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USE OF EXTRATERRESTRIAL RESOURCES FOR MARS BASING

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USE OF EXTRATERRESTRIAL RESOURCES FOR MARS BASING

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The advent of manned space flights to destinations within our solar system and the possible future establishment of more or less permanent exploratory bases on the Moon and Mars will lead to complex logistics, if all supplies have to be provided from the Earth. Use of regeneration techniques to recover water and oxygen, and hydroponic gardening to grow food can reduce the logistics requirements to a small fraction of the original value and so reduce the cost of resupply. A further drastic reduction of space transportation costs can be achieved by using lunar and planetary resources for the local production of water, which together with its decomposition products represents over 90% of all the logistic needs of humans and which can also satisfy rocket propulsion needs for spacecraft if used in its dissociated state and liquefied form as LH_2 and LO_2. With refueling facilities at the remote terminals, the use of locally-produced fuels will drastically change the operating modes, resulting in a high degree of reusability of spacecraft which otherwise would have to be discarded. An "Advanced Technology Program" is evolved in broad terms outlining areas of applied research and advanced development necessary to achieve this objective. Besides water, other locally produced chemical compounds suitable as fuels for spacecraft and extraterrestrial surface and flight vehicles or as nutrients for the local production of food and for the photosynthetic regeneration of oxygen are discussed. The early prototype development of mining, processing and regeneration equipment for the above purposes is encouraged on the basis of economic pay-offs resulting from their use at extraterrestrial exploratory bases where they should also contribute enhanced flexibility and increased safety to such operations.

This paper was prepared for presentation at a Symposium on The Exploration of Mars held in Denver, Colorado, June 6-7, 1963.

INTRODUCTION

Both the United States and the Soviet Union have established as national objectives the manned exploratory landing of spacecraft on the moon. The successful accomplishment of such an objective by either one of these two nations will have as a further consequence the establishment of manned lunar exploratory bases which, in the early periods of their operation, will depend on shipments of fuel, food, equipment, and other vital items from the earth. The cost of such vital logistics has been analyzed and predicted in many studies and it has become apparent that the degree of logistics required and its cost will depend on the possibility of finding and utilizing lunar resources for water, return fuels, compounds for the replenishment and operation of life support supplies, and building materials. Previous studies have further shown that within a few years after a successful manned landing on the moon, technology will have also opened the possibility of establishing manned observational orbits around the planet Mars and the landing on Mars itself. The possibility of establishing and maintaining permanent exploratory bases on Mars will depend to even a higher degree on the use of local resources to relieve or make unnecessary logistics from the earth for return fuels, life support and food. The present study, much of which evolved during the one year's work of the "Working Group on Extraterrestrial Resources," an informal group from NASA, the Air Force, the Army Corps of Engineers, JPL, and RAND, supported by members of universities and industrial firms, deals with this possibility. The results of this work and of many other investigations show that if water can be found in the form of water of crystallization in rocks or in subsurface deposits in the form of permafrost, a very major portion of the total logistics requirements for permanent lunar and planetary bases can be supplied locally, particularly if LH_2 and LO_2 are used as the principal propellants for the return vehicles. The supporting technology to achieve this capability should be developed in parallel with the lunar transportation technology so as to make use of local resources as early as possible.

THE ROLE OF EXTRATERRESTRIAL RESOURCES IN THE ESTABLISHMENT OF LUNAR AND PLANETARY BASES

General Remarks

In RAND Publication P-2515 (Ref. 1), the author discussed the possibility of using local resources in the operation and logistics of a scientific exploration of Mars and has shown that the utilization of chemically bound water for producing return fuels, and water for food production and life support may radically reduce the logistics requirements from earth and hence the operating cost of a permanent base. The possibility of initially using one of the two natural satellites as an interim step and possibly later as a permanent refueling site for return flights and exploratory flights towards the Jovian Planets has been indicated.

H. H. Koelle in his study On the Evolution of Earth-Lunar Transportation Systems (Ref. 2) has shown that the costs of operation of earth-lunar round trips can be reduced by a factor in excess of twenty-five if lunar refueling is used, as compared to the round trip cost using the planned Apollo vehicles. By using indigenous materials for life support, base operation, further base establishment, and lunar surface transportation, the overall mission cost would be further reduced. Figure 3 of Reference 2 indicates that postulated advanced systems such as the use of nuclear propulsion from earth orbit to lunar orbit, fully recoverable systems, etc., do not appear to equal the capabilities of lunar refueling systems before 1980 and it is questionable whether these can be matched even at that period. It is further expected that the use of indigenous resources, combined with more advanced nuclear ferry systems, may reduce the cost trend further in the post-1980 era and so pave the way to intensive interplanetary exploration within the limitations of our national resources.

