lunar rock to produce 8.33 pounds of oxygen, a yield of approximately 28.8 percent. However, at the site of the first lunar base, where according to recent surface material analysis (fig. 2) rocks rich in O_2, Si_2, and Mg should be found, one cannot expect that raw materials providing the above fuels or similar fuels to go with the oxygen would also be available. A long time may pass before raw materials for these companion fuels may be

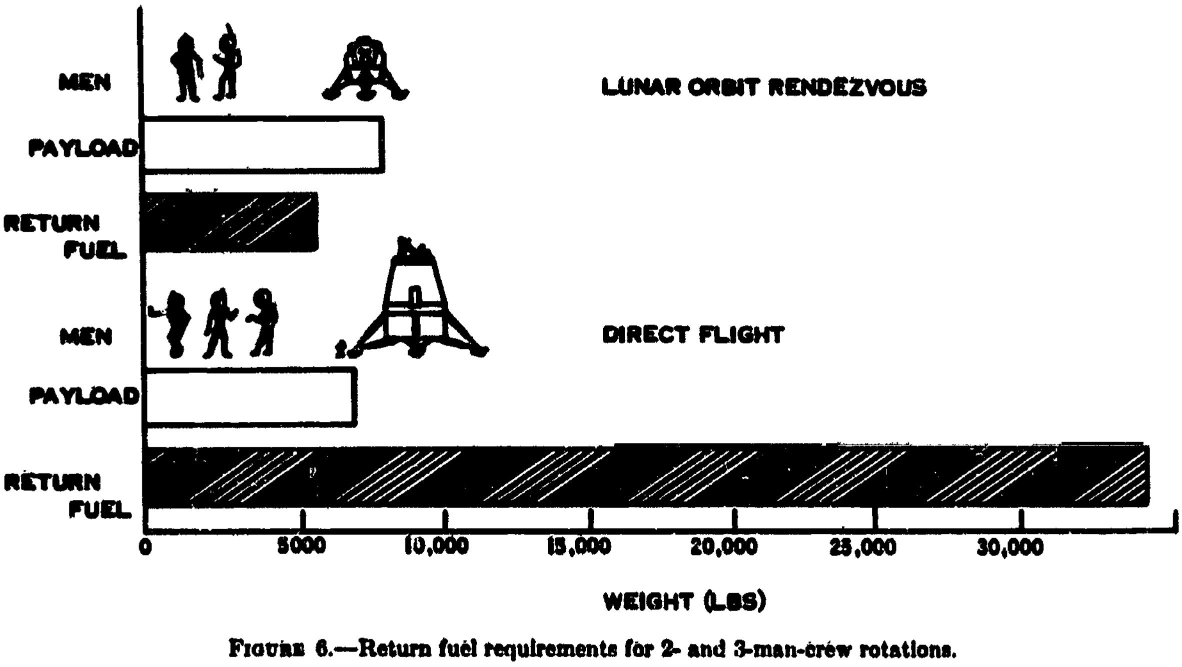

FIGURE 6.—Return fuel requirements for 2- and 3-man-crew rotations.

