MSC-06816

NASA TECHNICAL MEMORANDUM

NASA TM X-58087
May 1972

EXTRATERRESTRIAL CONSUMABLES PRODUCTION AND UTILIZATION

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

MANNED SPACECRAFT CENTER

HOUSTON, TEXAS 77058

1. Report No. TM X-58087	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle EXTRATERRESTRIAL CONSUMABLES PRODUCTION AND UTILIZATION		5. Report Date May 1972
		6. Performing Organization Code
7. Author(s) Alfred P. Sanders, MSC		8. Performing Organization Report No. MSC-06816
9. Performing Organization Name and Address Manned Spacecraft Center Houston, Texas 77058		10. Work Unit No. 914-43-00-00-72
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		13. Type of Report and Period Covered Technical Memorandum
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

Potential oxygen requirements for lunar-surface, lunar-orbit, and planetary missions are presented with emphasis on (1) emergency survival of the crew, (2) provision of energy consumables for vehicles, and (3) nondependency on an Earth supply of oxygen. Although many extraterrestrial resource processes are analytically feasible, this study has considered hydrogen and fluorine processing concepts to obtain oxygen or water (or both). The results are quite encouraging and are extrapolatable to other processes.

Preliminary mission planning and sequencing analysis has enabled the programmatic evaluation of using lunar-derived oxygen relative to transportation cost as a function of vehicle delivery and operational capability. It appears possible to reduce the round trip (Earth to Moon to Earth) dollars-per-kilogram cost to less than $880/kg and to obtain one-way trip costs of $660/kg and $440/kg (Earth to Moon and Moon to Earth, respectively).

17. Key Words (Suggested by Author(s))	18. Distribution Statement
• Lunar Bases • Lunar Logistics • Extraterrestrial Resources	

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
None	None	97	

NASA TM X-58087

EXTRATERRESTRIAL CONSUMABLES PRODUCTION AND UTILIZATION

Alfred P. Sanders
Manned Spacecraft Center
Houston, Texas

CONTENTS

Section | Page

Section | Page

TABLES

FIGURES

Figure		Page

Figure		Page

EXTRATERRESTRIAL CONSUMABLES PRODUCTION AND UTILIZATION

By Alfred P. Sanders
Manned Spacecraft Center

SUMMARY

The NASA Manned Spacecraft Center has performed a significant amount of in-house work related to the use of extraterrestrial resources. The results of these efforts are quite encouraging in presenting the advantages and disadvantages of the considered extraterrestrial oxygen production concepts.

Potential oxygen requirements and applications for lunar-surface, lunar-orbit, and planetary missions are presented. The major areas of discussion are emergency survival of the crew, provision of energy consumables for vehicles, and nondependency on an Earth supply of oxygen. Many other potential benefits and utilization concepts can be visualized for the byproducts (titanium, silicon, iron, et cetera) that are available for use in space activities by the addition of separating equipment.

Both the hydrogen and fluorine processing concepts are being considered for reducing the oxides contained in the lunar fines to obtain oxygen. Both concepts are analytically feasible and both have advantages and disadvantages. Inherent in both techniques are soil movers, electrolysis units, electrical power sources, storage tanks, and oxygen transfer facilities.

Preliminary mission planning and sequencing analysis has enabled the programmatic evaluation of the use of lunar-derived oxygen from the viewpoint of transportation cost as a function of vehicle delivery and operational capability. It appears possible to reduce the round-trip (Earth to Moon to Earth) dollars-per-kilogram cost to less than $880/kg and to obtain one-way trip costs of $660/kg and $440/kg (Earth to Moon and Moon to Earth, respectively).

Internal Manned Spacecraft Center space-tug studies were based on a space-tug useful life of 10 full burns; however, mission/cost analyses indicated that 40 to 50 full burns were necessary for the concept to be attractive economically. The consensus of a survey of Manned Spacecraft Center, NASA Lewis Research Center, and contractor propulsion experts was that 40 to 50 full burns are within the technological capability and that 100 full burns, while possible, present technological problems.

A preliminary parametric analysis of the cost of a lunar-surface oxygen processing plant as a function of oxygen consumption, dollars-per-kilogram cost, and vehicle amortization allows programmatic evaluation from the viewpoint of cost as a function of yield. The results of this analysis indicate where and how potential benefits are realizable.

The report concludes with a summary of related activities and recommendations for evolving the use of extraterrestrial resources for efficiency in space activities.

INTRODUCTION

The consumables on which space-flight vehicles and facilities depend for their operational capabilities or for the support of man as a crewman (or both) are essential to the success of the United States space program. The delivery of these consumables to the operational environment in which they will be used represents a major payload requirement.

If a critical consumable can be generated in meaningful quantities within the operational environment, a major breakthrough in space exploration will have occurred. Space missions would then be closer to being self-sustaining and further away from the costly dependence on total Earth logistic support for in-progress missions.

Programmatic effectiveness is the primary consideration in the evaluation of proposed concepts. To be effective, a concept must not only be technically feasible and economically rational; it must also be correlatable with future planned and forecasted space activities. The concept of the production of oxygen (O_2) on the surface of the Moon addressed herein in depth appears to satisfy these requirements. The immediately identifiable benefits and advantages of this process appear to be the following.

1. Economical advantages:

    a. Reduces Earth-to-Moon transportation costs (dollars per kilogram)

    b. Reduces the number of required Earth-launched logistic flights

    c. Provides free cargo space on Earth-launched flights for other cargo

2. Exploration benefits:

    a. Provides the opportunity to open the first extraterrestrial production facility

    b. Provides the first opportunity to exploit the resources of an extraterrestrial body

    c. Provides a potential "gas station" in space as a continuous support facility for on-going programs

3. Logical progress advantages:

    a. Provides the major critical consumable for Earth-independent operation on the Moon

b. Provides the opportunity to develop technology and operational experience for using the extraterrestrial resources of the planets (Mars, Venus, et cetera) and their satellites

c. Provides a logical follow-on to the experience gained and obtained in the Apollo Program

In this report, potential requirements and applications for using extraterrestrial oxygen are presented. The extraterrestrial material composition used as the baseline reference is that of a typical sample obtained by an Apollo lunar-landing mission. Preliminary information on two of the possible techniques (fluorine (F_2) reduction and hydrogen (H_2) reduction) are discussed in moderate detail. Various levels of oxygen production and the major production-system components are presented together with individual component weight, dimensions, cost, and schedule. Time lines for various production levels are also included.

This preliminary study has required many inputs from many individuals to obtain a reasonable credibility level. The individual contributors, their parent organizations, and the dates and types of contributions are listed in the appendix.

POTENTIAL EXTRATERRESTRIALLY DERIVED OXYGEN REQUIREMENTS AND APPLICATIONS

The four essentials for human life are oxygen, water (H_2O), food, and a controlled environment. On the surface of the Earth, these four essentials may be obtained with relative ease; however, as man extends his domain either below the surface of the Earth (as in the exploration of the oceans) or above the surface of the Earth (as in the exploration of space), these essentials become progressively more difficult to provide. Short-duration missions of a limited nature into either of these alien domains can be accomplished with moderate difficulty. Long-duration missions of a less limited nature become progressively more difficult. These difficulties in providing the essentials for human life are directly related to the provision of the consumables of which these essentials are composed. Because oxygen is 100 percent of the first essential and 89 percent of the second essential, the potential reduction in the difficulties related to providing space-activities essentials by using extraterrestrial oxygen is obvious and significant.

Oxygen for the provision of these essentials may be extracted from extraterrestrial materials containing its compounds by various techniques. The quantity of oxygen thus obtained will vary with the type of compound available and the technique applied. Because of the lower binding energy of some iron oxides, any technique capable of extracting oxygen from more tightly bound compounds will extract oxygen from these weakly bound iron oxides. This is important because it is known that the lunar-surface material (and possibly the surface material of Mars) contains weakly bound iron oxides. There is also good rationale to support the assumption that many other solar system bodies have surface materials containing weakly bound iron oxides. Obviously, a technique applicable to one of these solar system bodies may very possibly, with modifications, be applicable to any of the others.

The possible uses for extraterrestrially derived oxygen are many and range from emergency survival to interplanetary refueling. Some of the more obvious uses, which may include manned or unmanned activities, are categorized as surface, orbital, and interplanetary and are discussed in the following sections.

LUNAR SURFACE

Lunar-Surface Base

A lunar-surface base or shelter could be independent of Earth from the oxygen viewpoint by producing oxygen on the Moon.

Lunar Mobility

Lunar-rover, flyer, and space-tug (ST) trips to other surface areas could be accomplished using lunar-surface-produced oxygen. For an extensive lunar-surface operation requiring large quantities of oxygen (as a propulsion system bipropellant or as a fuel-cell chemical reactant for electrical power), a lunar-surface processing plant may be economically advantageous.

Emergency Survival

In the event of an emergency when immediate return to Earth or to another satisfactory environment is impossible, a small system to provide emergency oxygen, water, and perhaps electrical power for the crew appears possible. The weight of such a system is estimated to be ~45.36 kilograms per crewman.

LUNAR ORBIT

Lunar Orbital-Surface-Orbital Mobility

The orbiting lunar station (OLS) can be provided with all forecasted oxygen requirements by a lunar-surface oxygen production plant. Preliminary investigations indicate that this is economically attractive.

Emergency Survival

In the event difficulties occurred on the OLS, an ST flight to the production plant would allow access to as much oxygen, water, and electrical power as desired.

INTERPLANETARY MISSIONS

High Earth Orbit

A large-scale production plant on the Moon might provide oxygen to an elliptical high Earth orbit for a planetary manned mission. This procedure might be either economically competitive or advantageous for supporting planetary missions that use a liquid-hydrogen/liquid-oxygen propulsion stage in which the oxygen content is ~80 percent.

Planetary Surface

The arguments presented for lunar-surface utilization, emergency survival, surface mobility, and base support apply equally well to extracting consumables from other planetary surface soils and are therefore not repeated here.

PRELIMINARY PLANT CONCEPTS FOR PRODUCING OXYGEN

LUNAR SOIL COMPOSITION

A typical analysis of the particulate material on the lunar surface (lunar fines) is as follows.

Particulate material	Percent
Silica (SiO_2)	43
Alumina (Al_2O_3)	13
Titania (TiO_2)	7
Iron oxide (FeO)	16
Magnesia (MgO)	8
Calcium oxide (CaO)	12
All others	1

There are many techniques that can be used to extract oxygen from the oxides of the lunar fines listed. Activities implemented at the NASA Manned Spacecraft Center (MSC) and at the NASA Lewis Research Center (LeRC) investigated two possible techniques (hydrogen reduction and fluorine reduction, respectively) for obtaining oxygen and water from simulated lunar material. A comparison of some of the advantages and disadvantages of each technique is as follows.

Hydrogen process	Fluorine process
State of the art	More development required
Hazards known; do not appear excessive	More hazardous
Low yield	High yield (5 to 1)
Electrolysis of water with subsequent hydrogen recycling[1]	Electrolysis of potassium fluoride (KF) with subsequent fluorine recycling
Yields water directly	Yields oxygen directly
Does not yield almost pure metals	Yields almost pure metals
Embrittlement of metals by hydrogen	Corrosiveness of potassium fluoride
Less complicated	More complicated

HYDROGEN PROCESSING CONCEPTS

Water Process

Water (steam) is obtained by using Earth-supplied hydrogen to reduce the oxides of iron (ilmenite in particular) present in the lunar fines. Because this reduction activity occurs at a temperature between 500° and 1500° C, heat must be applied to the lunar fines. The simplest source of thermal energy on the Moon appears to be the Sun; solar radiation at a 90° Sun angle on the Moon provides ~1.97 cal/min/cm^2. Two types of solar concentrators, a Fresnel lens and a solar reflector, were considered. The solar reflector was selected after total design considerations.

To avoid process losses, a batch-loaded pressure vessel concept was selected as the technique to pursue. Two other possible concepts were identified but required more investigation than commensurate with a preliminary feasibility study. The design concept uses a pressure vessel that incorporates a sublimator (sodium-lithium (Na-Li) combination) to maintain a specific temperature without causing melting or sticking of the lunar fines to the inside of the pressure vessel. The vessel is conceptually designed to accommodate 45 kilograms of material, with a density of 1602 kg/m^3, in less than one-half its internal volume. This vessel is less than 0.6 meter in diameter and weighs less than 27 kilograms.

[1]Nonelectrolysis separation (by membrane diffusion at elevated temperatures) of water into hydrogen and oxygen appears possible but was not incorporated into this study because of level-of-effort constraints.

If the lunar fines are first magnetically separated to concentrate the iron oxides, a yield of ~5.37 kilograms of water (4.78 kilograms of oxygen and 0.59 kilogram of Earth-supplied hydrogen) from each 45.4 kilograms of ilmenite is theoretically possible. If the lunar fines are not magnetically separated to concentrate the iron oxides, then a yield of ~0.77 kilogram of water (0.69 kilogram of oxygen and 0.08 kilogram of Earth-supplied hydrogen) from each 45.4 kilograms of lunar fines is theoretically possible. These activities are repeatable and the pressure vessel is not damaged by the process. The necessary conceptual equipment is shown in figure 1.

A crewman in a space suit requires ~0.18 kilogram of oxygen per hour and 1.18 kilograms of water per hour. For an emergency survival system, the crew might load and unload the pressure vessel with magnetically separated or unseparated lunar material. The process could be automated if desired. Naturally, the quantity of hydrogen necessary for the desired quantity of water must be transported from the Earth to the Moon, and a storage tank for the generated quantity of water is also necessary.

Oxygen Process

The oxygen process is simply an extension of the water-producing process by electrolysis of the water and subsequent recycling of the hydrogen to make the process a self-sufficient oxygen-generation facility. As before, the pressure vessel is loaded and the process started; however, a solar array for electrical energy, an electrolysis cell to separate water into hydrogen and oxygen, and hydrogen recycle lines and pump are now added to the system. This conceptual system is capable of producing oxygen at a rate dependent on the frequency of lunar materials reloading, the electrical energy available, and the size of the electrolysis cell.

Present engineering technology indicates that ~0.45 kilogram of hydrogen or 3.64 kilograms of oxygen may be liberated by 15 kilowatts. Because space activities are weight/cost sensitive, it is apparent that the weight/cost of equipment must be carefully balanced against the desired production rate. For example, estimates are that 0.45 kilogram of oxygen per hour and 0.05 kilogram of hydrogen per hour can be obtained from a 27.3-kilogram electrolysis cell provided with 2.5 kilowatts of power, or that 4.54 kilograms of oxygen per hour and 0.57 kilogram of hydrogen per hour can be obtained from a 209-kilogram electrolysis cell provided with 25 kilowatts of power. Also, the weight of the electrical power source warrants careful consideration. (For 1 kilowatt from a solar array, the present estimate is 59 kilograms.) The necessary conceptual equipment is shown in figure 2.

Hydrogen Process

The hydrogen deposited in the lunar fines by the solar wind evolves at a relatively low temperature. Approximately 0.7 cubic centimeter (at standard Earth sea-level conditions) of hydrogen per gram of lunar fines is available by heating the fines to between 120° and 600° C. This indicates that ~4.59 grams of hydrogen are theoretically available from each 45.4 kilograms of lunar fines.

If the lunar fines are heated, then the gas evolving must be trapped; a semisphere (open-bottomed enclosure) resting on the lunar surface is envisioned for this purpose.

The semisphere must be constructed of transparent material to allow the concentrated solar energy to be focused through it onto the lunar surface. A pump is required to remove the evolving gas from the interior of the semisphere before it escapes into the lunar atmosphere. Energy must be provided to the pump, and the trapped hydrogen must be stored for later use.