The Role of Extraterrestrial Production of Rocket Fuels

During the period of selection of the Apollo operating mode, various approaches involving refueling in earth orbit, in lunar orbit and on the lunar surface were studied and the presently favored operational mode of lunar orbit rendezvous was selected. It is evident that in the further evolution of lunar and planetary flights and operating modes, the use of refueling rendezvous at both ends of the transfer trips between Earth-Moon, Earth-Mars and possibly Earth-Moon-Mars, will become standard operating modes, with the latter trend more questionable however. This approach is applicable not only to the use of chemical propulsion systems but also to various types of nuclear propulsion. A trend can be foreseen, that with the development of a high payload volume, partly or fully recoverable Earth surface to orbit, and Mars surface to Mars orbit, lunar surface to lunar orbit transport vehicles and transport techniques using rendezvous techniques to deliver their cargo and fuels will come into more common use. Ferry vehicles, flying from Earth orbit to lunar orbit and from Earth orbit to planetary orbits (e.g. Earth to Mars) or to intermediate planetary orbits (e.g. Mars orbit) to final planetary orbit (e.g. Jupiter, Saturn or to orbits around one of the major satellites of these planets) will then handle the transfer orbits between the two terminal orbits. In this mode of operation, these vehicles will become reusable subject to maintenance and resupply at both terminal orbits, and will be reused many times for flights between these terminal orbits. Within these terminal orbits, rendezvous then will be made with supply vehicles, ascending from Earth or lunar surface and from the Mars surface; and manned orbital terminals will very probably be used to facilitate fuel transfer, personnel transfer and maintenance. In Mars orbit, the natural satellite Phobos could be used for such purposes. The use of the Moon as an intermediate terminal, however, results in too high a penalty on account of the magnitude of the lunar gravity. Use of a lunar orbit terminal station would be more advisable. Energy requirements for such shuttle missions are detailed in References 1 and 3. The above described shuttle-type interplanetary transportation system requires the availability of sufficient amounts of fuel at the planetary terminal stations and can be realized economically only if these fuels can be produced on the surface of the Moon, the planets and/or at the surface of the natural satellites of the planets. If one uses LH_2 and LO_2 as the basic fuel for the propulsion of space ferries, then water can be the raw material for producing these fuels, provided nuclear electric power is available at the location of the production facilities. Cargo volumes which could be brought to their destination then could be 3 to 5 times as large as they would be if refueling could be performed at only one terminal rather than at both ends of the round trip of the space ferry. Furthermore, the single-terminal refueling method would involve the discarding of intermediate stages and therefore would impair the full reusability of such ferry systems, unless nuclear and electrical propulsion systems of rather high Δv capability and very high specific impulses were used.

In the event of the use of nuclear and electrical propulsion systems, fuels other than LH_2 and LO_2 can be used with the objective of increasing storability, reducing effects of corrosion and possibly obtaining denser fuels to reduce required tank volumes and structural weight fractions. Fuels in this category are NH_3, N_2H_4, and related chemical compounds. Raw materials for these fuels may not be abundant on the Moon or on Mars but are expected to be in ample supply at the Jovian planets and possibly on some of their satellites. Little is known about techniques for mining and manufacturing these in the expected environments of the outer planets except that such efforts would have to take place in extremely hostile environments. At Jupiter it may be possible to scoop up gaseous hydrogen and helium during the closest approach of elliptical orbits on the fringes of the Jovian atmosphere, using nuclear heating of part of the atmospheric gases to provide enough propulsion to overcome the atmospheric drag and using liquefaction techniques to store the balance of the collected fuel in the liquid state. It appears that heat rejection in the presence of severe aerodynamic heating could pose sufficient problems to make such operations impractical. Here skip techniques in which collection takes place within the atmosphere and heat rejection outside of the atmosphere using the heat sink capability of frozen hydrogen for the liquefaction of gaseous hydrogen during the skip may permit this approach to fuel collection. Data on temperature, density, and composition of the Jovian atmosphere as a function of height above the surface should help to establish the feasibility or nonfeasibility of such refueling and should be obtained by unmanned probes as soon as Jovian round trips become feasible.

From the preceding it may be concluded that the full exploitation of the techniques of mining and processing of extraterrestrial resources for fuel production is an important technological task, which, if successful, will greatly reduce the cost of exploring our planetary system, regardless of whether chemical, nuclear or electric propulsion systems are planned for use during the various time periods independent of the technical superiority of the individual techniques.

The Role of Extraterrestrial Acquisition of Life Supporting Supplies

In Reference 1, the needs of human crews of spacecraft and extraterrestrial bases for life supporting supplies have been summarized. From this it appears that water can provide more than 90% of all these supplies if closed-loop systems are used and maximum use is made of regeneration of the individual life support compounds. The development of these techniques is mandatory in any event for long duration interplanetary trips such as Earth-Mars trips. The expansion of these developments to extraterrestrial base operations is but one more step and should include, as an additional extension of capabilities, the local production of food by means of hydroponic techniques as soon as water can be mined and produced, using water of crystallization, available in many rocks in varying percentages. In Table 4 of Ref. 1, it is shown that, if full life support logistics has to be supplied from Earth, 5.5 kg of supplies per man and day must be brought to the extraterrestrial base, assuming no use of regeneration techniques. This reduces to 2.28 kg per man and day, if only water is regenerated and recycled. If photosynthesis is used (e.g. with algae cultures or hydroponics) this reduces still further to .57 kg per man and day. There is a good possibility that many of the needed resupply constituents can be found on the Moon and Mars, so that the actual logistics requirement could be a small fraction of .57 kg/man-day. From these figures one can appraise the importance of the utilization of extraterrestrial resources for reducing the logistic effort to support lunar or planetary bases. It is obvious that the logistic supplies for return flights could also be produced at these bases. The savings in logistics for which the original transfer vehicles were dimensioned then could be used to make faster transfer trips between earth and Mars orbit, for example, so as to progressively shorten the waiting times during which transfer flights could not be made economically because of the excessive energy requirement to achieve the needed Δv range.