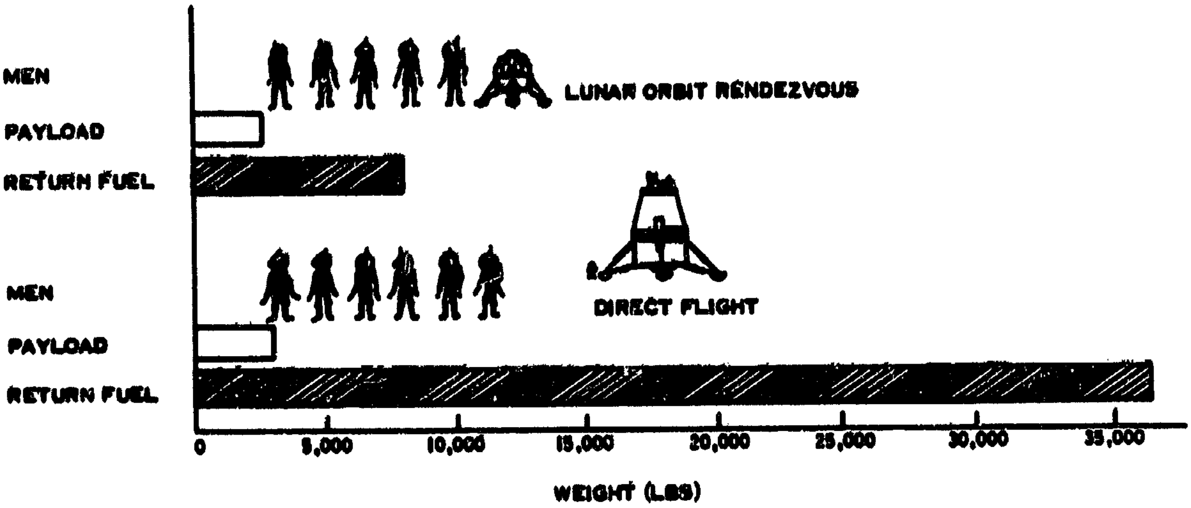

FIGURE 7.—Return fuel requirements for 5- and 6-man-crew rotations.

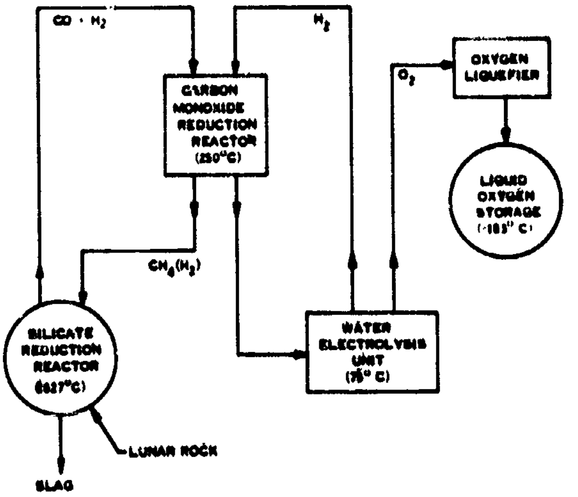

FIGURE 8.—Simplified flow sheet for Aerojet carbothermal process.

found. I think that the prospect of finding water in minable form may be better.

However, this process could be the second step in a bootstrap buildup of space-flight capabilities. The first step would not be to bring oxygen and hydrogen separately as fuels, but would be to bring water to Earth and lunar orbit and eventually to the lunar surface and to dissociate and liquefy it there. Packaged nuclear electric powerplants could be used to dissociate it and radiators could be used to reject excess heat to cosmic background in order to liquefy its components. After starting Rosenberg's process, one need bring only half the amount of weight in methane instead of water to the lunar location. Methane packs more than twice as much H_2 per pound than water does and one would dissociate hydrogen from methane instead of from water. This means that for return flights from the Moon, if there is an oxygen supply there, a weight only half that of water would have to be ferried in from Earth; and carbon gas would be left on the Moon as an extra bonus for further use as a fuel. One can see that this approach has the potential of cutting fuel logistics on the lunar base by better than half. This possibility points up the need for further analysis of other possibilities of processes and compounds which have still higher H_2 yields but have a high enough specific density to reduce the transport volume further.

While the weight factor of 1 to 9 between hydrogen and water is attractive, the low density of even liquefied hydrogen gas requires storage volumes and structural tank weight fractions which might be impractical as an avenue toward the final goal of independence from Earth logistics with current space system components used as reusable carriers. Then, if water as a compound is found in minable