Because this concept has not been investigated in depth and because the production yield of hydrogen is very low, it is presently thought that this option may not be economically attractive. Further investigation of the mobile plant unit and of the hydrogen annual requirements may or may not result in a favorable economic trade-off. For example, a hydrogen requirement of 460 kilograms would require the heating of ~4540 megagrams of lunar soil to 600° C. If the mobile plant could heat 45.4 kilograms of soil (0.6 by 0.6 by 0.074 meter) to 600° C every minute, a lunar-surface area of 92 500 meters would have to be traversed and heated to 600° C within 1.9 years to satisfy the 460-kilogram requirement. The necessary conceptual equipment is shown in figure 3.

FLUORINE PROCESSING CONCEPTS

Oxygen Process

Oxygen is obtained by using Earth-supplied fluorine to reduce the oxides in the lunar materials. This reduction activity occurs at a relatively low temperature, and the addition of thermal energy to cause the reaction to occur is not necessary.

To avoid process losses, a batch-loaded pressure vessel concept was selected as the process to pursue. The preliminary concept is to use a pressure vessel incorporating a potassium iodide (KI) purifier (oxygen purification) and a closed-loop potassium fluoride electrolysis separator with recycle lines. The vessel was conceptually designed to accommodate 205 kilograms of material, with a density of 1602 kg/m^3, in less than one-half its internal volume. This vessel is ~0.6 meter in diameter and ~0.9 meter high and weighs less than 90 kilograms.

Lunar fines are placed within the pressure vessel, and a yield of ~19.1 kilograms of oxygen from each 45.4 kilograms of lunar material is theoretically possible. These activities are believed to be repeatable without damage to the pressure vessel.

The electrolysis of potassium fluoride requires an electrolysis system, the size of which is, again, a function of the yield rate. For a system yielding 4.54 kilograms of oxygen per hour, 10.1 kilograms of fluorine per hour, and 4.51 kilograms of potassium per hour, a 273-kilogram electrolysis system with a power requirement of 24 kilowatts is envisioned.

The necessary conceptual equipment is shown in figure 4. The crew would load and unload the pressure vessel with lunar material.

Water Process

The water process is simply an extension of the oxygen process with Earth-supplied hydrogen combined with lunar-derived oxygen to produce water and, as a bonus, electricity. The necessary conceptual equipment is shown in figure 5.

FLUORINE OR HYDROGEN PLANT CONCEPT

A chemical production plant on the Moon will require the same types of components (storage tanks, soil movers, chemical processing equipment, and product transportation) that an Earth strip-mining facility requires. This section describes some of these components, in a very preliminary manner, to enable sizing of the scope and magnitude of a lunar production plant.

In order to scope a facility of this nature, an annual oxygen production rate must be assumed (together with many other assumptions). An annual rate of 400 megagrams of oxygen (45.4 kg/hr continuously) was selected. For this production rate, the hydrogen process requires ~3000 kilograms (1.842 cubic meters with a density of 1602 kg/m^3) of lunar material per hour and the fluorine process requires ~108.2 kilograms (0.067 cubic meter) of lunar material per hour. Because the hydrogen process uses magnetic separation (3000 kilograms yields 435 kilograms maximum of ilmenite concentrate), the hydrogen concept needs to process 437 kilograms of material per hour, whereas the fluorine concept needs to process only 108 kg/hr.

These consumption rates for lunar materials may be easily visualized by considering 2.59×10^6 square meters (1 square mile) of the lunar surface. If this surface area was "strip mined" to a depth of 0.9 meter, 2.37×10^6 cubic meters of lunar soil would have been excavated. This is sufficient material for 146 years of operation of a hydrogen plant or 4000 years of operation of a fluorine plant. A conceptual visualization of a lunar-surface oxygen production facility is depicted in figure 6.

Functionally, a lunar-surface oxygen plant requires approximately 10 major items. These items are shown in figure 7 in a flow sequence. The correlation and differences of the hydrogen and fluorine concepts are presented above the major items in figure 7. It is easily seen that the differences would affect, at most, four of the 10 major items.

A conceptual lunar-surface plant layout is shown in figure 8. Although this layout probably will have little resemblance to an actual layout, it has resulted in several major item location considerations. The lunar-soil mover (LSM) will probably generate a "dust cloud" during loading and unloading operations. A dust cloud probably will also be generated during the landing and ascent operations of the ST. Because the solar-array cells depend on sunlight, the two dust-generating activities should be as far away from the solar array as is practical. It would also be desirable to land a reasonable distance from the propellant storage depot.

Another important consideration is that the solar array should be able to view the Sun through all Sun phase angles. This indicates that structures should be placed in a manner to reduce to minimum the generation of shadows on the solar array.

A final important consideration is that the same propellant transfer system could move the oxygen to and from the storage tanks. By using the same cryogenic lines for fill and empty operations between the liquefier and the storage tanks, piping requirements and the number of plant components are reduced.

LUNAR-SOIL MOVER

Lunar material to be processed by the plant and postprocessing residuals are transported by the LSM. The LSM is a four-wheeled transportation vehicle with an automatically adjusting conveyor belt for the loading of lunar material and an openable bottom for load dumping. Lunar material loading is accomplished by commanding the conveyor belt to the load position (surface contact depth estimated at 7.6 centimeters) and, with the belt in operation, commanding the vehicle forward at a slow rate of speed. Because the conveyor belt is essentially many small buckets, the LSM is soon filled. As an example, if the operation excavated a continuous 0.6-meter-wide trench 7.6 centimeters deep, then for every 0.6 meter of vehicle forward motion, 0.0283 cubic meter of lunar material would be loaded on the LSM.

If the desired oxygen production rate is 91 kg/hr (plant operation during the lunar daylight period only), a maximum of 5920 kilograms (3.68 cubic meters) of lunar fines must be magnetically separated to obtain ~860 kilograms (0.18 cubic meter) of ore for every hour of plant operation. At an LSM forward speed of 0.03 m/sec during soil loading operations, it would require ~20 seconds to transport every 0.0283 cubic meter of lunar fines past the magnetic separator. To obtain 860 kilograms of magnetically separated ore would require ~2600 seconds (43.3 minutes).

If it is assumed that 50 minutes of LSM soil loading operation is sufficient to load 860 kilograms of ore into the LSM, then each hour of LSM operation may be considered as being the sum of 50 minutes of loading and 10 minutes of transportation. If the round-trip transportation time required was 2 hours, then the LSM would have to load continuously for ~12 hours. In 12 hours, 10 350 kilograms of ore (2.19 cubic meters) would have been loaded into the vehicle.

If the LSM payload volume had the same total surface area that the manned rover has (2.06 by 3.08 meters), the height of the payload volume walls would have to be ~0.35 meter. One LSM concept is depicted in figure 9.

For the hydrogen plant lunar material transportation, a conveyor belt and a magnetic separator are mounted on the vehicle. This arrangement enables separation of the iron oxides from the lunar soil during the loading and thereby makes it unnecessary to transport much of the unprocessable material present in the lunar soil. For the fluorine plant lunar material transportation, the conveyor belt and magnetic separator are omitted.

LUNAR-SOIL PROCESSOR

Production Plant Soil Processor — Hydrogen Technique

For the hydrogen plant soil processor, three processing spheres are located in a line except during soil loading and unloading operations. During loading and unloading, the appropriate sphere is automatically driven 6 meters out of line. The sphere is automatically inverted for the dump operation, returned to the upright position for soil loading, and subsequently returned to the processing line for the hydrogen reduction operation. Flexible tubing allows this operation to occur without disconnecting the hydrogen or oxygen lines. This arrangement allows the solar reflector to remain in a fixed position, excluding reflector rotation, in the processing line. A second advantage is that the dust cloud generated by soil loading and unloading operations is at least 3 meters away from the solar concentrators. With proper dust shielding, the degradation of the surfaces of the solar concentrators should be minimized.

Each processing sphere is a double-jacketed reactor using a sodium-lithium heat transfer fluid to achieve a controlled reaction temperature in excess of 500° C. A 2-hour operating cycle life for each sphere with an internal charge capacity of 1440 kilograms of soil (90 kilograms of oxygen maximum yield) at a 50-percent fill factor was selected. This results in a double-jacketed reactor with a 1.5-meter inside diameter and a 1.8-meter outside diameter.

The total lunar-soil-processor unit weight is estimated to be 1364 kilograms, and the stowage volume is 9.6 cubic meters. A hardware cost of $10 million and a time of 24 months to flight-unit completion are estimated.

Production Plant Soil Processor — Fluorine Technique

For the fluorine plant soil processor, two processing cylinders are located in a line. Loading is accomplished through a top portal and dumping through a bottom portal. No motion of the cylinders, in or out of line, is required. Because the reaction does not require the addition of thermal energy, the dust cloud generated by loading and dumping operations presents no problem.

Each processing sphere is copper lined, and the maximum internal temperature during the reduction reaction is estimated to be ~900° C. A 2-hour operating cycle life for each cylinder with an internal charge capacity of 200 kilograms of soil (84.7 kilograms of oxygen maximum yield) at a 50-percent fill factor was selected. This results in a steel-jacketed copper-lined reactor with external dimensions of 0.6 meter in diameter and 1 meter in length.

The total lunar-soil-processor unit weight is estimated to be 273 kilograms, and the stowage volume is 0.62 cubic meter. The estimated hardware cost is $15 million, and the estimated flight-unit completion time is 48 months.

ELECTROLYSIS UNITS

Water Unit

In the hydrogen processing plant concept, the steam evolving from the reduction of the lunar-surface material must be electrolyzed to obtain the oxygen product and the hydrogen for recycling. A system to accomplish this would weigh between 1800 and 3600 kilograms and occupy between 2.8 and 5.7 cubic meters of volume in the stored configuration. A power requirement of ~250 kilowatts is estimated. The system heat rejection rate will be ~37.8 million cal/hr. Cost estimates are $12 million for development, $8 million for verification, $5 million for a prototype system, and $15 million for a flight system. The estimated total cost is $40 million, and the estimated flight-unit completion time is 48 months.

Potassium Fluoride Unit

In the fluorine processing plant concept, the fluorine is combined with potassium vapor to form liquid potassium fluoride. The potassium fluoride must then be electrolyzed to separate the potassium and fluorine for recycling. A system to accomplish this would weigh ~4500 kilograms and occupy 5.7 cubic meters of volume in the stored configuration. A power requirement of ~250 kilowatts is estimated, and a system heat rejection rate of ~37.8 million cal/hr is needed. A total cost of $50 million and a time of 60 months to flight hardware availability are estimated.

RADIATOR

The liquefier and electrolysis units are estimated to require a thermal transfer rate of ~45.4 million cal/hr from a source temperature of ~316° C. A tent-shaped radiator having a surface area of ~11 square meters appears to be sufficient. The weight of the total radiator subsystem, including liquid, pumps, lines, and thermal transfer jackets, is ~230 kilograms. The stowed volume is ~2.55 cubic meters. The hardware is estimated to cost approximately $3 million and to require ~18 months for a flight unit.

LIQUEFICATION UNIT

The oxygen produced by the lunar-surface plant must be converted to a liquid for storage and for vehicle/facility use. A system to accomplish this needs approximately a 5.0-million-cal/hr capability (45.4 kilograms of oxygen per hour at an estimated 0.11 million cal/kg). To accomplish this type of activity, a turbomachinery-type operation appears reasonable and requires ~300 kilowatts. The compressor is estimated to have dimensions of approximately 1.4 by 0.9 by 2.1 meters, and the cold box is approximately 2.8 meters long with a 1.4-meter diameter. The estimates are $40 million for system cost and 48 months for hardware availability.

CRYOGENIC STORAGE ON THE LUNAR SURFACE

After the lunar soil has been processed by the chemical plant to extract the oxygen and small quantities of hydrogen and water, the residual material is deposited in open areas on the lunar surface for subsequent use. The plant gaseous product is liquefied and placed in storage until a sufficient quantity has been accumulated for effective economical transfer to user vehicles, facilities, and fuel depots in space.

The storage containers (collapsible spheres) for oxygen and hydrogen are identical. In the launch configuration, each sphere is in a collapsed condition and is disklike in appearance. Each disk is ~6.1 meters in diameter and ~0.6 meter high. In the extended configuration on the lunar surface, each sphere is ~6.1 meters in diameter. The sphere wall thickness is ~0.08 centimeter, and the Earth-launched mass per sphere is ~273 kilograms (fig. 10).

The densities of liquid oxygen and liquid hydrogen are ~1140 kg/m^3 and ~72 kg/m^3, respectively. With an internal storage capability of ~119 cubic meters per sphere, each sphere could store either 136 megagrams of oxygen or 8.6 megagrams of hydrogen. For the purpose of this study, it has been assumed that the requirement is to store 2 gigagrams of oxygen and 42.7 megagrams of hydrogen. Accordingly, 15 spheres are needed for the storage of oxygen and five spheres are needed for the storage of hydrogen. A total of 20 spheres would have a combined mass of ~5.46 megagrams and would be ~12.2 meters high in the stored configuration. The plumbing for the spheres and the thermal insulation are estimated to require ~10.92 megagrams of payload capability (5.46 megagrams each).

The cryogenic storage spheres when deployed on the lunar surface are placed on top of the disk plates to eliminate puncturing of the spheres by surface rocks. The spheres are shaded from direct and reflected sunlight by solar-reflecting surfaces, leaving as much sphere surface area as possible exposed to deep space for simple thermal control.

The pumping system with each sphere is provided with liquid cryogen by gravity feedlines, thus enabling filling and emptying through the same supply lines. The oxygen and hydrogen tanks are separately multiplexed to the cryogenic feed system connecting with the production plant. Booster pumps may be located in the main feed system at the multiplexing junctions and at the production plant.

CONSUMABLES TRANSFER FACILITY

The oxygen stored in the spherical storage tanks is pumped back through the liquefication unit and subsequently routed to the consumables transfer facility. This facility is remotely controlled by a manned control console located at the facility, in the ST, or in the OLS. The facility consists of a pressurized shelter, a command console, propellant pumps, a propellant storage reservoir, and articulating remotely controlled flexible tubing and structure for propellant transfer.

After the ST being used to transport the propellant lands on the lunar surface, the propellant lines are connected to the ST by equipment remotely controlled by the crew. Oxygen is transferred from the reservoir to the ST and the lines are disconnected. The ST is then ready to perform another ascent and descent activity, and the cycle is repeated.

The transfer facility mass is estimated to be ~6.82 megagrams and to occupy ~88.8 cubic meters. A cost of approximately $60 million and a flight-unit completion time of 48 months are estimated.

ELECTRICAL POWER SYSTEMS

Four conceptual types of electrical power systems appear applicable for consideration as the energy source for electrolysis and subsystems requirements. These are (1) a large sphere or spherical array of solar cells and solar concentrators, (2) 42 disks of solar cells and solar concentrators (Mariner-type array), (3) a large solar parabolic reflector and a Rankine system, and (4) a nuclear thermal source and a Brayton system. The first three systems are limited to daylight operation; the fourth system may be operated during both daylight and nighttime. The first two concepts are discussed in depth in the following sections and the last two concepts are discussed briefly.

Spherical or Semispherical Array

A Sun-facing sphere or semispherical erectable structure with solar arrays covering the projected area (πr^2) is envisioned. In current solar-array technology, the weight, per kilowatt of obtained energy, of the rollup-type solar arrays is estimated to be ~27.7 kilograms for the thin-film arrays and ~26.4 kilograms for the supporting structure. These values appear applicable to this concept. Using the total weight of 54.1 kg/kW, a 250-kilowatt array should weigh ~13.5 megagrams (54.1 kg/kW × 250 kilowatts).