RESOURCES, EQUIPMENT AND TECHNIQUES FOR THE UTILIZATION OF EXTRATERRESTRIAL RESOURCES IN THE OPERATION OF LUNAR AND PLANETARY BASES

General

Considerable speculation has been engaged in as to the mineral resources to be expected on the Moon and whether these are similar to those found in the Earth's crust. Here the relation of the origin of the Moon and its historical evolution to what we see and observe today will have a considerable bearing on the distribution and abundance of the various expected chemical compounds and rock elements. Among others, researchers at JPL have studied the limits of possible concentrations of H, O, H_2O, of the most common metals, refractories and carbonaceous materials which could serve as raw [illegible]ials for the support of life on the Moon and to provide fuels for surf[illegible]ehicles, for shuttle flights from the lunar surface to lunar orbit and [illegible] flights from lunar to Earth orbit.

If the original materials of the Earth's crust and the lunar crust had a close chemical resemblance as to composition and frequency of distribution of the various minerals, the hard vacuum at the surface and the exposure to solar and cosmic radiation combined with the extreme temperatures (from +112°C to -153°C) may have led to a considerable degree of outgassing and mechanical as well as chemical decomposition of the various surface minerals.

With the expected increased success of future Ranger missions and more sophisticated Surveyor missions, new knowledge about the surface composition of the Moon should be obtained, permitting a better interpretation of the Moon's history and its major constituents. Tests are going on in many university and industrial laboratories to determine the behavior of common minerals of the Earth under lunar environmental conditions. These studies will obtain more definite direction with the availability of lunar surface data. Optical and spectroscopic observations from above the Earth's atmosphere will provide data of interim value prior to the availability of surface probe information. Even with the scant information on hand, analytical work can be performed to cover processing requirements within the limits of expected abundance of hydrogen, oxygen, water and metals as well as other useful materials. Processing equipment covering these postulated ranges can be designed. The power requirements for operating this equipment and ways of determining the range of operation and requirements on design of heat rejection and heat utilization equipment can then be derived.

More detailed information on lunar surface features beyond what is available today will affect designs of surface transportation modes to permit at least limited range exploration around future manned lunar bases. Availability of indigenous fuel resources then will permit the use of rocket power for transportation to more remote locations on the lunar surface by use of ballistic rocket flights using rocket power to decelerate before impact to achieve soft landings. The lunar gravity of 162 cm sec^{-2} will make this kind of operation more practical than on the Earth and can utilize the same techniques as applied by the lunar excursion vehicle of the Apollo program. Utilization of storable, non-cryogenic fuels would be preferable if raw materials for the production of these can be found and suitable processing techniques developed. Much of the development of these techniques could be done concurrently with the evolution of the Apollo System and some of the equipment could be on hand at the first manned landing on the Moon. It has been suggested that one piece of equipment to be present at the first manned landing on the Moon should be a water extraction plant with a capacity of about one gallon of water per day. It is quite obvious that such a plant might be invaluable for extending the life of expedition members in case of an unforeseen delay of the first return flight. Another worthwhile objective would be to have a small prepackaged hydroponic plant, supplying experimental data on germination and initial growth of plants under lunar gravity and illumination conditions, and incidentally regenerating O_2 from exhaled CO_2. Measurements of germination rates and growth rates would be of considerable interest and a worthwhile by-product of the first manned exploration.

Surface features, surface composition and degree of decomposition and modification of surface materials could be quite different on Mars, while conditions on Phobos could be more closely related to those on the Moon, with the exception of volcanic activity, which some authorities believe is possible on the Moon.

While the absence of an atmosphere on the Moon and the daily temperature cycle and solar radiation incidence would make underground lunar base establishment more practical, bases on Mars could be constructed on the surface and protected where necessary by light soil coverage to reduce radiation incidence to long term earth levels. The Martian atmosphere will probably permit airborne transportation means of covering the larger distances from the initial base, while surface transportation can be more closely related to Earth transportation methods based on the apparently much smoother Martian surface features. With very little or no oxygen in the Martian atmosphere, oxidizers in addition to fuel have to be carried for vehicles on Mars as well as on the Moon. Fuel cell powered power plants using LH_2 and LO_2 could store the combustion products for later regneration at the home base, while the products of other fuel combinations, not leading to liquid-combustion products, could be released after the reaction.

While the water vapor content in the Martian atmosphere, based on recent measurements with Stratoscope II from the fringes of the Earth's atmosphere, is apparently as low as 1/1000 to 4/1000 of the water vapor content in the Earth's atmosphere, there is considerable evidence that the polar caps consist of hoarfrost possibly only a few millimeters thick. The existence of even minor amounts of water on Mars encourages one to expect to find water of crystallization bearing rock formations and the possibility of volcanic action with gaseous discharges, including water and hydrocarbons in vapor form. On the Moon as well as on Mars or Phobos, electric power will be needed to separate useful chemical compounds from their original matrices; and there is a need to develop suitable techniques and equipment compatible in weight, reliability, and ease of operation with the cost of first transportation to their destination. Here a wide area of applied research and advanced technology is indicated for study to determine whether the successful use of these techniques could be achieved. The development of sealed ecological cycles to prevent losses of valuable compounds, and regeneration and recycling techniques are other important development goals.