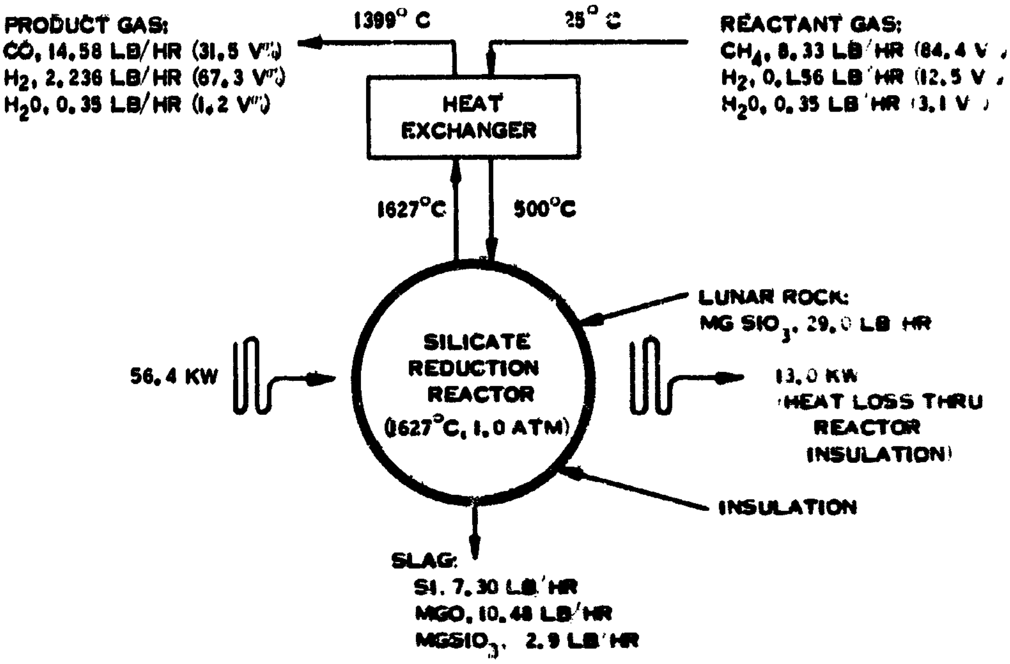

FIGURE 9.—Silicate reduction reactor section; values based on oxygen production of 6000 pounds per month.

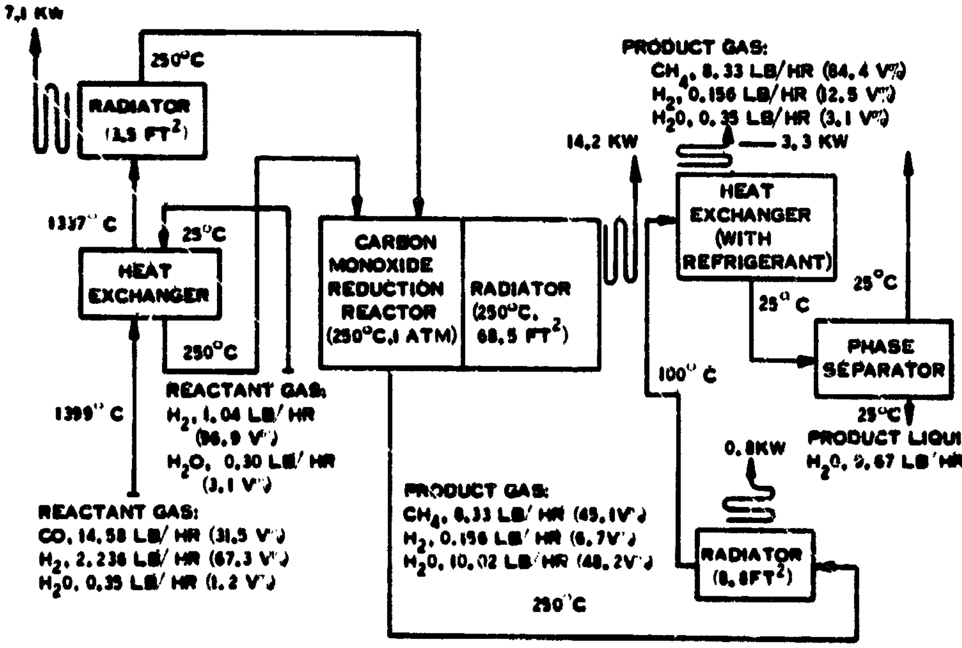

FIGURE 10.—Carbon dioxide reduction reactor section, figures based on oxygen production of 6000 pounds per month.