To accommodate nonoperation of the oxygen plant during the complete lunar night, the daylight production rate and mass are doubled. The lifetime of the system is estimated to exceed 3 years. The estimates are $400 million for system cost and 60 months for hardware availability. A conceptual system is shown in figure 11.

Mariner-Type Array

For the Mariner panel-type array, 42 automatically pointed solar-array disks are envisioned. These disks are composed of many discrete solar cells with individual solar concentrators around each cell. In appearance, each solar cell and concentrator unit would resemble a square wastepaper basket. These solar-array disks are ~5 centimeters thick and ~6 meters in diameter (stored or operational). Approximate subsystem weights are as follows: solar array, 4578 kilograms; structure, 910 kilograms; packaging and deployment, 210 kilograms; and power cables and connectors, 727 kilograms. A 250-kilowatt solar array should weigh ~6.43 megagrams. Doubling the lunar-day energy level results in a system mass of ~11.35 megagrams. The lifetime of the system is estimated to exceed 10 years. The estimates are $125 million for system cost and 30 months for hardware completion. A conceptual system is shown in figure 12.

Solar Reflector and Rankine System

A large parabolic reflector to collect the solar energy for redirection, by smaller reflectors, to concentrate the received energy on a Rankine system is envisioned. Present estimates are that a system of this type, to produce 250 kilowatts, would have a mass of ~10.8 megagrams. Again, if the production rate is doubled to accommodate nonoperations during the lunar night, the estimated mass is doubled. The solar reflector is estimated to have a mass of less than 4.89 kg/m^2, and ~929 square meters of surface area are needed. The system approximation estimating factor is 43.4 kg/kW, and the lifetime of the system should exceed 5 years. Estimates are $500 million for system cost and 60 months for hardware availability.

Nuclear Thermal and Brayton System

A radioactive source provides the thermal energy for operation of the Brayton cycle. Present estimates are that a system of this type, to produce 250 kilowatts, would weigh ~8.5 megagrams (unshielded). If the system could not use the lunar soil for shielding, the basic weight would increase from ~8.5 to ~14.2 megagrams. The system estimating factor is 34.1 kg/kW (unshielded). The lifetime of the system should exceed 5 years. Estimates are $500 million for system cost and 60 months for hardware availability.

Electrical Power Systems Synopsis

The fourth system, being nuclear, has obvious difficulties and problems that the first three systems do not have. It is believed at this time that the Mariner-type solar-array concept appears to be the most reasonable.

PLANT COMPONENTS, COST, AND SCHEDULE

The type, size, volume, cost, and hardware schedules are defined in a very preliminary manner in this section. All these characteristics are very dependent on the production rate and the type of reaction (hydrogen or fluorine) used.

The characteristics of the components previously described in the lunar oxygen plant discussion are listed in table I. The cost and schedules of these components are given in table II. This plant configuration was for a production rate of ~45.4 kilograms of oxygen per hour. It should be emphasized that these presented characteristics are the averaging or selection of the values thought most reasonable as a result of research activities. The variation range of these characteristics, or the uncertainty, is clearly presented in the following analysis of three different levels of production and operational use.

Level I

The objective of production level I is to provide the life-support oxygen required for a six-man crew during 14 days of lunar daylight operation. This production rate of oxygen (12 kg/day) is based on the following requirements.

Crew breathing:	0.91 kg/day/man × six men	5.46 kg/day
Shelter leakage:	2.18 kg/day	2.18 kg/day
PLSS[2] activities:	0.182 kg/man/hr × four men × 6 hours	4.36 kg/day
Total oxygen required		12.00 kg/day

The components to accomplish this production operation and their estimated characteristics are presented in table III, and time lines of activities are shown in figures 13(a) and 13(b).

Because the hydrogen process produces water as a primary product that must then be electrolyzed to obtain breathing oxygen and hydrogen for recycling, water for operational requirements may be obtained rather easily using additional Earth-delivered hydrogen and the production plant. Water is ~89-percent oxygen by weight; therefore, the procedure is advantageous because this weight no longer must be transported from the Earth to the Moon. The production rate of water (53 kg/day) is based on the following requirements.

Crew consumption:	3.64 kg/day × six men	21.8 kg/day
Crew hygiene:	0.45 kg/day/man × six men	2.7 kg/day
PLSS activities:	1.18 kg/hr/man × six men × 6 hours	28.4 kg/day
Total water required		52.9 kg/day

Because 53 kg/day of water is approximately equivalent to 5.88 kg/day of hydrogen and 47.2 kg/day of oxygen, a 14-day supply of hydrogen (82.3 kilograms) and ~182 kilograms of additional equipment are required in addition to the equipment listed in table III. This activity is time lined in figures 14(a) and 14(b).

---

[2]Portable life-support system.

By producing 746 kilograms of water on the lunar surface, it is no longer necessary to transport 663 kilograms of oxygen (89 percent of water) to the surface of the Moon, and a weight savings of 398 kilograms (663 kilograms - 265 kilograms) is obtained. It should be noted that the production rate of oxygen to produce water and free oxygen is now approximately 5 times as high as for the oxygen-only rate. This means that ~5 times the quantity of lunar soil must also be moved. To produce oxygen only, the system requires ~780 kilograms (0.482 cubic meter) of in situ lunar soil or ~113.5 kilograms (0.0242 cubic meter of magnetically separated, relatively pure ilmenite with a density of 4690 kg/m^3) per day for the hydrogen process. To produce oxygen and water, the system requires ~3840 kilograms (2.41 cubic meters) of unseparated lunar soil or ~559 kilograms (0.34 cubic meter) of relatively pure ilmenite per day. Approximately 28.7 kilograms of lunar soil is required to produce 12 kilograms of oxygen or ~140 kilograms of lunar soil is required to produce 58 kilograms of oxygen by the fluorine process.

In the event the requirement was to provide the life-support oxygen required for a three-man crew during 28 days of lunar daylight and darkness operation, the production rate of oxygen (14.2 kg/day) is based on the following requirements.

Crew breathing:	0.91 kg/day/man × three men	2.73 kg/day
Shelter leakage:	2.18 kg/day	2.18 kg/day
PLSS activities:	0.182 kg/man/hr × two men × 6 hours	2.18 kg/day
Total oxygen required		7.09 kg/day

Because the plant can only operate during the lunar daylight, the 7.09-kg/day rate must be doubled and the oxygen stored for lunar-night activities. The daylight production rate is therefore 14.2 kg/day. This rate causes an increase of ~91 kilograms to the equipment listed in table III. This activity is time lined in figures 15(a) and 15(b).

In the event the requirement was to provide the life-support oxygen, water, and electrical power for a three-man crew during 28 days of lunar daylight and darkness operation, the production rate of oxygen (103.1 kg/day) is based on the following requirements.

1. Oxygen production:

Crew breathing:	0.91 kg/day/man × three men	2.73 kg/day
Shelter leakage:	2.18 kg/day	2.18 kg/day
PLSS activities:	0.182 kg/man/hr × two men × 6 hours	2.18 kg/day
Total oxygen required		7.09 kg/day

The rate must be doubled for the daylight-only production rate and is therefore 14.2 kg/day.

2. Water production:

Crew consumption:	3.64 kg/day/man × three men	10.92 kg/day
Crew hygiene:	0.45 kg/day/man × three men	1.35 kg/day
PLSS activities:	1.18 kg/hr/man × two men × 6 hours	14.18 kg/day
Total water required		26.45 kg/day

This daily water consumption rate (26.45 kg/day) is an oxygen daily consumption rate of 23.6 kg/day. This rate must be doubled for the daylight-only production rate and is therefore ~47.2 kg/day.

3. Electrical power:

Fuel-cell oxygen:	0.347 kg/kW-hr × 5 kW-hr × 24 hours	41.7 kg/day

This is the production rate during daylight. The electrical power source during daylight may be solar cells but fuel cells (or nuclear power) are appropriate during the nighttime. The selection of fuel cells for night activities necessitates the production of sufficient oxygen during daylight for nighttime needs.

The total oxygen production rate required for this type of operation is 103.1 kg/day (14.2 kg/day + 47.2 kg/day + 41.7 kg/day). This is ~7 times the rate of production referenced in table III, and multiplication of table III values by ~10 will yield values believed to be appropriate. This activity is time lined in figures 16(a) and 16(b).

Level II

The objective of production level II is to provide sufficient life-support oxygen for level I activities and 50 percent of the oxygen required for ST orbit-to-surface-to-orbit operations. The production rate of oxygen is based on the following requirements.

Level I activities:	12 to 103.1 kg/day	103.1 kg/day maximum
ST requirements (50 percent):	22 770 kg/trip × six trips/yr × 1 yr/365 days	374 kg/day

Because the level I activities include both day and night operations, the 103.1-kg/day value is acceptable; however, the ST rate of 374 kg/day must be doubled for daylight-only production and is therefore 748 kg/day. The total daylight production is therefore less than the 910-kg/day (103.1 kg/day + 748 kg/day) rate for which the components and characteristics are listed in table IV.

Level III

The objective of production level III is to provide sufficient life-support oxygen for level I activities, 100 percent of the oxygen required for ST orbit-to-surface-to-orbit operations, and the OLS oxygen requirements. The production rate of oxygen is based on the following requirements.

Level I activities:	12 to 103.1 kg/day	103.1 kg/day maximum
ST requirements (100 percent):	45 540 kg/trip × six trips/yr × 1 yr/365 days	748.6 kg/day
OLS requirements:	12 to 103.1 kg/day	103.1 kg/day

Again, the ST requirement per day must be doubled for the daylight-only production rate, resulting in 1497.2 kg/day. Because the OLS-crew oxygen requirement is not expected to exceed the surface-crew oxygen requirement, the production of oxygen is less than the 1820-kg/day (103.1 kg/day + 1497.2 kg/day + 103.1 kg/day) rate for which the components and characteristics are listed in table V.

SPACE-TUG PROPULSION SYSTEM ESTIMATED CAPABILITY

Three major transportation links — Earth surface to Earth orbit, Earth orbit to and from lunar orbit, and lunar orbit to and from lunar surface — are applicable in implementing the lunar-surface oxygen plant. Using the Earth-to-orbit shuttle (EOS), the chemical stage (CS), and the ST, respectively, as the transportation vehicles for the three links, and considering the respective vehicle amortization costs per flight of approximately $7, $3.6, and $5.5 million, the areas of high cost are immediately identified. These areas are the Earth-surface to Earth-orbit and the lunar-orbit to and from lunar-surface links. For the former link, the EOS is considered to be capable of 100 flights. For the latter link, the ST was considered, by internal studies, to be capable of 10 flights.

It is apparent from the mission analysis data and complementary parametric cost data that, to be really cost competitive, the ST needs to be capable of 40 to 50 flights. In attempting to obtain sufficiently valid data on which to justify considering the useful life of the ST to be 40 to 50 flights, propulsion experts from the MSC, the LeRC, and the liquid-hydrogen/liquid-oxygen rocket contractor were contacted. The consensus of the experts contacted is that an oxygen/hydrogen propulsion vehicle could have a useful life of 40 to 50 flights of the type defined for the lunar-surface oxygen plant activities.

Moreover, the opinion was further expressed that 100 flights would not be an impossible task. It should be emphasized that these opinions are not supported by qualification test data.

In addition to asking these individuals their personal opinions concerning the estimated capability of the ST, the questions listed in table VI were asked both MSC and LeRC personnel. The answers are, in some cases, qualification specification values and, in other cases, engineering evaluations.

MISSION/COST ANALYSES

Program cost effectivity has been approached from three different directions in an attempt to establish as much depth and scope as is practical for this preliminary effort. The three approaches are as follows.

1. Programmatic comparisons of activities with and without a lunar-surface oxygen plant are discussed, and the cost savings available as a result of having a surface plant are presented.

2. A parametric cost analysis, performed by the MSC Operations Analysis Branch, allows the evaluation of the lunar-surface oxygen plant production rate as a function of plant cost and ST reuses.

3. A preliminary mission planning and sequencing analysis, generated by MSC in-house activities and verified by the Flight Studies Section, was performed to identify (approximately) the effective transportation comparisons. This analysis, which is being computer simulated to enable rapid variable evaluation and automatic sequencing optimization, allows the various space vehicle types, trajectory changes, space vehicle characteristic changes, and payload changes to be evaluated. A simple cost evaluation also is an output of this simulation.

PROGRAMMATIC COMPARISONS

If each ST lunar orbit-to-surface-to-orbit sortie requires full ST propellant tanks (27.3 megagrams of propellant) and the propellant use ratio is approximately 5 to 1 for oxygen and hydrogen, respectively, ~22.76 megagrams of oxygen and 4.54 megagrams of hydrogen propellant are used per sortie. If a lunar-surface oxygen plant was in operation, it could provide the ST sortie oxygen propellant requirements. This would reduce the Earth-supplied logistic requirement from 27.3 to 4.54 megagrams per sortie.

For the Earth logistic sequence presented in figure 17, 14 EOS flights are required to support one CS round trip that delivers ~45.7 megagrams of payload to lunar orbit. If this 45.7 megagrams is oxygen and hydrogen, sufficient propellant for 1.67 (45.7 megagrams ÷ 27.3 megagrams) ST flights is delivered to lunar orbit. For 10 ST sorties, this Earth logistic sequence would have to be repeated six times. Conversely, if the 45.7 megagrams of payload is hydrogen and if lunar-derived oxygen is available, sufficient hydrogen propellant for ~10 (45.7 megagrams ÷ 4.54 megagrams) ST flights is delivered to lunar orbit in one Earth logistic sequence.

Because the Earth logistic sequence presented in figure 17 has a vehicle amortization cost of approximately \$101.6 million, each 10 ST sorties using lunar-derived oxygen and one Earth logistic sequence for the hydrogen propellant represent a cost savings of approximately \$508 million (\$101.6 million × 5). At five ST sortie flights per year, each 2-year period would represent a cost savings of \$508 million. If the cost of the lunar-surface oxygen production facility was \$508 million, it would pay for itself in 2 years.

The indicated programmatic cost savings are perhaps more properly represented by considering a high level of lunar activity (five ST sorties per year) under constrained budgetary conditions. Under these conditions, a \$508 million lunar-surface oxygen production facility — after the first 2 years of operation — could support five ST sorties per year at approximately one-sixth the funding level required if such a facility did not exist.

PARAMETRIC COST ANALYSIS

The MSC Operations Analysis Branch conducted a preliminary survey of the economic feasibility of a lunar-surface oxygen production facility. The analysis and resulting conclusions presented in this section should be considered only an approximation of the actual relationships that would exist, presuming that the assumptions on which the analysis was based are valid. The analysis depends on these assumptions for its consistency; any change to one or more of these assumptions would require that a new analysis be made.

Two related problems were considered: the first was a study of the feasibility of production and usage of oxygen on the lunar surface and the second concerned production on the lunar surface with delivery to and usage in lunar orbit. A third problem, delivery and usage beyond lunar orbit, was considered to be an extension of the lunar-orbit problem and was not separately treated in the survey.

The hydrogen reduction process was used in these analyses because it was believed that it could be more easily defined than the fluorine reduction process as a result of the less severe anticipated requirements for advanced technological development. There is also a possibility that a limited amount of hydrogen can be obtained from the lunar soil, which might offset process losses through facility operation and reactant transfer. However, the fluorine option should not be discarded as a viable process alternative until further description of the facility characteristics is made because the potential oxygen recovery from fluorine reduction of the lunar soil is many times greater than that from hydrogen reduction. Approximately 5 percent of the lunar soil is suitable for hydrogen processing, whereas essentially all the soil would be suitable for fluorine processing (table VII).