Development of Resources

Fuels Considering the weight fraction involved in lunar and planetary mission supply operations, the production of fuels from indigenous resources is a most prominent requirement. For chemically fueled power plants, at least until 1975 or 1980, hydrogen and oxygen comprise the most desirable fuel combination for transfer flights from the lunar surface to lunar orbit and for ferry flights from lunar orbit to Earth orbit. For local flights between points on the lunar surface, fuels of lower efficiency could be used provided these were producible with less requirement on power or their raw materials were more abundant than water or H_2 and O_2.

These fuels might include hydrocarbons, nitrogen compounds, fluoride, and boron compounds, to name a few. When using reaction propulsion, the combustion products are lost and are difficult or impossible to recover; however, the use of fuel cells and turbine or combustion engine type power plants may permit the storage and regeneration of the combustion products, if energy is available for this purpose. From the preceding it is obvious that one goal of the early exploratory work should be to classify the expected mineral resources for each of the planned bases (Moon, Mars, Phobos) giving consideration to abundance, power required for extraction and the economy of the extraction process from all aspects, including weight of mining, processing and storing equipment, the degree of regenerability, and resulting requirements on heat rejection (radiator surface area). The preferred basic mining and processing methods for the Moon, Mars and Phobos may be quite different from each other. Process waste product disposal is another area meriting attention.

Development, Operation and Maintenance of Extraterrestrial Power Plants From the standpoint of weight economy, it appears that solar energy power plants, chemical reaction power plants (fuel cells and gas turbines) and nuclear electric power plants are the classes most likely to find widespread use in extraterrestrial bases for transportation and electric energy production. While many examples of such equipment are presently being designed and developed for use on space vehicles, development specifically for use and installation in extraterrestrial bases would be worthwhile. In order to achieve high reliability of this equipment in its specific operating environment and to minimize the physical labor needed for operation and maintenance, a high degree of self-contained operation and automation should be planned. Simulation facilities for reproducing realistic operational environments are mandatory for the successful development of this type of equipment prior to its placement into extraterrestrial operating conditions. Modes of emplacement and provisions for later accessibility should also be given considerable attention. Required heat rejection equipment and its emplacement, operation and maintenance should be thoroughly studied before final design selections are made.

Establishment of Closed Ecological Systems Including Food Supply and Waste Regeneration It is fortunate that there exists an approximate balance between the food intake of a man, his CO_2 exhalation, the CO_2 demand of plants, their O_2 production, and the O_2 consumption of man. This fact makes possible the design of ecological systems that could be fully autarkic or self-contained if all leakage losses could be avoided and the energy used up by the man is replaced by nuclear, chemical or solar energy. Once established such a system could run indefinitely if a complete regeneration of the entire overall cycle is achieved.

However, the achievement of such a perfect regeneration cycle is probably not practical since the equipment weight and complexity would probably exceed that necessary for a less perfect operation having a low replenishment rate.

An example of the value of regeneration may be seen in the requirement for water in hydroponic culture, assuming full leakage losses (comparable to the growth of plants under earth surface environment). In this case from 180 to 900 lb of water per lb of produced dry matter are needed to produce conventional growth of food plants producing cereals, legumes, and vegetables. The water consumption necessary for these plants could be reduced to zero after the initial supply, if all leakages could be avoided, and the moisture content of the fresh vegetables could be recovered by the loss-free regeneration of human exhalation and waste products. It can be seen further, that even partial success in the development of a moisture recovery system, for instance the reduction of evaporation losses in plant cultivation, may make possible the production of food in semiclosed cycles on certain areas of the Earth that are presently unsuited to food production because of insufficient soil moisture and limited availability of water but that have either solar or artificial energy available in sufficient amounts. Development of these techniques for extraterrestrial use may provide the technologic and economic feasibility for their use on the Earth itself when made necessary by increasing population pressures or difficult logistic conditions. (Ref. 4, Hydroponics or Soilless Culture, by H. D. Chapman, University of California Riverside, California)

In a closed ecology, after initial investment of all operating compounds, only those supplies have to be replaced that are lost by leakage in the broadest possible sense, including combustion products in closed-cycle propulsion systems. The requirement for extraterrestrial resources could be restricted to the replacement of leakage losses of the major constituents. A study of the regeneration equipment weights and energy requirements could lead to an evaluation of replenishment requirements versus equipment weight needs, and identify these compounds that could be resupplied more economically from earth at various logistics levels. One such class of compounds might be trace minerals for hydroponic cultures which are needed in concentrations of 1×10^{-6} to 1×10^{-8} of the amount of water in the nutrient solution, and regeneration of such materials may not pay off even at very large bases or long duration extraterrestrial base operations. It is important to notice that the specifications and objectives for the development of regeneration equipment for closed ecological cycles are independent of the mineral resources found at the extraterrestrial base environment, since the amounts needed for replenishment could be supplied also from the Earth if the leakage is small. Conversely the degree of system leakage can become higher the more plentiful the required minerals and the easier their mining and processing. Many of the factors involved in mining and processing, as e.g., energy requirements, can be predetermined from laboratory projects and theoretical studies on Earth even before detailed information is available on the surface components near the extraterrestrial base site. Many technical developments can be made with only a few actual environmental details.