and processable qualities, the Rosenberg process could be replaced by more efficient processes involving extraction and dissociation to obtain LO_2 and LH_2. Every one of the described steps would reduce the logistic requirement and lead to a higher degree of economy and independence from Earth. For a while, these processes could be used parallel to each other until the less efficient one can be replaced by a proven and more efficient process.

A next step could be the establishment of a third space terminal at one of the lunar libration points which would serve as a point of departure for interplanetary missions which would be supplied with fuel first from Earth and later from the Moon.

RECOMMENDATIONS FOR AND MODEL OF A SPACE TRANSPORTATION SYSTEM

From the preceding discussion, we can conclude that a partly reusable transportation system which should include landing at and establishment of a lunar orbital terminal as well as a surface terminal can be considered well within the realm of possibilities of current technology and planned vehicles. If this proposed approach is to be used, however, it must be included in our national space plans and implemented as we go along in using the Saturn V system to expand our space capabilities. The real step forward toward a highly economic Earth-surface to Earth-orbit system would come when this part of the space transportation link would be made at least partly recoverable and would use components which are part of existing or near-future aerospace systems, as far as either components or technology of these systems are concerned. The current limited number of annual space launches of NASA and the Department of Defense does not justify the early replacement of the current nonreusable space launch systems, and a desire for their replacement would not find strong support in either camp. However, thoughts have been advanced throughout the scientific community for gradually improving subsystems which eventually would prepare the way toward more economic space flight, including at least partial reusability of space vehicles. One item that could pave the way is a fully recoverable reentry vehicle with a capability of launching and returning from orbit a large payload weight (40 000 to 60 000 pounds per flight). The other possibility would be to develop a mobile reusable space-launch platform, using horizontal takeoff and landing on existing military runways as needed. Several approaches for such a launch platform, good for the range from subsonic launch speed to hypersonic launch speed, have been advanced by the scientific community and by industry. Although one can obtain higher payloads per pound of takeoff weight by going to high separation speeds, there is much indication that degree of reusability, level of preventive maintenance, cost of initial development, test, and procurement, and the technological risks and uncertainty involved would make such an approach a long-leadtime approach and could be detrimental to the level of cost effectiveness needed to effect space-launch cost favorably even with high launch numbers. Use of the lower speed spectrum from the range of high subsonic to low supersonic transport speeds provides interesting possibilities besides furnishing a reduction in technological risk, and could turn out to be economically superior to other advanced solutions. Further scrutiny, however, may place a higher ΔV burden on the upper stage or stages or require the reentry vehicle to have a limited ΔV capability of its own. The interim stage or stages would use conventional space launch systems technology.

This approach, if jointly undertaken by DOD and NASA, could first lead to a space rescue system which would be desirable as a point of departure and as a means of rapid access to low Earth-orbit targets, independent of inclination and ephemeris, as well as to space stations. For the latter, the space rescue system could serve as a crew rotation vehicle. Since it initially uses a subsonic space-launch platform, it would not involve major advances in space technology and would require only the typical leadtime of a development within current state of the art for design and construction or modification of aircraft and rocket boosters. It, therefore, could be available within less than a decade, if such an approach would become part of a national program.

Even if the military side of our national space effort would gain only a rescue, crew rotation, and in-space maintenance capability out of this approach, since the takeoff site would be independent of the ephemeris data of the target orbit and could be land based on one of our military bases a big step forward in enhancing industrial and research utilization of space might possibly result. Increased industrial utilization of space then would tend to increase progressively the annual number of space launches, and so, in turn, make reusable space systems increasingly more attractive as compared with currently uneconomic systems.