A simple linear relationship was established for the lunar-surface problem (fig. 18). For the facility, alternative first-unit costs were estimated at \$100 million,

$400 million, and $1.0 billion, respectively. Each plant was equipped with two lunar-soil movers and associated equipment at an estimated additional cost of $60 million. It was assumed that two ST flights would deliver the plant and supporting equipment to the lunar surface. Because the ST vehicles would not be required to support the lunar-surface oxygen production facility once it was installed, the production cost of the space tugs ($55 million each) was not included in the total cost. Furthermore, it was assumed that no maintenance would be required on the lunar facility during its useful lifetime. It was also assumed that sufficient hydrogen would be recovered from the process to make the facility self-sufficient in hydrogen; that is, no additional hydrogen would be needed to maintain production once the facility was operational.

For the first alternative, the total cost for the facility once installed was approximately $300 million ($100 million for the first-unit facility cost, $60 million for auxiliary equipment, $120 million for launch costs to lunar orbit (124 megagrams at $197/kg), $11 million for ST flight depreciation, and $9 million for miscellaneous). Presuming that there are no operational costs once the facility is installed and assuming that the minimum cost of delivery to the lunar surface using the advanced logistic system (ALS) (the EOS and nuclear stage (NS)) is $544/kg, it can be seen from figure 18 that the facility becomes cost effective at a cumulative production of 115.6 megagrams of oxygen. If the facility can produce this amount in 1 year of operation, it would be 1 year before the system would become cost effective. Assuming that the facility first-unit costs were to rise to $400 million or $1.0 billion with other constraints remaining unchanged, the cost-effective cumulative oxygen production level would increase to 226.8 and 453.6 megagrams, respectively.

The investigation of the case for delivery to and usage of oxygen in lunar orbit presents a more complex analytical problem. The assumptions used for the lunar-surface case were also used for the lunar-orbit case with the following modifications and additions. First, it was assumed that the two space tugs should become part of the facility because they would be used extensively in the delivery of oxygen to lunar orbit. The analysis was conducted for reuse limits of 10, 25, 50, and 100 flights per ST lifetime. Second, two hydrogen fuel depots in lunar orbit at a cost of $14 million each were included for the space tugs. These additions and modifications resulted in an increased installation cost for the $100 million first-unit cost facility from the former total of $300 million for lunar-surface operation to approximately $495 million for lunar-orbit operation. Third, it was assumed that the ST would refuel with hydrogen in lunar orbit and with oxygen on the lunar surface. The hydrogen would be transported from the Earth surface to lunar orbit by the ALS for $197/kg. The ST would land empty (weight of 5443 kg) at the lunar surface except for sufficient hydrogen fuel (2.064 megagrams) to return to lunar orbit. Fourth, ST performance was predicated on the 27.216 megagrams vehicle size with a descent mass ratio of 1.584 and an ascent mass ratio of 1.483. The ST would require 4.150 megagrams of hydrogen and 24.904 megagrams of oxygen propellant per round trip, for a net payload of 10.725 megagrams of oxygen to lunar orbit per round trip. Finally, the reference cost of $197/kg for the ALS delivery to lunar orbit from Earth surface was used as the baseline cost-effectiveness determinant because the cost of production and delivery to lunar orbit from lunar surface could not be cost competitive with the ALS unless it could cost less than this amount. No change in design or first-unit cost of the lunar-surface production facility was hypothesized from the configuration used for the lunar-surface case analysis.

The results of this analysis are shown in figure 19 (which is applicable to the \$100 million first-unit cost lunar-surface production facility only). As can be determined from the curves, the ST with only a 10-reuse capability cannot be cost competitive with the ALS cost of delivery from Earth surface to lunar orbit of \$197/kg because the ST delivery cost to lunar orbit from the lunar surface (not including prorate costs of the lunar-surface production facility) is \$296/kg. If the ST lifetime can be extended to 25, 50, or even 100 reuses, the cost of ST delivery can be reduced to \$164/kg, \$120/kg, and \$98/kg, respectively. This cost is independent of the facility cost per se. The facility cost is a decreasing "delta cost" to be added to the delivery cost as a function of the amount of oxygen delivered to lunar orbit.

The effect of decreasing the facility cost as a function of the amount of oxygen produced and delivered to lunar orbit can be seen in figure 19. For the \$100 million first-unit cost facility, the total facility cost determines the cost-effective cumulative oxygen delivery levels for the various predicted ST flight lifetimes. At 25 reuses per ST, the cost per kilogram of oxygen delivered approaches \$197/kg at ~2950 megagrams delivered to lunar orbit (that is, the cost of delivery, \$164/kg, plus the amortized cost of the facility, \$34.5/kg, equals the total cost, \$198.5/kg). Similarly, the delivery levels for the 50 and 100 ST reuse cases are also depicted.

The effect of increasing the facility cost from \$100 million to \$400 million or \$1.0 billion would naturally increase the cumulative oxygen delivery levels (for all three reuse cases) required to reach the break-even point. These calculations, although not included in figure 19, show break-even quantities for the \$400 million first-unit cost facility to be 5080, 2130, and 1680 megagrams of oxygen delivered to lunar orbit for the 25, 50, and 100 ST reuse cases, respectively. Similar calculations for the \$1.0 billion first-unit cost facility show these rates to be 3760 and 2360 megagrams of oxygen delivered to lunar orbit, respectively, for the 50 and 100 ST reuse cases. In all these case analyses for lunar-orbit delivery, it should be remembered that ~1.05 kilograms of oxygen for ST propellant usage had to be produced in addition to each kilogram of oxygen delivered to lunar orbit.

MISSION PLANNING AND SEQUENCING ANALYSIS

To evaluate the economic advantages of using lunar-derived oxygen instead of Earth-supplied oxygen, a preliminary logistic model had to be generated. In this logistic model, payloads were delivered to different destinations by using combinations of vehicles and vehicle capabilities. It was quickly realized that mission sequencing was necessary to maximize the effective use of transportation systems in minimizing payload delivery costs. This mission sequencing and the associated programmatic data were derived using the following guidelines and assumptions.

1. A lunar-surface oxygen plant exists.

2. A 22.7-megagram-payload EOS is used as a baseline vehicle for analysis simplification.

3. A CS, for Earth-to-Moon shuttle activities, may exist and was used as one baseline vehicle type.

4. An NS, for Earth-to-Moon shuttle activities, may exist and was used as one baseline vehicle type.

5. An ST, for lunar orbital-surface-orbital activities, may exist and was used as one baseline vehicle type.

6. Vehicles could not transfer fuel from payload volumes; fuel transfer could only be accomplished by fuel depots in Earth orbit, in lunar orbit, and on the lunar surface.

7. The baseline vehicle characteristics are as shown in table VIII.

8. A full burn is when a vehicle that is completely loaded with internal fuel completely expends all internal propellant. If a vehicle uses only 50 percent of the internal fuel capacity, this is regarded as 0.5 full burn for vehicle amortization calculations.

9. The transportation links, basic orbits, and applicable vehicles considered are those shown in figure 20.

10. For the purposes of this preliminary analysis, vehicle costs and uses as listed in table IX were assumed.

The interaction of spacecraft capabilities, spacecraft lifetimes, propellant requirements, and delivered payloads with the Earth/Moon gravitational systems is a very complicated subject requiring expertise for exacting analyses. Adding the use of lunar-derived oxygen as a fuel for applicable liquid-hydrogen/liquid-oxygen-propelled spacecraft increases the complexity.

A preliminary analysis of this complex problem was obtained by generating simplified reference figures from which missions, or segments of missions, could be developed. The missions or mission segments — each called a basic building block (BBB) — were then iteratively used in various combinations to obtain profiles for the effectivity of transportation systems as a function of delivered payloads. Sensitivity graphs of vehicle amortization costs as a function of delivered payloads were then derived from these profiles. These reference figures (figs. 21 to 23), basic building blocks (figs. 24 to 42), profiles (tables X to XVIII), and sensitivity graphs (figs. 43 to 51) are discussed in the following sections.

Reference Figures

Reference figure 1. - The characteristics for the low-Earth-orbit to high-Earth-orbit to low-Earth-orbit portion of a mission for both the CS and NS are shown in figure 21. It was assumed that the CS and NS could use all their respective internal propellant except for sufficient propellant to return the vehicles to their initial starting points in low Earth orbit. Using this rationale, the maximum payload deliverable to high Earth orbit by either vehicle was determined. These maximum payload values and the respective vehicle amortization costs per flight (from table IX) were used in conjunction with the number of required EOS flights and their amortization costs to develop BBB 1.

Reference figure 2. - The low-Earth-orbit to lunar-orbit to high-Earth-orbit to low-Earth-orbit characteristics for both the CS and NS are shown in figure 22. For the low-Earth-orbit to lunar-orbit part of the logistic model, it was assumed that the CS and NS could use all their respective internal propellant except for 0.9 megagram of reserve. From lunar orbit to high Earth orbit, it was assumed that the payload to be delivered to high Earth orbit, by either vehicle, was 181.8 megagrams. From high Earth orbit to low Earth orbit, it was assumed that no payload was transported and that the internal propellant of both vehicles could be completely used. These maximum payload values to lunar orbit, partial payload values to high Earth orbit, and zero payload values to low Earth orbit (and the percentage of a full burn accomplished per vehicle) were used in conjunction with the mass ratios and changing mission sequencing payload requirements to develop basic building blocks 2, 4 to 7, 9 to 13, and 15 to 19.

Reference figure 3. - The lunar surface-to-orbit-to-surface ST cycle for effective transportation of lunar-derived oxygen to lunar orbit is shown in figure 23. This cycle eliminates the unnecessary transportation of Earth-supplied hydrogen all the way to the lunar surface by using a lunar-orbit hydrogen propellant depot. In the ST operational cycle, sufficient hydrogen for one orbit-to-surface-to-orbit cycle is loaded into the ST internal propellant tanks in lunar orbit; when the ST is on the lunar surface, sufficient oxygen for one surface-to-orbit-to-surface cycle is loaded into the ST internal propellant tanks. This cycle, once initiated, continues for the lifetime of the ST as described in the following paragraphs.

Before the descent maneuver, the ST is loaded with sufficient internal propellant (1) to support the descent maneuver and (2) to transport sufficient hydrogen propellant to the lunar surface to support the subsequent ascent maneuver. After landing on the lunar surface, the ST is loaded with oxygen payload and sufficient internal oxygen (1) to support the ascent maneuver and (2) to transport sufficient oxygen propellant to lunar orbit to support the subsequent descent maneuver. As can be seen, this is a bootstrap-type operation.

Numerical iterations resulted in the values presented in figure 23. Note that on the descent maneuver, the ST hydrogen tank has a maximum loading of 4.41 megagrams (3.0 megagrams + 1.41 megagrams) and that on the ascent maneuver, the ST oxygen tank has a maximum loading of 22 megagrams (14.95 megagrams + 7.05 megagrams). The ST concept used for this study allowed a maximum of 4.54 megagrams of hydrogen internal propellant and 22.7 megagrams of oxygen internal propellant. These maximum loadings are therefore within the concept maximums, and the mission sequencing is as follows.

Starting in lunar orbit, the ST is loaded with 8.46 megagrams of internal propellant (7.05 megagrams of oxygen and 1.41 megagrams of hydrogen) for the descent maneuver and 3.0 megagrams of internal hydrogen for the subsequent ascent maneuver. After landing on the lunar surface, the ST is loaded with 18.18 megagrams of oxygen payload and 22 megagrams of oxygen internal propellant. At the completion of the ascent maneuver, the ST has burned the 3.0 megagrams of internal hydrogen and 14.95 megagrams of the internal oxygen. The remaining internal oxygen (7.05 megagrams) is that quantity necessary to support the subsequent ST descent maneuver. The oxygen payload (18.18 megagrams) is transferred from the ST to the lunar-orbit oxygen storage facility, and 4.41 megagrams of hydrogen are transferred from the lunar-orbit hydrogen propellant depot to the ST. The ST is now loaded with 8.46 megagrams of internal propellant, and this sequence is repeated for the lifetime of the ST.

The data used to derive this logistic model and the values derived for figure 23 were used in generating basic building blocks 3, 8, and 14.

Basic Building Blocks

The basic building blocks were generated using the specific impulses, delta velocities, inert vehicle masses, and mass ratios presented in reference figures 1, 2, and 3 (figs. 21 to 23). For example, BBB 2 (fig. 25) depicts the transportation of two space tugs and cryogenic hydrogen to lunar orbit. Each of the two space tugs (inert weight of 9.1 megagrams) contains ~5 megagrams of internal propellant to accommodate any initial lunar orbital maneuver requirements. Included on this BBB are the required number of EOS flights, the type of EOS payload, the cost per EOS flight, the number of CS flights, the type of CS payload, the amortization costs of the EOS and CS, and the total amortization cost. Each BBB contains similar information (as applicable) for the generation of the profiles.

BBB 1 (fig. 24). - Basic building block 1 shows the Earth-surface to high-Earth-orbit to Earth-surface sequence, using an EOS and CS or NS, with ~195 megagrams of oxygen delivered to high Earth orbit and with the CS or NS returned to low Earth orbit. The costs and consumables per mission are given.

BBB 2 (fig. 25). - Basic building block 2 shows the Earth-surface to low-Earth-orbit to lunar-orbit sequence, using an EOS and CS, with a payload of 99.2 megagrams of hydrogen and two space tugs (each 9.09 megagrams of inert weight with 4.54 megagrams of hydrogen and 0.92 megagram of oxygen internal propellant) delivered to lunar orbit by an expended CS. For this part of the mission model, the maximum payload deliverable to lunar orbit by completely using the total CS internal propellant was determined. The costs of this type of activity also were determined. The sequence is as follows.

Seven EOS flights are required to deliver 140 megagrams of hydrogen (7×20 megagrams), nine EOS flights to deliver 204.3 megagrams of oxygen (9×22.7 megagrams), and two EOS flights to deliver two space tugs (14.55 megagrams each) to low Earth orbit. This is a total of 18 EOS flights, which, at $7 million per flight, is a cost of approximately $126 million.

Because the CS has a maximum internal propellant loading of 245.5 megagrams, the maximum payload that the CS can deliver from low Earth orbit to lunar orbit is ~128.3 megagrams. The payload configuration for this particular BBB was selected to be 99.2 megagrams of hydrogen and two space tugs of 14.55 megagrams each. Because the CS completely depletes its full internal propellant loading in delivering this payload, this is one full burn for vehicle amortization costing purposes or $3.6 million.

The empty CS in lunar orbit is used in subsequent blocks to transport payloads from lunar orbit to high or low Earth orbit. Propellant for the CS to accomplish this is obtained by using lunar-derived oxygen and some of the hydrogen delivered to lunar orbit by the CS.

A total cost of \$129.6 million (\$126 million + \$3.6 million) to deliver 128.3 megagrams (99.2 megagrams of hydrogen and 29.1 megagrams of space tugs) can be obtained; when this total cost is divided by the delivered payload, a cost of \$1010/kg of payload delivered is obtained.

BBB 3 (fig. 26). - The lunar orbit-to-surface-to-orbit sequence using an ST and delivering 18.18 megagrams of oxygen to lunar orbit per ST round trip is shown in BBB 3.

A condensation of pertinent data from figure 23 is provided in table XIX, which gives the assumed ST amortization costs as a function of the number of full burns the vehicle was assumed to be capable of accomplishing. These amortization costs were used to generate the mission sequences profile costs. The profile costs were then used to generate the sensitivity graphs. On the sensitivity graphs, the ST amortization cost was selected as the Y-axis variable, which allowed the ST amortization cost to be varied as desired and removed the effect of assuming ST amortization cost.

Table XIX also is a summary of the important variables of ST round-trip flights and was used in the generation of profiles 1 to 9. An explanation of the boxheads used in table XIX is given in the following paragraphs.

Full-burn capability: The full-burn capability is the number of full burns the ST is assumed to be capable of performing.