Development of Mining and Processing Technology While many details of the most probable environmental conditions have been deduced from observations, our data on the actual surface composition of the Moon, Mars and Phobos are much more questionable. The variety of processing requirements for minerals, of which only a few elements are certain to exist in sufficiently abundant quantities within surface or near surface layers, makes it more difficult to forecast the details of mining and extraction processes and the resultant power and energy rejection requirements than is the case with the development of closed-cycle environmental systems. In the case of the Moon it will be from two to three years and after the completion of a number of successful unmanned lunar probes before a higher degree of certainty of knowledge in this field can be achieved. However, some degree of process development can go forward during the interim. Studies by R. C. Speed (Ref. 5) and his colleagues at JPL and other centers will be quite helpful in determining the operating ranges within which propsective mining and processing equipment will have to operate on the Moon. The primary goals of such studies should be the establishment of the most promising sources of water because, with the low replenishment requirements of highly closed ecological systems, water as a raw material for return fuels is the single most important compound needed to be found and processed. Each ore processing sequence is basically a process of extraction and enrichment to obtain the more or less pure product at the end. One could start by planning the development of the equipment backwards from that required to achieve the pure state towards the degree of lesser concentration and purity until one ends up with the range of the more or less promising raw materials. Looking at it this way one finds that there is a similarity in the objectives of ore processing and processes in closed cycle technology.

ENERGY SUPPLY AND EQUIPMENT TO PRODUCE ENERGY FOR EXTRATERRESTRIAL BASE OPERATIONS

The principal sources of heat and electrical energy are solar radiation, chemical and electrochemical reactions including combustion, and nuclear reactions. For small amounts of energy but long duration operation, solar energy receivers are practical sources. For short duration and relatively high outputs, chemical and electrochemical reactions are practical since little weight penalty may be involved. For high energy level, long duration operation, nuclear and nuclear-electric energy sources will require the least effort for maintenance and fuel replenishment. With high energy demands for the extraction and processing of fuels, particularly from crystalline water-bearing raw materials, nuclear and nuclear-electric sources are the most practical approach, since the kwh/lb ratio (weight effectiveness) rates highest among the various power generators. To replenish these generators, only fuel elements have to be resupplied, while the other major components could be designed to serve reliably during long-duration operation.

In order to maintain flexibility of operation, easy maintainability and reliability of supply, multiple units should be provided, as e.g. 4 to 5 of the SNAP—50 type, so as to include the requirements of waste product regeneration, and utilization and processing of extraterrestrial resources for the production of fuel and water. This equipment should be designed specifically for unattended operation, automatically controlled and suitable for stationary installation, and ready to be plugged in after completion of its emplacement and installation. Emplacement should require a minimum of auxiliary equipment and manpower.

Fuel cells appear to be desirable for standby purposes, vehicle propulsion and cases where regeneration of the propellants is practical.

Solar power should be used for situations in which small equipment has to be operated during daylight cycles and is left unattended for long times. Except for fuel cells and hydrogen-oxygen turbines, chemical reactors should be used for energy generation only in those cases in which the reactants are in plentiful supply and can be mined and processed easily. However, it is doubtful that one could forecast or predict such a possibility at this time without the availability of more complete details as to the surface and near surface composition of the Moon and the planets in question.

BASE MODULES AND HOUSING

Much has been written about concepts for the establishment of extraterrestrial camps to house manned exploration teams. Since the environments of the Moon and planets are extremely hostile compared to any terrestrial environment, great care should be taken in the design of housing and laboratory base units to make each unit easy to install and connect with other units of the base complex. Outside use of physical labor should be minimized wherever possible and a shirtsleeve environment created indoors, whenever safety considerations permit. Since oxygen will be a major constituent of the internal atmosphere, inflammability and combustibility of any pieces of equipment and base material should be rigorously avoided. Prefabrication of modules should be used to a maximum degree and automatic operation emphasized. Leakage losses should be held to a minimum by design and use of efficient air locks that are evacuated before the outer lock is opened. Each unit should have a high degree of self-containment in the event of equipment failure in individual units and should have safety equipment to prevent danger or death to expedition members in case of such failures. All such equipment can be designed, tested and operationally debugged before ever being used under extraterrestrial operating conditions. All modules should be units of such a size that a complete workable unit can be supplied by a single logistics flight so that the loss of one flight does not leave part of a base installation without some vital parts or components, making this base unit useless. Telemetering equipment for communicating with the Earth could be a valuable adjunct to other equipment for reporting operational details and malfunctions. Base modules and supplies should be landed first whenever possible and their condition checked out remotely before men are landed at such bases. Automatic emplacement and radiation shielding should be provided before men use these units to reduce the danger of radiation exposure.