One may witness a similar situation in early air transportation, where improvements in military aircraft spawned greater commercial use and, in turn, produced other military aircraft improvements. If this element of mutual interaction had been missing, the progress of aviation would have been less dramatic than it has been. This story may be repeated again in space flight if we as a nation look at those elements of progress which are affected by a high degree of mutual support between commercial and military use aspects.

On the basis of the preceding discussion, one could recommend that a vigorous national program be established to study the adaptability of the subsystems of all of our current space-launch and spacecraft systems from the aspect of their usefulness as reusable components of a new system. The study should include:

(1) Establishment of Earth- and lunar-orbit terminals made up mainly of spent S-IVB and S-II stages and equipped so that they can be used to house personnel, shop facilities, and fuel storage appendices.

(2) Reuse of lunar landing and rendezvous modules as reusable shuttles between lunar surface and lunar orbit.

(3) Use of S-II and S-IVB's which have been modified so that they become optimum for shuttles between Earth orbit and lunar orbit on a reusable basis.

(4) Augmentation of the current space-launch vehicles by an Earth-surface to low-Earth-orbit partially reusable system, in which the first stage would be a horizontal-takeoff, horizontal-landing aircraft of subsonic ($M \leqq 0.9$) or low-supersonic second-stage launch speed (M 2.7 to 3.0). The second stage should be a hydrogen-oxygen-fueled expendable rocket stage and should be augmented by the already proposed moderate ΔV (approximately 5.0 fps) fully recoverable upper (third) stage of a 40000- to 60000-pound payload capability. In the event a mach 2.7 to 3.0 first stage is used, it could be possible to lay out the third-stage capability so that all of the second stage reaches orbit and all expensive major components could be recovered again with the third, fully land-recoverable, stage after disassembly of the second stage at the orbital terminal. The tanks of the second stage could be salvaged for orbital fuel storage and other purposes. This possibility is based on LH_2–LO_2 as standard fuel for these missions and would be more difficult to achieve if use of LH_2–LF_2 were planned.

With liquefaction and dissociation capabilities for water, it is visualized that by equipping these terminals with nuclear electric powerplants, water rather than fuel could be brought to orbit and converted to fuel there; this would save transport volume and insulation during ascent through the dense Earth atmosphere. With this capability, return fuel should be dissociated in lunar orbit, and the lunar reusable shuttle system inaugurated to establish service between the lunar-orbit terminal and lunar surface.

The next step could be the establishment of a lunar oxygen extraction plant, as proposed by Dr. Rosenberg, which provides interim oxygen supply. If now the water is replaced by CH_4 to be brought in from Earth, the S-II and S-IVB stages could be flown back to Earth orbit using H_2 fuel derived from CH_4 and oxygen supplied from the Moon. It is quite obvious that this approach increases cargo capabilities both ways and could lead to industrial exploration and possibly exploitation of commercial uses in Earth and lunar orbits as well as on the lunar surface.

With progressing lunar-surface exploration and growth of our selenographical knowledge, sources for lunar water may now be established and the mining technology projected which will be needed to convert it from either water of hydration, permafrost, or subselenian water to liquid oxygen and hydrogen. I have presented only a gross layout of these possibilities. By a closer analysis, one will find that there exist a number of interim steps, in which newly achieved capabilities will, as they reach their eventual maturity and capacity, gradually relieve the earlier modes of operation.

Contributions of the members of the Working Group toward the approaches sketched in this treatise may go a long way toward increasing U.S. space-flight capabilities and space-flight contributions to this Nation's welfare and future stature. Some of the recent spectacular findings of U.S. lunar landers and orbiters have confirmed earlier postulations of our group and brought many of the technical thoughts advanced by its members closer to reality than the majority of the scientific community would have believed possible. The fact that the major professional societies pay increasing attention to this area by including it in their session programs testifies to the importance which our work may achieve in our Nation's space operation and exploration objectives. Timely inclusion of these presented possibilities in advanced technology plans would aid this work in remaining in the forefront of progressive space technology and provide the means to advances which would otherwise be difficult to achieve.