Cost per full burn: This column shows the total cost of each full burn.

Number of space tugs: This column gives the number of space tugs available in lunar orbit for the round-trips sequence.

H_2 burned per round trip: This is the total quantity of hydrogen consumed by the ST in performing one descent and one ascent as specified in figure 23.

O_2 burned per round trip: This is the total quantity of oxygen consumed by the ST in performing one descent and one ascent.

Number of ST round trips: This is the number of round trips that the ST is assumed to perform.

Total H_2 burned: This column shows the product of the quantity of hydrogen consumed per ST round trip and the number of ST round trips.

Total O_2 burned: This is the product of the quantity of oxygen consumed per ST round trip and the number of ST round trips.

Number of ST full burns used: Because an ST full internal propellant load is 22.7 megagrams of oxygen and 4.54 megagrams of hydrogen, completely expending this 27.24 megagrams of propellant is, by definition, one full ST burn. Completely expending 27.24 megagrams of propellant may occur during 50 ignitions of 9.5 seconds duration or during one ignition of 475 seconds duration. For the full internal loading of 27.24 megagrams, the required 26.54 megagrams is really a 0.97 burn; however, for numerical simplicity, the 0.97 is considered to be 1.0. This column is the product of the number of ST round trips and the propellant consumed divided by the maximum propellant.

Number of ST full burns left: Multiplication of the number of full burns the ST is assumed capable of performing by the number of space tugs available equals the number of ST burns possible. Subtracting the number of ST burns used from the number of ST burns possible equals the number of ST burns remaining. This column shows that value.

BBB 4 (fig. 27). - Basic building block 4 shows the lunar-orbit to high-Earth-orbit to lunar-orbit sequence, using a CS, with 177.3 megagrams of oxygen delivered to high Earth orbit. This BBB enables the evaluation of the effect of transporting 177.3 megagrams of oxygen from lunar orbit to high Earth orbit and then back to lunar orbit. In going from lunar orbit to high Earth orbit, the CS consumes 78.5 megagrams (94 megagrams - 15.5 megagrams) of propellant and delivers 177.3 megagrams of oxygen payload. This indicates that the ratio of delivered-oxygen to consumed-propellant mass is ~2.25 (177.3 megagrams ÷ 78.5 megagrams). Because the 78.5 megagrams of propellant consumed is ~13.0 megagrams of hydrogen and 65.5 megagrams of oxygen, the delivered-oxygen to consumed-hydrogen propellant ratio is ~13.6 (177.3 megagrams ÷ 13.0 megagrams).

The remainder of the basic building blocks contain the same type of logic as described for BBB 1, BBB 2, BBB 3, and BBB 4 and are therefore described in an abbreviated format in the subsequent descriptions.

BBB 5 (fig. 28). - Basic building block 5 depicts an Earth-surface to low-Earth-orbit to lunar-orbit sequence, using an EOS and NS, with 82.7 megagrams of hydrogen and four space tugs delivered to lunar orbit by an expended, but reusable, NS.

BBB 6 (fig. 29). - Basic building block 6 shows the lunar-orbit to high-Earth-orbit to lunar-orbit sequence, using a CS, with 158.7 megagrams of oxygen delivered to high Earth orbit.

BBB 7 (fig. 30). - Basic building block 7 shows the lunar-orbit to high-Earth-orbit to lunar-orbit sequence, using a CS, with 231 megagrams of oxygen delivered to high Earth orbit.

BBB 8 (fig. 31). - Basic building block 8 shows the lunar-orbit to high-Earth-orbit to low-Earth-orbit to Earth-surface sequence, using a CS and EOS, with 256.5 megagrams of oxygen delivered to high Earth orbit and with crew rotation.

BBB 9 (fig. 32). - The lunar-orbit to high-Earth-orbit to low-Earth-orbit to Earth-surface sequence is shown in BBB 9. This BBB uses a CS and EOS to deliver 154 megagrams of oxygen to high Earth orbit; crew rotation is also shown.

BBB 10 (fig. 33). - Basic building block 10 shows the Earth-surface to low-Earth-orbit to lunar-orbit sequence, using an EOS and CS, with 70 megagrams of hydrogen and four space tugs delivered to lunar orbit by an expended, but reusable, CS.

BBB 11 (fig. 34). - Basic building block 11 shows the Earth-surface to low-Earth-orbit to lunar-orbit sequence, using an EOS and CS, with 128.2 megagrams of hydrogen delivered to lunar orbit by an expended, but reusable, CS.

BBB 12 (fig. 35). - Basic building block 12 shows the Earth-surface to low-Earth-orbit to lunar-orbit sequence, using an EOS and NS, with 111.8 megagrams of hydrogen and two space tugs delivered to lunar orbit by an expended, but reusable, NS.

BBB 13 (fig. 36). - Basic building block 13 shows the lunar-orbit to low-Earth-orbit to Earth-surface sequence, using an EOS and CS, with 18.18 megagrams of payload delivered to low Earth orbit by the CS and to the Earth surface by the EOS.

BBB 14 (fig. 37). - Basic building block 14 shows the lunar orbit-to-surface-to-orbit sequence, using an ST, with 9.1 megagrams of payload carried on the round-trip sequence.

BBB 15 (fig. 38). - Basic building block 15 shows the Earth-surface to low-Earth-orbit to lunar-orbit sequence, using an EOS and NS, with 70 megagrams of payload delivered to lunar orbit and with the NS returned to low Earth orbit.

BBB 16 (fig. 39). - The lunar-orbit to low-Earth-orbit to Earth-surface sequence, using an NS and EOS, for crew rotation, is shown in BBB 16.

BBB 17 (fig. 40). - Basic building block 17 shows the lunar-orbit to high-Earth-orbit to low-Earth-orbit to Earth-surface sequence, using an NS and EOS, with 363 megagrams of oxygen delivered to high Earth orbit. Crew rotation is also shown.

BBB 18 (fig. 41). - Basic building block 18 shows the lunar-orbit to high-Earth-orbit to lunar-orbit sequence, using an NS, with 225 megagrams of oxygen delivered to high Earth orbit.

BBB 19 (fig. 42). - Basic building block 19 shows the Earth-surface to low-Earth-orbit to lunar-orbit sequence, using an EOS and NS, with 141 megagrams of hydrogen delivered to lunar orbit.

Profiles

The basic building blocks were used in various combinations to derive nine sequential mission profiles (tables X to XVIII). The approach used in deriving the profiles was to minimize cost and maximize activity yield. The cost of the activity is essentially the type and number of vehicles used and their amortization costs. The yield of the activity is the operation supported or the quantity of oxygen delivered to a specific location in space.

Because it was not possible to maximize the profiles completely in this simple analysis, a third aspect — credits — was included. Credits are simply those unused resources (vehicle flights and consumables) remaining within the profile that are still available for use but that do not represent yield as defined previously.

For each profile, the number of EOS, CS or NS, and ST flights was tabularly summed (debits) as the resource being used, and the oxygen delivered to the desired destination was either tabularly or accummulatively summed as the yield results. Division of the yield by the debits was interpreted to result in transportation cost per payload delivered (dollars per kilogram). This particular method of arriving at a dollars-per-kilogram value allows updating the vehicle amortization costs without requiring the reanalysis of mission sequencing.

To have any bank balance sheet perfectly correct, both the assets and the debits must be considered and balanced. This has been done for each of the nine profiles and the results are presented at the bottom of each table. To avoid controversy, this adjusted dollars cost per payload delivered was not used in any of the effectivity comparisons. The contents of the profiles are explained briefly in the following paragraphs.

Profile 1 (table X). - Profile 1 is a grouping and tabulation of six different basic building blocks for mission analysis and evaluation of the delivery of oxygen to lunar orbit to support 20 lunar orbit-to-surface-to-orbit missions. An EOS, CS, and 10-full-burn ST are used. The costs, consumables, and banker's tally are given.

Three round trips between the Earth surface and lunar orbit, including 20 ST lunar orbit-to-surface-to-orbit sorties, are contained within this profile at a cost of $714 million. This is an effective cost per sortie of $35.7 million ($714 million ÷ 20). If Apollo hardware was used to make 20 lunar-surface landings — at an approximate $450 million per mission — it would cost approximately $9000 million. This operational profile appears cost effective.

Profile 2 (table XI). - Profile 2 is a grouping and tabulation of five different basic building blocks for mission analysis and evaluation of the delivery of oxygen to support an oxygen propellant depot in lunar orbit. An EOS, CS, and 10-full-burn ST are used. The costs, consumables, and banker's tally are given.

This sequencing has an amortization cost of $1174.9 million to deliver 1355.1 megagrams of oxygen propellant to a lunar-orbit propellant depot. This is an effective delivery cost of $867/kg ($1174.9 million ÷ 1355.1 megagrams). Because the amortization cost and delivered payload of figure 17 are $101.6 million and 45.7 megagrams, respectively, the delivery cost of oxygen propellant to lunar orbit (without a lunar-surface oxygen production facility) is approximately $2030/kg ($101.6 million ÷ 45.7 megagrams).

Profiles 3 to 6 (tables XII to XV, respectively). - Profiles 3 to 6 are groupings and tabulations of various building blocks for mission analysis and evaluation of the delivery of oxygen to support an oxygen depot in high Earth orbit. The EOS, CS, and ST are used.

The major variables affecting the cost of lunar-delivered oxygen are the lifetime and cost per flight of the ST. The ST lifetimes used are 10, 20, 40, and 100 full burns for profiles 3, 4, 5, and 6, respectively. The reference cost of each ST ($55 million) was kept constant for this analysis.

Profiles 7 to 9 (tables XVI to XVIII). - Profiles 7 to 9 are groupings and tabulations of various building blocks for mission analysis and evaluation of the delivery of oxygen to support an oxygen depot in high Earth orbit. The EOS, NS, and space tugs are used.

The ST lifetimes used are 10, 20, and 40 full burns for profiles 7, 8, and 9, respectively. Again, the reference ST cost ($55 million) was held fixed.

Sensitivity Graphs

In the profiles presented previously, the ST cost was held constant at $55 million per copy. Because it is not realistic to assume that space tugs with different lifetimes (that is, the number of possible full burns) would have the same cost per copy, a method of correlating ST cost variations to operational and payload delivery costs was developed.

Sensitivity graph for profile 1 (fig. 43). - The cost per sortie in profile 1 was obtained by summing the costs of the EOS, CS, and ST flights and dividing this sum by the number of sorties. This may be expressed as follows.

$$\frac{\text{Cost of EOS flights + cost of CS flights + cost of ST flights}}{\text{number of sorties}} = \frac{\text{cost}}{\text{sortie}}$$

Rearranging this relationship results in

$$\text{Cost of EOS flights + cost of CS flights + cost of ST flights} = \frac{\text{cost}}{\text{sortie}}\,(\text{number of sorties})$$

In this relationship, the number and cost of EOS and CS flights, the number of ST flights, and the number of sorties are held constant. By appropriate manipulation, this relationship may be expressed as a simple linear equation. The manipulation is as follows. Let C_1 represent the cost of EOS and CS flights and C_2 represent the number of sortie flights. Then

$$C_1 + \text{cost of ST flights} = C_2(\text{cost/sortie})$$

Let the cost of ST flights be represented by Y and the cost/sortie be represented by X. This results in the following simple linear equation.

$$C_1 + Y = C_2X$$

This equation is used in figure 43 in the sensitivity graph for profile 1. The vertical and horizontal axis intercepts have been left on figure 43 to enable quick verification or replotting. For this profile, the vertical axis intercept is at -$406 million and the horizontal axis intercept is at $20.3 million per sortie.

The vertical axis has dual scales. The inner scale is the total cost of all ST flights used for the profile. The outer scale is the ST amortization cost per flight. It can be seen that decreasing the ST amortization cost per flight by $1 million reduces the lunar-landing-sortie cost by approximately $2.8 million per sortie. Conversely, increasing the ST amortization cost per flight by $1 million increases the cost per sortie by $2.8 million.

The Earth logistic sequence presented in figure 17 needs to be repeated six times to support 10 ST lunar-landing sorties. At $101.6 million per sequence, $609.6 million would be required for 10 ST sorties. This is equivalent to $60.96 million per sortie. The vertical dashed line at $60.96 million per sortie represents the lunar-landing-sortie cost if a lunar-surface oxygen production facility does not exist.

Sensitivity graphs for profiles 2 to 9 (figs. 44 to 51, respectively). - By substituting the quantity of delivered oxygen (megagrams) and the cost per delivered kilogram for the number of ST flights and the cost per sortie, respectively, the same derivation may be used to obtain a similar linear equation for evaluating the sensitivity graphs for profiles 2 to 9.

The oxygen delivery cost (in dollars per kilogram) and variations as a function of ST costs are illustrated in the sensitivity graphs for profiles 2 to 9 and synopsized in table XX.

CONCLUDING REMARKS AND RECOMMENDATIONS

The following statements constitute a synopsis of the study and related activities on the production and utilization of extraterrestrial consumables.

1. Potential requirements and advantages of using extraterrestrially derived oxygen have been determined.

2. Various levels of oxygen production and plant components have been preliminarily evaluated and their characteristics determined.

3. Investigations to determine conceptual validity and operational characteristics of fluorine and hydrogen extraction techniques have been initiated at the NASA Manned Spacecraft Center and supported at the NASA Lewis Research Center.

4. Simulated lunar material was obtained from the Manned Spacecraft Center Science and Applications Directorate for use in Engineering and Development Directorate process activities.

5. The Engineering and Development Directorate has verified the hydrogen reduction of simulated lunar material. The Lewis Research Center has verified the fluorine reduction of simulated lunar material.

6. The Science and Applications Directorate has performed preliminary investigations on lunar "cuttings" to determine the feasibility of concentrating the ferrous oxides by magnetic separation.

7. The NASA management has been continuously informed of activities progress. Some activities have received publicity.

As a result of the study of the proposed extraterrestrial oxygen production concepts, the following recommendations are made.

1. The hydrogen engineering feasibility activities at the Manned Spacecraft Center should be continued.

2. The fluorine engineering feasibility activities at the Lewis Research Center should be continued.

3. A liaison with the "Working Group on Extraterrestrial Resources" should be established, and other feasible extraction techniques should be evaluated.

4. New study activities to determine the full potential yield of side products and supportable activities made attractive by processes utilization should be commenced.

5. The necessary studies and developments required to support the utilization of extraterrestrial resources should be determined and funded (or performed in-house).

Manned Spacecraft Center
National Aeronautics and Space Administration
Houston, Texas, May 23, 1972
914-43-00-00-72

TABLE I. - CHEMICAL PROCESSING PLANT COMPONENTS FOR THE HYDROGEN OR FLUORINE REDUCTION CONCEPTS

Components	Stored dimensions, m				Volume (each), m^3	Mass (each), kg	Quantity	Total volume, m^3	Total mass, kg
	Width	Height	Depth	Diameter					
Ore-supplying equipment									
LSM	3	2	0.6		3.6	2 300	2	7.2	4 600
Conveyor belts	6	1	.3		1.8	230	2	3.6	460
Terminal funnel	.6	1.2	1.5		1.08	230	2	1.08	460
Processing equipment									
Processing sphere[a]				1.8	3.05	450	3	9.15	1 350
Condenser		3		1	2.36	100	1	2.36	100
Electrolysis unit	1.0	.8	1.0		.8	3 600	1	.8	3 600
Radiator	1.5	1.8	1		2.7	230	1	2.7	230
Liquefier	2.1	2.5	1.2		6.3	4 500	1	6.3	4 500
Magnetic separator[a]	.3	.8	1.2		.28	140	1	.28	140
Electrical power source		6		6	16.94	11 400	1	16.94	11 400
Structure		.3		6	.85	4 500	1	.85	4 500
Processing cylinder		1		6	2.83	140	2	5.66	280
Storage equipment									
Oxygen or hydrogen tanks		.6		6	1.7	280	20	34	5 600
Thermal shades, insulation, and reflectors		3		6	8.47	4 500	1	8.47	4 500
Liquid transfer pumps and lines		3		6	8.47	9 000	1	8.47	9 000
								107.86	50 720

[a]Not necessary for the fluorine process.