Module sizes and material strengths should be chosen so that units are self-supporting under shielding material load if they are not pressurized, with the exception of inflatable maintenance hangar modules which will possibly be needed to maintain and service mobile equipment and launch or shuttle vehicles. Nonreturnable supply canisters should be designed whenever possible for use as auxiliary base modules including use as containers for the storage of cryogenic fuels. In the planning of fuel storage facilities, fuels and oxidizer storage tanks should be widely separated to prevent accidental explosions and loss of more than one storage unit. (Ref. 6, "Extraterrestrial Housing and Facilities," by George W. S. Johnson, Lt. Colonel, USAF, member and subgroup chairman on Housing and Facilities of the Working Group on Extraterrestrial Resources.)

Emplacing shielding materials should require the simplest technological means and involve a minimum of manual labor. Equipment and shelters for temporary occupancy should be the same equipment as for permanent base installation, with more of the same units for the latter case. Each unit should contain sufficient emergency supplies to permit the crews to survive in case of emergency until other nearby crew units can come to their assistance. Supplies should be stocked such that the crew can survive the failure of at least two supply vehicles to arrive on planned schedules, their launch facilities turn-around time on Earth included. The advisability of using an orbiting base station auxiliary to the surface base should be studied. Such an orbiting base could serve as a communications link to Earth at times when the main base is on the planetary surface away from the Earth. This same orbiting base could serve as the arrival and refueling terminal for ferries arriving from Earth orbit or shuttles arriving from the lunar or Martian surface. The use of Phobos as an intermediate base for Mars should be studied.

ADVANCED TECHNOLOGY OBJECTIVES

General

Two major advanced technology objectives should be pursued to achieve major relief from logistics support of lunar and planetary exploratory bases. The first of these is the achievement of a high degree of regenerability of all human waste products and the provision of a self-contained food supply system using photosynthetic regeneration of CO_2 with minimum leakage losses. The second is the achievement of highly automated operation by the local production of the chemical compounds needed for life support systems and fuel for locomotion including shuttle and ferry flights between base locations and orbiting terminals, and Earth terminals and extraterrestrial orbiting terminals.

While the products of the second objective also can be supplied from Earth, life cannot be supported unless the proper range of environmental conditions is maintained at all times. The amount of logistics needed from Earth depends upon the degree of regenerability of the human waste products and on the rate of leakage in the life support system. For instance, one less advanced and leaking system, initially supporting only a few crew members, could support more crew members as progress is made in the prevention of losses.

One can therefore visualize that the degree of self-containment of such an extraterrestrial base can be increased in a modular fashion whereby additional modules are added as these become available and so increasingly replace logistics from Earth by an increased degree of local regeneration. One can start out from that end of the environmental control plant that controls the actual physical environment of the crew and by gradually adding additional regeneration modules to it stepwise reduce logistics from Earth by local regeneration of more and more of the chemical constituents of the human waste products. Without regeneration, the major life support supplies in descending order are: (Ref. 1)

Water	3.122	kg per man day
Oxygen	0.909	kg per man day
Food	0.568	kg per man day (containing all major and minor nutrient and trace minerals required)

Nitrogen in the breathing air is not listed here since it is not consumed in the sense that oxygen is, but needs to be replenished as small fractions of it are lost continually by leakage.

From the above numbers one can conclude that by reclaiming water one can cut the life support supply requirement to 32 per cent of the supply required in the case of no regeneration effort. If oxygen is additionally regenerated by chemical means, e.g. with the Sabatier process (Ref. 1), only the amount of oxygen required to balance leakage and part of the hydrogen for the reaction have to be supplied from external sources. In this event, less than 20 per cent of the original amount must be supplied, the major item of which is food. From the same reference we find that water regeneration becomes competitive with direct supplies within 7 days of operation, and with inclusion of O_2 regeneration within 39 days. Be replacing chemical O_2 regeneration with photosynthetic regeneration, using algae cultures or hydroponics in closed cycle operation, one can reduce the supply requirement further to below 10 per cent of the original amount.

None of these steps required the use of any extraterrestrial resources and are based on initial supply as well as re-supplies from Earth for the replenishment of leakage losses. The degree of logistic support is actually inversely proportional to the degree of sophistication of the regeneration system, which will become increasingly complex with further decrease below 10 per cent of the original supply volume without any regeneration. Electricity and heat are sources for the energy needed in these processes.

With the reduction of the life support supply volume, the cargos to extraterrestrial bases will mainly consist of fuel for extraterrestrial surface transportation vehicles and fuel for the return of spacecraft to Earth orbit or Earth.

Existence of water in a form that can be mined at the destination base can further reduce the logistics without requiring extreme measures to reduce leakage losses and can supply the raw material for fuels if H_2 and O_2 are used as the propellant components of surface vehicle as well as spacecraft fuel. Increases in equipment weight as a result of increased regeneration equipment sophistication are then replaced by transfer of mining, processing and power generating equipment to the extraterrestrial base, allowing local replenishment of the major leakage losses, and at the same time leading to the capability of local fuel production.