TABLE II. - COST AND SCHEDULE OF LUNAR-SURFACE OXYGEN PLANT COMPONENTS

Component	Hydrogen plant			Fluorine plant		
	Quantity	Total cost, millions of dollars	Schedule, months	Quantity	Total cost, millions of dollars	Schedule, months
LSM	2	80	36	2	80	36
Conveyor belts	2	10	18	2	10	18
Terminal funnel	1	2	12	1	2	12
Processing sphere	3	10	24			
Processing cylinder				2	15	48
Condenser	1	1	6	1	1	6
Electrolysis unit	1	40	48	1	50	60
Liquefier	1	40	48	1	40	48
Magnetic separator	1	3	36			
Electrical power[a]						
Solar array	1	250	30			
Nuclear				1	400	60
Structure	1	20	24	1	20	24
O_2 and H_2 storage tanks	20	40	18	20	40	18
Thermal shades	20	10	12	20	10	12
Liquid transfer	2	60	48	2	60	48
Radiator	1	3	18	1	3	18
		569			731	

[a]The two plants could use the same type of electrical power source.

TABLE III. - CHARACTERISTICS OF COMPONENTS NEEDED TO PRODUCE 12 kg OF OXYGEN PER DAY (DAYLIGHT ONLY) BY HYDROGEN OR FLUORINE REDUCTION (LEVEL I)

Component	Reduction process		Mass, kg	Volume, m^3	Cost, millions of dollars
	H_2	F_2			
Pressure vessel	X		18.2 to 27.3	0.03 to 0.04	0.1 to 0.5
Magnetic separator	X		91 to 136.4	.05 to .11	.5 to 1.5
Conveyor belt	X		13.6 to 27.3	.23 to .30	.5 to 1.5
Terminal funnel	X		9.1 to 45.4	.08 to 1.41	.5 to 1.5
H_2 tank (2.27 kg of H_2 included)	X		3.6 to 5.9	.03 to .04	.1 to .5
Condenser	X	X	2.3 to 4.5	.06 to .11	.1 to .5
Electrolysis unit	X	X	22.7 to 45.4	.02 to .03	2.0 to 5.0
Solar array (3 kW/hr)	X	X	91 to 159	.17 to .85	3.0 to 8.0
O_2 tank (gaseous storage)	X	X	13.6 to 36.3	.08 to .11	.2 to 1.0
Insulation	X	X	4.5 to 45.4	.57 to .71	.1 to 1.0
Structure	X	X	9.1 to 45.4	.14 to .57	2.0 to 5.0
F_2 tank (20.5 kg of F_2 included)		X	25 to 38.6	.23 to .25	1.0 to 5.0
K[a] tank (9.1 kg of K included)		X	13.6 to 18.2	.02 to .05	.5 to 2.0
Processing cylinder		X	22.7 to 31.8	.05 to .08	1.0 to 8.0
Hydrogen process totals			278.7 to 578.3	1.46 to 4.28	9.1 to 26.0
Fluorine process totals			204.5 to 424.6	1.34 to 2.76	9.9 to 35.5

[a]Potassium.

TABLE IV. - CHARACTERISTICS OF COMPONENTS NEEDED TO PRODUCE 910 kg of OXYGEN PER DAY (DAYLIGHT ONLY) BY HYDROGEN OR FLUORINE REDUCTION (LEVEL II)

Component	Reduction process		Mass, kg	Volume, m^3	Cost, millions of dollars
	H_2	F_2			
Pressure vessel	X		364 to 540	2.83 to 3.40	3.0 to 7.0
Magnetic separator	X		137 to 182	.14 to .34	1.0 to 3.0
Conveyor belt (2)	X		68 to 182	2.27 to 3.40	2.0 to 4.0
Terminal funnel	X		18 to 64	.08 to 1.42	.5 to 1.5
H_2 tank no. 1 (4.5 kg of H_2 included)	X		9 to 13	.05 to .08	.5 to 1.0
H_2 tank no. 2 (60 kg of H_2 included)	X		100 to 137	1.42 to 1.47	1.0 to 1.5
O_2 tank no. 1 (for 910 kg of O_2 storage)	X	X	80 to 130	.80 to .85	2.0 to 3.0
O_2 tank no. 2 (for 18 000 kg of O_2 storage)	X	X	1 300 to 1 800	28.30 to 61.00	5.0 to 10.0
Condenser	X	X	5 to 9	.56 to 1.98	1.0 to 3.0
Electrolysis unit	X	X	1 820 to 3 640	2.83 to 5.68	25.0 to 35.0
Solar array	X	X	12 700 to 18 200	14.20 to 85.00	250.0 to 450.0
Insulation	X	X	46 to 227	.71 to 3.54	2.0 to 4.0
Structure	X	X	460 to 1 820	5.68 to 22.70	10.0 to 30.0
Liquefier	X	X	3 180 to 5 400	3.40 to 5.10	10.0 to 20.0
Radiator	X	X	90 to 182	1.42 to 1.98	3.0 to 6.0
LSM	X	X	900 to 2 270	14.20 to 25.40	30.0 to 50.0
F_2 tank (91 kg of F_2 included)		X	115 to 159	.85 to 1.42	3.0 to 6.0
K tank (38.2 kg of K included)		X	55 to 73	.11 to .22	1.0 to 3.0
Processing cylinder		X	137 to 272	.28 to .37	5.0 to 10.0
Hydrogen process totals			21 277 to 34 796	78.89 to 223.34	346.0 to 629.0
Fluorine process totals			20 888 to 34 182	72.62 to 215.24	347.0 to 630.0

TABLE V. - CHARACTERISTICS OF COMPONENTS NEEDED TO PRODUCE 1820 kg OF OXYGEN PER DAY (DAYLIGHT ONLY) BY HYDROGEN OR FLUORINE REDUCTION (LEVEL III)

Component	Reduction process		Mass, kg	Volume, m^3	Cost, millions of dollars
	H_2	F_2			
Pressure vessel (2)	X		727 to 1 090	5.77 to 6.80	6.0 to 14.0
Magnetic separator (2)	X		273 to 363	.28 to .34	2.0 to 3.0
Conveyor belt (4)	X		137 to 368	4.53 to 6.80	4.0 to 8.0
Terminal funnel (2)	X		37 to 64	.17 to 2.83	1.0 to 3.0
H_2 tank no. 1 (9 kg of H_2 included)	X		14 to 18	.11 to .14	1.0 to 1.5
H_2 tank no. 2 (90 kg of H_2 included)	X		146 to 168	2.83 to 2.95	2.0 to 3.0
O_2 tank no. 1 (for 1820 kg of O_2 storage)	X	X	159 to 182	1.58 to 1.70	4.0 to 6.0
O_2 tank no. 2 (for 36 000 kg of O_2 storage)	X	X	2 500 to 3 600	130.00 to 200.00	7.0 to 13.0
Condenser (2)	X	X	9 to 18	1.13 to 3.96	2.0 to 4.0
Electrolysis unit	X	X	2 270 to 3 640	2.83 to 5.67	35.0 to 45.0
Solar array	X	X	19 100 to 25 000	28.30 to 170.00	400.0 to 550.0
Insulation	X	X	136 to 454	2.13 to 7.08	4.0 to 10.0
Structure	X	X	682 to 2 270	8.49 to 34.00	13.0 to 35.0
Liquefier	X	X	7 270 to 9 100	6.79 to 10.20	20.0 to 40.0
Radiator	X	X	136 to 182	1.98 to 2.83	5.0 to 8.0
LSM (2)	X	X	1 820 to 4 540	28.30 to 51.00	60.0 to 100.0
F_2 tank (182 kg of F_2 included)		X	227 to 318	1.70 to 2.83	6.0 to 12.0
K tank (75.51 kg of K included)		X	109 to 146	.23 to .45	2.0 to 5.0
Processing cylinder (2)		X	272 to 545	.56 to .73	10.0 to 20.0
Hydrogen process totals			35 416 to 51 057	225.22 to 506.30	566.0 to 843.5
Fluorine process totals			34 690 to 49 995	214.02 to 490.45	568.0 to 848.0

TABLE VI. - RESULTS OF ST PROPULSION SYSTEM QUESTIONNAIRE

Question	Answer
1. How many times could a liquid-oxygen/liquid-hydrogen propulsion system perform descent and ascent maneuvers similar to those of the lunar module on an Apollo mission?	1. This is a very difficult and complicated question. To avoid a lengthy dissertation, the answer, with many modifiers, is 25 to 50.
2. What is the level of refurbishment or repair required for various numbers of total ST flights? Examples: Full burns — Refurbishment or repair 10 — None, electronics system verification 50 — In-space or lunar-surface replacement of short-life components 100 — Return to Earth surface for overhaul and repair	2. This is too complicated a question to be answered in depth at this time.
3. What components have the highest likelihood of failure?	3. The components most likely to fail are the valves (through leakage), the pumps and turbines (gears and bearings), and the thrust chamber (between 10 000 and 20 000 seconds of lifetime).
4. What is the difficulty in replacing components that might fail?	4. Given the incorporation of the replacement philosophy in the design of the vehicle, the difficulties are astronaut activities, component accessibility, leakage after replacement, and system performance after replacement.
5. What technological problems appear to govern the useful life of a liquid-oxygen/liquid-hydrogen propulsion system for lunar surface/orbital operations?	5. The thrust chamber cooling tubes (thermal shock) and the bearings and gear trains (four or five unlubricated bearings, three gear trains, and a 30 000-rpm turbine) may cause problems. Some development may be necessary in thrust chamber materials, seals materials, and bearing materials or lubricants.
6. Are the lunar landings and dust blast clouds expected to have any severe life degradation effect on the propulsion system?	6. No.
7. From past testing activities on liquid-oxygen/liquid-hydrogen propulsion systems:	7.
a. What is the longest continuous burn on a single system?	a. The longest continuous burn was 470 sec in a ground test (vehicle system test). (MSC in-house data indicate that a round-trip ST flight may require a total engine burn time of ~475 sec).
b. What replacement or repair was necessary after this burn?	b. No replacements or repairs were necessary.
c. What has been the maximum number of restarts of a liquid-oxygen/liquid-hydrogen propulsion system?	c. The maximum number is 21 or 22 (engine qualifications test goal).
d. What replacement or repair was necessary after these burns?	d. The engine was torn down and inspected for wear and tear. No problems were evident.
8. Where is the crossover point at which new technology is needed to ensure successful full internal propellant burns without any inspection except automatic electronics systems verification?	8. Present crossover points are 1 to 5 hr engine time, 20 to 300 restarts, and 10 full burns.

TABLE VII. - POTENTIAL LUNAR-SURFACE OXYGEN-RECOVERY COMPARISON BETWEEN HYDROGEN AND FLUORINE PROCESSING[a]

Lunar-surface soil composition	Hydrogen reduction feasible	Fluorine reduction feasible
60-percent SiO_2	No	Yes
20-percent Al_2O_3	No	Yes
15-percent CaO and MgO	No	Yes
5-percent FeO	Yes	Yes

[a]The hydrogen reduction process would necessitate the electrolysis of water condensed from the steam generated when gaseous hydrogen is combined with heated ferric oxide. The fluorine process would necessitate the electrolysis of the metal fluorides resulting from the combination of fluorine with metal oxides causing a simultaneous release of pure oxygen.

TABLE VIII. - BASELINE VEHICLE CHARACTERISTICS

EOS	CS	NS	ST
Payload			
22.7-Mg payload to Earth orbit	27.3-Mg inert weight 245-Mg maximum fuel load 5 to 1 use ratio of O_2 to H_2	40-Mg inert weight 136-Mg maximum fuel load	9.1-Mg inert weight 27.3-Mg maximum fuel load
Cost			
$7 million/full burn	$3.6 million/full burn plus 11 EOS flights at $7 million/flight to refuel; total cost of $80.6 million/flight ($77 million + $3.6 million)	$19 million/full burn plus 6 EOS flights at $7 million/flight to refuel; total cost of $61 million/flight ($42 million + $19 million)	$5.5 million/full burn[a] plus cost of delivery to lunar orbit and refueling costs

[a]$5.5 million/full burn for 10 full burns; $2.75 million/full burn for 20 full burns; et cetera.

TABLE IX. - COST AND USAGE OF VEHICLES

Vehicle	Development cost, billions of dollars	Copy cost, millions of dollars	No. of flights per copy	Vehicle cost per complete internal propellant expenditure, millions of dollars
NS	1.4	190	10	19
CS	1.3	36	10	3.6
ST	1.5	55	10	5.5
EOS	12.5	700	100	7.0

TABLE X. - PROFILE 1 — LUNAR-ORBIT SUPPORT, 20 SURFACE SORTIES, CS, 10-FULL-BURN ST[a]

BBB	No. of EOS flights per BBB	No. of CS flights per BBB	Lunar-orbit H_2 delivered per BBB, Mg	Lunar-orbit H_2 used per BBB, Mg	Total lunar-orbit H_2 remaining, Mg	No. of ST flights used per BBB	No. of ST flights remaining	Lunar-surface O_2 used by ST per BBB, Mg	Lunar-orbit O_2 used by CS per BBB, Mg	Total O_2 in lunar orbit, Mg	Lunar-orbit O_2 used by ST per BBB, Mg	No. of surface sorties
2	18	1	99.2		99.2	0	20	0	0	0	0	
3	0	0	0	39.69	59.51	9	11	198	0	163.6	0	
14	0	0	0	18.18	41.33	4	7	0	0	72.8	90.8	4
13	1	.3	0	11.95	29.38	0	7	0	59.8	13.0	0	
10	18	1	70	0	99.38	0	47	0	0	13.0	0	
3	0	0	0	39.69	59.89	9	38	198	0	176.6	0	
3	0	0	0	39.69	20.40	9	29	198	0	340.2	0	
14	0	0	0	4.54	15.86	1	27	0	0	317.5	22.7	1
13	1	.3	0	11.95	3.91	0	27	0	59.8	257.7	0	
11	17	1	128.3	0	132.21	0	27	0	0	257.7	0	
14	0	0	0	45.40	86.81	10	17	0	0	30.7	227	10
3	0	0	0	39.69	47.32	9	8	198	0	194.3	0	
14	0	0	0	22.70	24.62	5	4	0	0	80.8	113.5	5
13	1	.3	0	11.95	12.67	0	4	0	59.8	21.0	0	
Total	[b]56	[b]3.9			[c]12.67	[b]56	[c]4			[c]21.0		[b]20
Cost[d]	×7	×3.6			[e]×2030	×5.5	×5.5			[e]×2030		
Total cost[d]	392	14.04			25.72	308	22			42.63		

[a]The banker's tally for profile 1 is as follows:

Debits

Total cost of EOS flights = $392.00 million
Total cost of CS flights = 14.04 million
Total cost of ST flights = 308.00 million
Total $714.04 million

Cost/sortie without using credits

$714.04 ÷ 20 sorties = $35.7 million/sortie

Credits

Value of H_2 remaining in lunar orbit = $25.72 million
Value of O_2 remaining in lunar orbit = 42.63 million
Value of ST burns remaining = 22.00 million
Total $90.35 million

Debits: $714.04 million
Credits: 90.35 million
Adjusted cost: $623.69 million

Cost/sortie using credits

$623.69 million ÷ 20 sorties = $31.2 million/sortie

[b]Tabularly summed. [c]Accumulatively summed. [d]In millions of dollars. [e]Dollars/kg.

TABLE XI. - PROFILE 2 — LUNAR-ORBIT SUPPORT, CS, 10-FULL-BURN ST[a]

BBB	No. of EOS flights per BBB	No. of CS flights per BBB	Lunar-orbit H_2 delivered per BBB, Mg	Lunar-orbit H_2 used per BBB, Mg	Total lunar-orbit H_2 remaining, Mg	No. of ST flights used per BBB	No. of ST flights remaining	Lunar-surface O_2 used by ST per BBB, Mg	Lunar-orbit O_2 used by CS per BBB, Mg	Total O_2 in high Earth orbit per BBB, Mg	Total O_2 in lunar orbit, Mg
2	18	1	99.2	0	99.2	0	20	0	0	0	0
3	0	0	0	57.33	41.87	13	7	286	0	0	236.3
13	1	.3	0	11.95	29.92	0	7	0	59.8	0	176.5
10	18	1	70	0	99.92	0	47	0	0	0	176.5
3	0	0	0	57.33	42.59	13	34	286	0	0	412.8
13	1	.3	0	11.95	30.64	0	34	0	59.8	0	353.0
11	17	1	128.3	0	158.94	0	34	0	0	0	353.0
3	0	0	0	57.33	101.61	13	21	286	0	0	589.3
3	0	0	0	57.33	44.28	13	8	286	0	0	825.6
13	1	.3	0	11.95	32.33	0	8	0	59.8	0	765.8
10	18	1	70	0	102.33	0	48	0	0	0	765.8
3	0	0	0	57.33	45.00	13	35	286	0	0	1002.1
13	1	.3	0	11.95	33.05	0	35	0	59.8	0	942.3
11	17	1	128.3	0	161.35	0	35	0	0	0	942.3
3	0	0	0	57.33	104.02	13	22	286	0	0	1178.6
3	0	0	0	57.33	46.69	13	9	286	0	0	1414.9
13	1	.3	0	11.95	34.74	0	9	0	59.8	0	1355.1
Total	[b]93	[b]6.5			[c]34.74	[b]91	[c]9				[c]1355.1
Cost[d]	×7	×3.6			[e]×2030	×5.5	×5.5				
Total cost[d]	651	23.4			70.5	500.5	49.5				

[a]The banker's tally for profile 2 is as follows:

Debits

Total cost of EOS flights = $651.0 million
Total cost of CS flights = 23.4 million
Total cost of ST flights = 500.5 million
Total $1174.9 million

Dollars/kg without using credits

$1174.9 million ÷ 1355.1 Mg = $867/kg

Credits

Value of H_2 remaining in lunar orbit = $70.5 million
Value of O_2 remaining in lunar orbit = 0 million
Value of ST burns remaining = 49.5 million
Total $120.0 million

Debits: $1174.9 million
Credits: 120.0 million
Adjusted cost: $1054.9 million

Dollars/kg using credits

$1054.9 million ÷ 1355.1 Mg = $778.5/kg

[b]Tabularly summed. [c]Accumulatively summed. [d]In millions of dollars. [e]Dollars/kg.

TABLE XII. - PROFILE 3 — PLANETARY SUPPORT, CS, 10-FULL-BURN ST[a]

BBB	No. of EOS flights per BBB	No. of CS flights per BBB	Lunar-orbit H_2 delivered per BBB, Mg	Lunar-orbit H_2 used per BBB, Mg	Total lunar-orbit H_2 remaining, Mg	No. of ST flights used per BBB	No. of ST flights remaining	Lunar-surface O_2 used by ST per BBB, Mg	Lunar-orbit O_2 used by CS per BBB, Mg	Lunar O_2 in high Earth orbit per BBB, Mg	Total O_2 in lunar orbit, Mg
2	18	1	99.2	0	99.2	0	20	0	0	0	0
3	0	0	0	57.33	41.87	13	7	286	0	0	236.3
9	1	.4	0	16.45	25.42	0	7	0	82.3	154	0
10	18	1	70	0	95.42	0	47	0	0	0	0
3	0	0	0	57.33	38.09	13	34	286	0	0	236.3
9	1	.4	0	16.45	21.64	0	34	0	82.3	154	0
11	17	1	128.3	0	149.94	0	34	0	0	0	0
3	0	0	0	57.33	92.61	13	21	286	0	0	236.3
3	0	0	0	57.33	35.28	13	8	286	0	0	472.6
6	0	.33	0	13.18	22.10	0	8	0	65.9	158.7	248.0
9	1	.4	0	16.45	5.65	0	8	0	82.3	154	11.7
Total	[b]56	[b]4.53			[c]5.65	[b]52	[c]8			[b]620.7	[c]11.7
Cost[d]	×7	×3.6			[e]×2030	×5.5	×5.5				[e]×2030
Total cost[d]	392	16.3			11.47	286	44				23.75

[a]The banker's tally for profile 3 is as follows:

Debits

Total cost of EOS flights = $392.0 million
Total cost of CS flights = 16.3 million
Total cost of ST flights = 286.0 million
Total $694.3 million

Dollars/kg without using credits

$694.3 million ÷ 620.7 Mg = $1118/kg

Credits

Value of H_2 remaining in lunar orbit = $11.47 million
Value of O_2 remaining in lunar orbit = 23.75 million
Value of ST burns remaining = 44.00 million
Total $79.22 million

Debits: $694.3 million
Credits: 79.2 million
Adjusted cost: $615.1 million

Dollars/kg using credits

$615.1 million ÷ 620.7 Mg = $991/kg

[b]Tabularly summed. [c]Accumulatively summed. [d]In millions of dollars. [e]Dollars/kg.

TABLE XIII. - PROFILE 4 — PLANETARY SUPPORT, CS, 20-FULL-BURN ST[a]

BBB	No. of EOS flights per BBB	No. of CS flights per BBB	Lunar-orbit H_2 delivered per BBB, Mg	Lunar-orbit H_2 used per BBB, Mg	Total lunar-orbit H_2 remaining, Mg	No. of ST flights used per BBB	No. of ST flights remaining	Lunar-surface O_2 used by ST per BBB, Mg	Lunar-orbit O_2 used by CS per BBB, Mg	Lunar-orbit O_2 to high Earth orbit per BBB, Mg	Total O_2 in lunar orbit, Mg
Initial sequencing											
2	18	1	99.2	0	99.2	0	40	0	0	0	0
3	0	0	0	74.97	24.23	17	23	374	0	0	309
9	1	.4	0	16.45	7.78	0	23	0	82.3	154	72.7
11	17	1	128.3	0	136.08	0	23	0	0	0	72.7
3	0	0	0	74.97	61.11	17	6	374	0	0	381.7
8	1	.6	0	22.38	38.73	0	6	0	112.1	256.5	13.1
Repeat initial sequencing once											
Two-sequence subtotals	74	6			77.46	68	12			821	26.2
Final sequencing											
2	18	1	99.2	0	176.66	0	52	0	0	0	26.2
3	0	0	0	74.97	101.69	17	35	374	0	0	335.2
9	1	.4	0	16.45	85.24	0	35	0	82.3	154	98.9
11	17	1	128.3	0	213.54	0	35	0	0	0	98.9
3	0	0	0	74.97	138.57	17	18	374	0	0	407.9
3	0	0	0	74.97	63.60	17	1	374	0	0	716.9
7	0	.5	0	18.40	45.20	0	1	0	92.1	231	393.8
8	1	.6	0	22.38	22.82	0	1	0	112.1	256.5	25.2
Total	[b]111	[b]9.5			[c]22.82	[b]119	[c]1			[b]1462.5	[c]25.2
Cost[d]	×7	×3.6			[e]×2030	×2.75	×2.75				[e]×2030
Total cost[d]	777	34.2			46.32	327	2.75				51.16

[a]The banker's tally for profile 4 is as follows:

Debits

Total cost of EOS flights = \$777.0 million
Total cost of CS flights = 34.2 million
Total cost of ST flights = 327.0 million
Total \$1138.2 million

Dollars/kg without using credits

\$1138.2 million ÷ 1462.5 Mg = \$778/kg

Credits

Value of H_2 remaining in lunar orbit = \$46.32 million
Value of O_2 remaining in lunar orbit = 51.16 million
Value of ST burns remaining = 2.75 million
Total \$100.23 million

Debits: \$1138.2 million
Credits: 100.2 million
Adjusted cost: \$1038.0 million

Dollars/kg using credits

\$1038 million ÷ 1462.5 Mg = \$710/kg

[b]Tabularly summed. [c]Accumulatively summed. [d]In millions of dollars. [e]Dollars/kg.

TABLE XIV. - PROFILE 5 — PLANETARY SUPPORT, CS, 40-FULL-BURN ST[a]

BBB	No. of EOS flights per BBB	No. of CS flights per BBB	Lunar-orbit H_2 delivered per BBB, Mg	Lunar-orbit H_2 used per BBB, Mg	Total lunar-orbit H_2 remaining, Mg	No. of ST flights used per BBB	No. of ST flights remaining	Lunar-surface O_2 used by ST per BBB, Mg	Lunar-orbit O_2 used by CS per BBB, Mg	Lunar-orbit O_2 to high Earth orbit per BBB, Mg	Total O_2 in lunar orbit, Mg
Initial sequencing											
2	18	1	99.2	0	99.2	0	80	0	0	0	0
3	0	0	0	74.97	24.23	17	63	374			30.9
9	1	.4	0	16.45	7.78	0	63		82.3	154	72.7
11	17	1	128.3	0	136.08	0	63				72.7
3	0	0	0	74.97	61.11	17	46	374			381.7
9	1	.4	0	16.45	44.66	0	46		82.3	154	145.4
11	17	1	128.3	0	172.96	0	46				145.4
3	0	0	0	74.97	97.99	17	29	374			454.4
3	0	0	0	74.97	23.02	17	12	374			763.4
8	1	.6	0	22.38	.64	0	12		112.1	256.5	394.8
Repeat initial sequencing twice											
Three-sequence subtotal	165	13.2			1.92	204	36			1693.5	1184.4
Final sequencing											
11	17	1	128.3	0	130.22	0	36				1184.4
7	0	.5	0	18.40	111.82	0	36		92.1	231	861.3
7	0	.5	0	18.40	93.42	0	36		92.1	231	538.2
8	1	.6	0	22.38	71.04	0	36		112.1	256.5	169.6
11	17	1	128.3	0	199.34	0	36				169.6
3	0	0	0	74.97	124.37	17	19	374			478.6
3	0	0	0	74.97	49.40	17	2	374			787.6
7	0	.5	0	18.40	31.00	0	2		92.1	231	464.5
8	1	.6	0	22.38	8.62	0	2		112.1	256.5	95.9
Total Cost[d]	[b]201 ·7	[b]17.9 ·3.6			[c]8.62 [e]·2030	[b]238 ·1.38	[c]2 ·1.38			[b]2899.5	[c]95.9 [e]·2030
Total cost[d]	1407	64.4			17.49	328	2.76				194.6

[a]The banker's tally for profile 5 is as follows:

Debits

Total cost of EOS flights - $1407.0 million
Total cost of CS flights - 64.4 million
Total cost of ST flights - 328.0 million
Total $1799.4 million

Dollars/kg without using credits

$1799.40 million ÷ 2899.5 Mg - $621/kg

Credits

Value of H_2 remaining in lunar orbit - $17.49 million
Value of O_2 remaining in lunar orbit - 194.60 million
Value of ST burns remaining - 2.76 million
Total $214.85 million

Debits: $1799.40 million
Credits: 214.85 million
Adjusted cost: $1584.55 million

Dollars/kg using credits

$1584.55 million ÷ 2899.5 Mg - $546/kg

[b]Tabularly summed. [c]Accumulatively summed. [d]In millions of dollars. [e]Dollars/kg.

TABLE XV. - PROFILE 6 — PLANETARY SUPPORT, CS, 100-FULL-BURN ST[a]

BBB	No. of EOS flights per BBB	No. of CS flights per BBB	Lunar-orbit H_2 delivered per BBB, Mg	Lunar-orbit H_2 used per BBB, Mg	Total lunar-orbit H_2 remaining, Mg	No. of ST flights used per BBB	No. of ST flights remaining	Lunar-surface O_2 used by ST per BBB, Mg	Lunar-orbit O_2 used by CS per BBB, Mg	Lunar-orbit O_2 to high Earth orbit per BBB, Mg	Total O_2 in lunar-orbit, Mg
2	18	1	99.2	0	99.2	0	200	0	0	0	0
3	0	0	0	74.97	24.23	17	183	374	0	0	309
9	1	.4	0	16.45	7.78	0	183	0	82.3	154	72.7
11	17	1	128.3	0	136.08	0	183	0	0	0	72.7
3	0	0	0	74.97	61.11	17	166	374	0	0	381.7
8	1	.6	0	22.38	38.73	0	166	0	112.1	256.5	13.1
11	17	1	128.3	0	167.03	0	166	0	0	0	13.1
3	0	0	0	74.97	92.06	17	149	374	0	0	322.1
9	1	.4	0	16.45	75.61	0	149	0	82.3	154	85.8
11	17	1	128.3	0	203.91	0	149	0	0	0	85.8
3	0	0	0	74.97	128.94	17	132	374	0	0	394.8
3	0	0	0	74.97	53.97	17	115	374	0	0	703.8
7	0	.5	0	18.40	35.57	0	115	0	92.1	231	380.7
8	1	.6	0	22.38	13.19	0	115	0	112.1	256.5	12.1
Total	[b]73	[b]6.5			[c]13.19	[b]85	[c]115			[b]1052	[c]12.1
Cost[d]	×7	×3.6			[e]×2030	×0.55	×0.55				[e]×2030
Total cost[d]	511	23.4			26.7	46.8	63.2				24.5

[a]The banker's tally for profile 6 is as follows:

Debits

Total cost of EOS flights = \$511.0 million
Total cost of CS flights = 23.4 million
Total cost of ST flights - 46.8 million
Total \$581.2 million

Dollars/kg without using credits

\$581.2 million ÷ 1052 Mg = \$522/kg

Credits

Value of H_2 remaining in lunar orbit = \$26.7 million
Value of O_2 remaining in lunar orbit = 24.5 million
Value of ST burns remaining = 63.2 million
Total \$114.4 million

Debits: \$581.2 million
Credits: 114.4 million
Adjusted cost: \$466.8 million

Dollars/kg using credits

\$466.8 million ÷ 1052 Mg = \$433/kg

[b]Tabularly summed. [c]Accumulatively summed. [d]In millions of dollars. [e]Dollars/kg.