While the initial step to regeneration of waste products leads to a general reduction of the logistics level to support an extraterrestrial base, it does not generally affect the entire mode of operation. The achievement of mining and processing capabilities, however, resulting in availability of water, O_2, N_2, and possibly K, P and other compounds or elements at the extraterrestrial base will have a profound influence on the economy as well as the preferred modes of lunar and planetary base operations. With the availability of local fuels at an extraterrestrial base, staging as a means of increasing performance, frequently associated with the abandonment of parts of the spacecraft to reduce its mass ratio, could be replaced by refueling operations at the orbital terminals at both ends of a journey and at the lunar and planetary surface itself.

Vehicles, which without refueling at their destinations are expendable and which would carry a still smaller return stage or would require for their return to the original departure terminal (e.g. Earth orbit) the assistance of special expendable refueling tankers, will become truly reusable vehicles, able to carry the same amount of cargo in either direction. The economic significance of this possibility is indicated in Ref. 2, Fig. 3, and points toward an earlier availability and possibly lower operating costs than using nuclear return spacecraft.

By-products of such an achievement would be the increased survivability of extraterrestrial bases in case of temporary logistics failure and the associated decline in cargo requirements which could be used to increase the mass ratio of the individual spacecraft with the aim of decreasing transit times to destinations and to reduce the waiting times during which the Δv requirement for transfers to destination orbits would be prohibitive for non-refueling type operations. Both factors increase the safety and flexibility of space research.

From the conclusions of the preceding paragraphs we can derive objectives for advanced technology work aimed at proving feasibility and achieving the capability of designing, manufacturing, testing, and operating equipment for the following purposes:

a. Long term, frequently unattended life support and food production facilities for extraterrestrial bases.
b. Mining, processing and storing of products of local mineral resources with the objectives of obtaining:
    1. water
    2. oxygen, hydrogen, and nitrogen in liquid and/or gaseous form
    3. N, K, P etc. for life support supply replenishment and fertilizer

Other objectives are:

c. To redesign and modify spacecraft operating methods to make maximum use of extraterrestrial fuel supplies and refueling techniques.
d. To study feasibility, desirability, and design requirements on orbiting spacecraft terminals which permit in-orbit refueling of ferry vehicles (transfer vehicles from Earth orbits to extraterrestrial orbits and vice versa) and use of special supply and shuttle vehicles to supply and refuel orbiting spacecraft terminals from the lunar or planetary surface.

Objectives for Life Support Equipment for Extraterrestrial Bases

To study the range of environmental conditions at the destination planet and their effects on life support equipment of a modular type, which a) recovers all waste water and restores this to a condition permitting use by humans, b) recovers O_2 from CO_2 at a minimum loss during the regeneration process commensurate with the equipment weight involved, c) keeps losses by leakage at a minimum again judged against weight penalty involved, d) is modular, has subsystem redundancy, is sufficiently automated to permit unattended operation over reasonably long periods and is subject to scheduled preventive maintenance and can operate either from a SNAP-type electric power supply or from hydrogen-oxygen turbines or fuel-cells, with storage facilities for the combustion products of the two latter types, e) has a mean time to failure of more than 10,000 hours, subsystems redundancy considered but no maintenance performed. Spare part and component levels should be such that 15 months' uninterrupted operation is possible, scheduled maintenance included. The equipment should be tested and operated under as close a simulation of the extraterrestrial environment as possible and tests completed two years prior to actual use on an extraterrestrial base to permit sufficient training of operation and maintenance personnel prior to field use.

The equipment should be designed such that the modular incorporation of more advanced equipment and companion equipment of the local food production type and food waste regeneration type could be performed at a later date and at the final destination without prior matching of equipment on earth (interface problems).

Food Production

The techniques of local food production based on the use of hydroponics in a closed cycle system and under either lunar or Martian environmental conditions should be studied, their feasibility analyzed and equipment designed, developed and tested, including the use of modular redundancy and scheduled maintenance techniques compatible with the equipment under waste regeneration. Optimization between "leakage losses", weight, complexity of design and operation, making extensive use of automation in all parts and functions of the equipment that would otherwise necessitate a high degree of operator specialization.

The objectives should include:

a) Determination of a combination of 6 - 12 plants, which together provide all the vegetable nutrients for continued maintenance of human life under normal and extreme working conditions together with a reasonable variety in the composition of meals. The determination should include the minimum amounts of animal proteins required and a trade-off between terrestrial logistics, extraterrestrial production of animal protein and weight, and increase of complexity in operation equipment and facilities involved. The determination of the above 6 - 12 plants should be also made from aspects of efficiency of hydroponic production, e.g. yield per ft^2, water used per lb dry matter.

b) Determination of trade-offs in regeneration technology of the various nutrients (major, minor and trace) from human and vegetable wastes and the associated equipment weights versus local production or supply from Earth indicating the time span in which local production or local (extraterrestrial) regeneration becomes competitive.

c) Determination of trade-offs between ratio of nutrient solution required (lbs), net weight of plants during growth, equipment weight and volume required and power requirements.

d) Determination of requirements for extra illumination to produce food at all seasons.

e) Development of food handling and food preservation techniques under extraterrestrial environments including closed system environment, and extra equipment required to do the job.

f) Determination of training requirements for operators of hydroponic facilities, nutrient solution restoration and maintenance tasks including components and subsystems exchange and repair. Determination of duration of necessary training until proficiency is achieved.

Equipment Testing

All the above tasks can be performed and tested under simulated environment on earth, except the radiation and reduced gravity environments, since all equipment will be used in a closed cycle environment. Use of terrestrial materials is satisfactory, since all initial supplies are brought in from earth. Maximum consideration should be given to use of spent modules of the spacecraft system which served as terminal transportation means to the base. In other words, spacecraft design and extraterrestrial support system design should use maximum mutual feed-back to achieve equipment compatibility. The later transition to use of extraterrestrial resources should be studied and necessary provisions to accomplish this should be made.

Objectives for the Use of Extraterrestrial Resources on Moon and Mars

Development of Background Information One of the major objectives of unmanned lunar and Mars probes should be to obtain information that discloses surface and near subsurface composition and identification of minerals important for the extraction of H_2O, O_2, N_2, and possibly K, P, S, etc. From second generation probes, soft landed mass-spectrograms should be obtained from a range of depths below the surface, sufficient to disclose changes of material composition as a function of depth, solar and cosmic radiation incidence, residual radioactivity, outgassing, and such other effects as can be reasonably expected in the particular environment. From Mars probes, additional data on atmospheric composition and temperature as a function of altitude, and incident radiation information should be obtained. Models of possible surface composition and texture conditions should be postulated and improved as additional data from observations are obtained.

The presently proposed techniques for water extraction, oxygen reduction from local ores, etc., should be reviewed from the aspects of power and heat consumption and suitability for use in closed extraterrestrial environments; they should be optimized for weight as a function of productivity and richness or concentration of the raw material and complexity of processes and equipment; and they should be selected so as to require a minimum of physical labor by base personnel outside the enclosed environment. It should be mentioned that extraordinary efforts in materials technology should be made to achieve lightweight, long unmaintained life and high efficiency of equipment. The problem of waste disposal should be studied.

Development of Water Processing Facilities To Produce LH_2 and LO_2 Since LH_2 and LO_2 as fuels can be brought more economically to a planetary destination in the form of raw water (saving volume and insulation), the first capability needed is to decompose water electrically into H_2 and O_2. The next step needed is to liquefy both for storage as fuel. The following objectives are proposed:

1. Design of an electric dissociation plant for water, producing 2 lb of H_2 per hour, with minimum weight of equipment commensurate with safety of operation, ease of handling, and maintainability suitable for extraterrestrial operation.

2. Design of a liquefaction plant for O_2 and H_2, having a capability adapted to production level under 1. and designed for the same environmental and operational considerations, again with weight an important design parameter. Include storage facility planning for 450 days of production.

3. Plan use of one unit of the nearest SNAP unit capable of doing the job of dissociation and liquefaction, including sizing of heat rejection equipment needed in a particular environment (lunar or Martian).

4. Test equipment under simulated environment for 450 days, to be completed 2 years prior to actual extraterrestrial use and subsequently used to train operating personnel in all operational and maintenance tasks. Tests should include demonstration of adequacy of heat rejection equipment, emplacement of equipment, and module assembly under closely simulated base conditions.

Development of Mining and Processing Technology Whether the end product is water, O_2, K, P or their chemical compounds, raw materials have to be found, brought to the processing plant, processed, the end product stored, and the waste products removed. If the desired element or its compound is found in local minerals, its concentration has to be determined, the mode of mining decided upon, the proper equipment for conveyance to the processing site selected, and the type of processing equipment chosen that works most efficiently with the concentration on hand. With little information to go on, one has to study the possible approaches to be taken based on the range of concentrations expected to be encountered, and then analyses must be carried out to determine practical design ranges of suitable equipment. Energy requirements for processing, and fuel requirements for moving raw materials from the mining site to the processing site and waste products from there to the waste disposal site, have to be determined. From this analysis one will find as trade-offs concentrations of each chemical compound as a function of equipment weight needed and power requirements for processing, at which one would break even, whether bringing the compound from Earth or producing it locally. The concentration level at which this occurs would vary from Moon to Mars or Phobos and so would affect the design of the equipment for each case. Assuming that no better raw materials than anticipated average concentration would be found, one would consider in the preliminary design of such equipment the range between break even concentration and average concentration. The design layout should be modular again so as to accommodate concentration variations encountered by choice of the number of modules used in parallel to cover the expected concentration range. Here the aspects of equipment redundancy to reduce mean time to failure of the overall plant become important, and also the effects of losing a cargo load from Earth must be considered. Much preliminary work can be done before actual surface composition data, indicating actual ranges of concentration are obtained, and alternate design solutions can be studied. Because of differences in gravity levels and operating environments, considerable differences in preferred modes of mining and transportation of raw materials at the various destinations should be expected. However, in spite of the existing uncertainties in concentrations of raw material, prototypes of equipment for those products rating highest in the trade-off studies should be developed and tested and a simulation of the entire processing chain performed on Earth in order to become acquainted with the problems facing us with the use of such equipment in a certainly hostile environment. These simulations will also serve to debug the equipment and to measure the mean time to failure of its components, to exercise repair and maintenance schedules, and to determine the type and number of spare parts needed. Before depending upon it, a laboratory-type set of equipment should be incorporated into earlier missions, fully supplied from Earth to become familiar with the actual operating problems at the destination.

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