TABLE XVI. - PROFILE 7 — PLANETARY SUPPORT, NS, 10-FULL-BURN ST[a]

BBB	No. of EOS flights per BBB	No. of NS flights per BBB	Lunar-orbit H_2 delivered per BBB, Mg	Lunar-orbit H_2 used per BBB, Mg	Total lunar-orbit H_2 remaining, Mg	No. of ST flights used per BBB	No. of ST flights remaining	Lunar-surface O_2 used by ST per BBB, Mg	Total O_2 in high Earth orbit per BBB, Mg	Total O_2 in lunar orbit, Mg
12	13	1	111.8	0	111.8	0	20	0	0	0
3	0	0.	0	57.33	46.15	13	7	286	0	236.3
16	1	.22	0	29.6	16.55	0	7	0	0	236.3
12	13	1	111.8	0	128.35	0	27	0	0	236.3
3	0	0	0	57.33	71.02	13	14	286	0	472.6
16	1	.22	0	29.6	41.42	0	14	0	0	472.6
19	13	1	141	0	182.42	0	14	0	0	472.6
3	0	0	0	57.33	125.09	13	1	286	0	708.9
17	1	.85	0	101	24.09	0	1	0	363	345.9
12	13	1	111.8	0	135.89	0	21	0	0	345.9
3	0	0	0	57.33	78.56	13	8	286	0	582.2
16	1	.22	0	29.6	48.96	0	8	0	0	582.2
19	13	1	141	0	189.96	0	8	0	0	582.2
18	0	.48	0	65.4	124.56	0	8	0	225	357.2
17	1	.85	0	101	23.56	0	8	0	357.2	0
Total	[b]70	[b]7.84			[c]23.56	[b]52	[c]8		[b]945.2	0
Cost[d]	×7	×19			[e]×1270	×5.5	×5.5			
Total cost[d]	490	149.0			29.92	286	44			

[a]The banker's tally for profile 7 is as follows:

Debits

Total cost of EOS flights = \$490.0 million
Total cost of NS flights = 149.0 million
Total cost of ST flights = 286.0 million
Total \$925.0 million

Dollars/kg without using credits

\$925.0 million ÷ 945.2 Mg = \$978/kg

Credits

Value of H_2 remaining in lunar orbit = \$29.9 million
Value of O_2 remaining in lunar orbit = 0 million
Value of ST burns remaining = 44.0 million
Total \$73.9 million

Debits: \$925.0 million
Credits: 73.9 million
Adjusted cost: \$851.1 million

Dollars/kg using credits

\$851.1 million ÷ 945.2 Mg = \$900/kg

[b]Tabularly summed. [c]Accumulatively summed. [d]In millions of dollars. [e]Dollars/kg.

TABLE XVII. - PROFILE 8 — PLANETARY SUPPORT, NS, 20-FULL-BURN ST[a]

BBB	No. of EOS flights per BBB	No. of NS flights per BBB	Lunar-orbit H_2 delivered per BBB, Mg	Lunar-orbit H_2 used per BBB, Mg	Total lunar-orbit H_2 remaining, Mg	No. of ST flights used per BBB	No. of ST flights remaining	Lunar-surface O_2 used by ST per BBB, Mg	Total O_2 in lunar orbit, Mg	Total O_2 in high Earth orbit per BBB, Mg
12	13	1	111.8	0	111.8	0	40	0	0	0
3	0	0	0	39.69	72.11	9	31	198	163.6	0
16	1	.22	0	29.6	42.51	0	31	0	163.6	0
19	13	1	141	0	183.51	0	31	0	163.6	0
3	0	0	0	39.69	143.82	9	22	198	327.2	0
3	0	0	0	39.69	104.13	9	13	198	490.8	0
17	1	.85	0	101	3.13	0	13	0	127.8	363
19	13	1	141	0	144.13	0	13	0	127.8	363
3	0	0	0	39.69	104.44	9	4	198	291.4	363
17	1	.85	0	101	3.44	0		0	0	654.4
Total Cost[d]	[b]42 ×7	[b]4.9 ×19			[c]3.44 [e]×1270	[b]36 ×2.75	[c]4 ×2.75			[c]654.4
Total cost[d]	294	93.1			4.37	99	11			

[a]The banker's tally for profile 8 is as follows:

Debits

Total cost of EOS flights =	\$294.0 million
Total cost of NS flights -	93.1 million
Total cost of ST flights -	99.0 million
Total	\$486.1 million

Dollars/kg without using credits

\$486.1 million ÷ 654.4 Mg - \$742/kg

Credits

Value of H_2 remaining in lunar orbit =	\$4.37 million
Value of O_2 remaining in lunar orbit =	0 million
Value of ST burns remaining =	11.00 million
Total	\$15.37 million

Debits:	\$486.1 million
Credits:	15.4 million
Adjusted cost:	470.7 million

Dollars/kg using credits

\$470.7 million ÷ 654.4 Mg = \$719/kg

[b]Tabularly summed. [c]Accumulatively summed. [d]In millions of dollars. [e]Dollars/kg.

TABLE XVIII. - PROFILE 9 — PLANETARY SUPPORT, NS, 40-FULL-BURN ST[a]

BBB	No. of EOS flights per BBB	No. of NS flights per BBB	Lunar-orbit H_2 delivered per BBB, Mg	Lunar-orbit H_2 used per BBB, Mg	Total lunar-orbit H_2 remaining, Mg	No. of ST flights used per BBB	No. of ST flights remaining	Lunar-orbit O_2 used by ST per BBB, Mg	Total O_2 in lunar orbit, Mg	Total O_2 in high Earth orbit per BBB, Mg
12	13	1	111.8	0	111.8	0	80	0	0	0
3	0	0	0	57.33	54.47	13	67	286	236.3	0
16	1	.22	0	29.6	28.87	0	67	0	236.3	0
19	13	1	141	0	165.87	0	67	0	236.3	0
3	0	0	0	57.33	108.54	13	54	286	472.6	0
17	1	.85	0	101	7.54	0	54	0	109.6	363
19	13	1	141	0	148.54	0	54	0	109.6	363
3	0	0	0	57.33	91.21	13	41	286	345.9	363
3	0	0	0	57.33	33.88	13	28	286	582.2	363
16	1	.22	0	29.6	4.28	0	28	0	582.2	363
19	13	1	141	0	145.28	0	28	0	582.2	363
17	1	.85	0	101	44.28	0	28	0	219.2	726
19	13	1	141	0	185.28	0	28	0	219.2	726
3	0	0	0	57.33	127.95	13	15	286	455.5	726
17	1	.85	0	101	26.95	0	15	0	92.5	1089
19	13	1	141	0	167.95	0	15	0	92.5	1089
3	0	0	0	57.33	110.62	13	2	286	328.8	1089
17	1	.85	0	101	9.62	0	2	0	0	1417.8
Total	[b]84	[b]9.84			[c]9.62	[b]78	[c]2			[c]1417.8
Cost[d]	×7	×19			[e]×1270	×1.38	×1.38			
Total cost[d]	588	186.9			12.22	107.6	2.76			

[a]The banker's tally for profile 9 is as follows:

Debits

Total cost of EOS flights = \$588.0 million
Total cost of NS flights = 186.9 million
Total cost of ST flights = 107.6 million
Total \$882.5 million

Dollar/kg without using credits

\$882.5 million ÷ 1417.8 Mg = \$622/kg

Credits

Value of H_2 remaining in lunar orbit = \$12.2 million
Value of O_2 remaining in lunar orbit = 0 million
Value of ST burns remaining = 2.7 million
Total \$14.9 million

Debits: \$882.5 million
Credits: 14.9 million
Adjusted cost: \$867.6 million

Dollars/kg using credits

\$867.6 million ÷ 1417.8 Mg = \$611/kg

[b]Tabularly summed. [c]Accumulatively summed. [d]In millions of dollars. [e]Dollars/kg.

TABLE XIX. - SUMMARY OF VARIABLES OF ROUND-TRIP ST FLIGHTS

ST full-burn capability	Cost per full burn, millions of dollars	No. of space tugs	H_2 burned per round trip, Mg	O_2 burned per round trip, Mg	No. of ST round trips	Total H_2 burned, Mg	Total O_2 burned, Mg	No. of ST full burns used	No. of ST full burns left
10	5.5	2	4.41	22	13	57.33	286	13	7
20	2.75	2	4.41	22	17	74.97	374	17	23
40	1.38	2	4.41	22	17	74.97	374	17	63
100	.55	2	4.41	22	17	74.97	374	17	183
10	5.5	2	4.41	22	9	39.69	198	9	11

TABLE XX. - COMPARISON OF DELIVERED-OXYGEN COSTS

O_2 propellant destination	With lunar-surface O_2 production facility					Without lunar-surface O_2 production facility		
	Profile no.	Vehicles used	ST full-burn capability	ST amortization cost and variation, millions of dollars	O_2 delivery cost and variation, dollars/kg	Earth logistic sequence reference	Vehicles used	O_2 delivery cost, dollars/kg
Lunar orbit						Figure 17	EOS, CS	2030
Lunar orbit	2	EOS, CS, ST	10	5.5 ± 1	867 ± 67	BBB 15	EOS, NS	1270
High Earth orbit	3	EOS, CS, ST	10	5.5 ± 1	1118 ± 84	BBB 1	EOS, CS	743
High Earth orbit	4	EOS, CS, ST	20	2.75 ± 1	778 ± 81	BBB 1	EOS, CS	743
High Earth orbit	5	EOS, CS, ST	40	1.38 ± 1	621 + 81	BBB 1	EOS, CS	743
High Earth orbit	6	EOS, CS, ST	100	.55 ± 1	552 + 63	BBB 1	EOS, CS	743
High Earth orbit	7	EOS, NS, ST	10	5.5 ± 1	978 ± 54	BBB 1	EOS, NS	627
High Earth orbit	8	EOS, NS, ST	20	2.75 ± 1	742 ± 96	BBB 1	EOS, NS	627
High Earth orbit	9	EOS, NS, ST	40	1.38 ± 1	622 + 55	BBB 1	EOS, NS	627

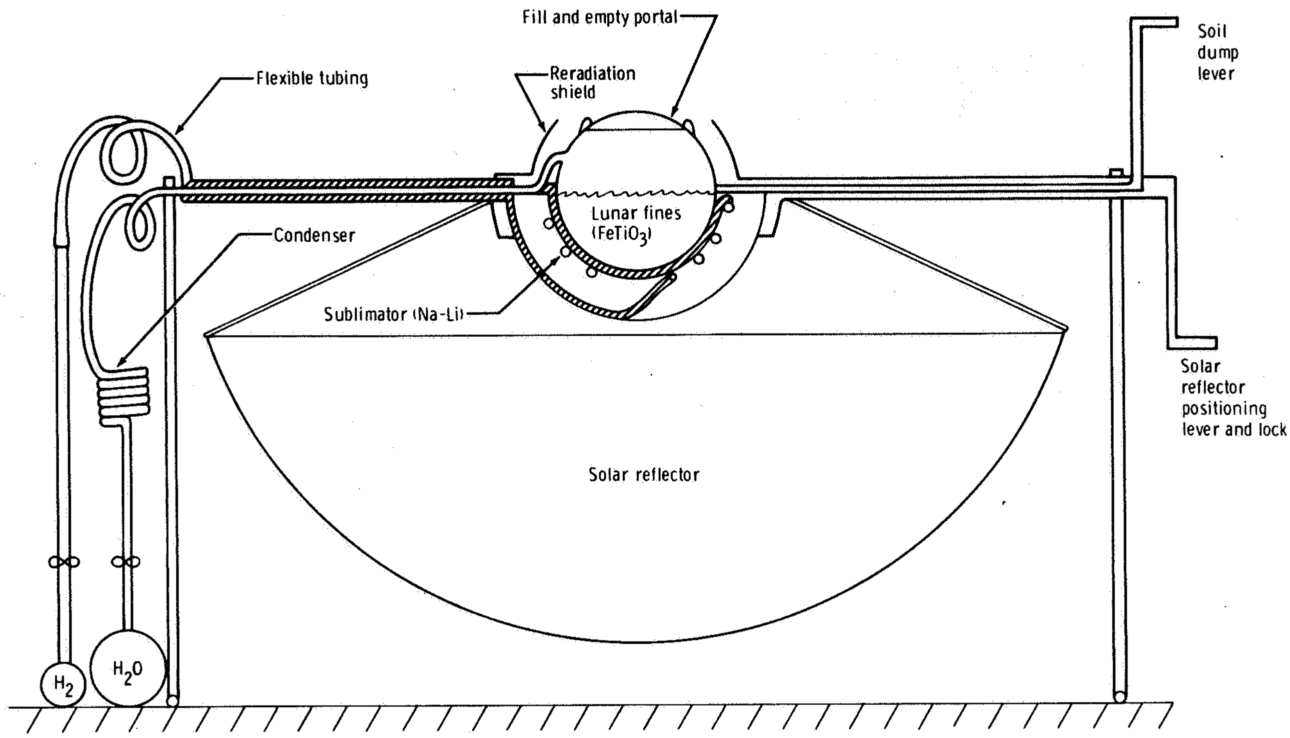


Figure 1. - Conceptual water production, hydrogen reduction process.

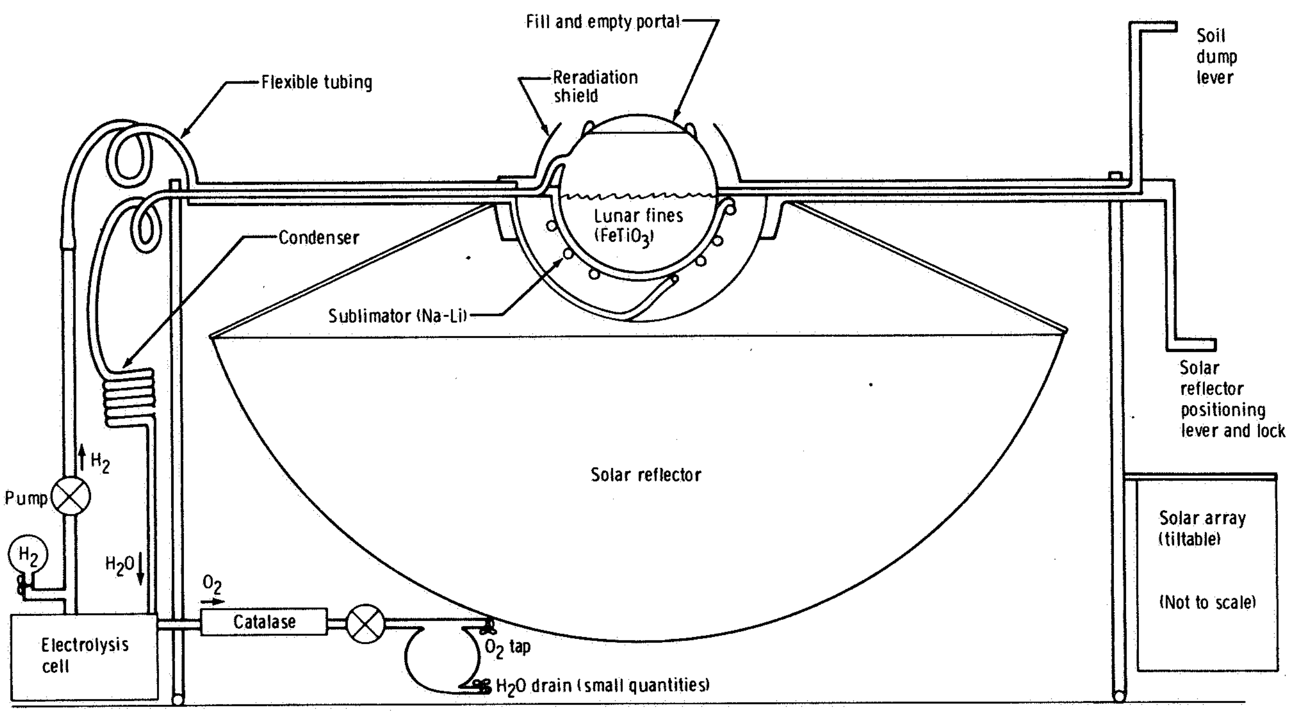


Figure 2. - Conceptual oxygen production, hydrogen reduction process.

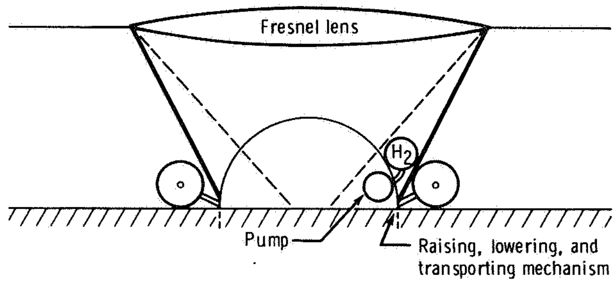


Figure 3. - Conceptual hydrogen extraction.

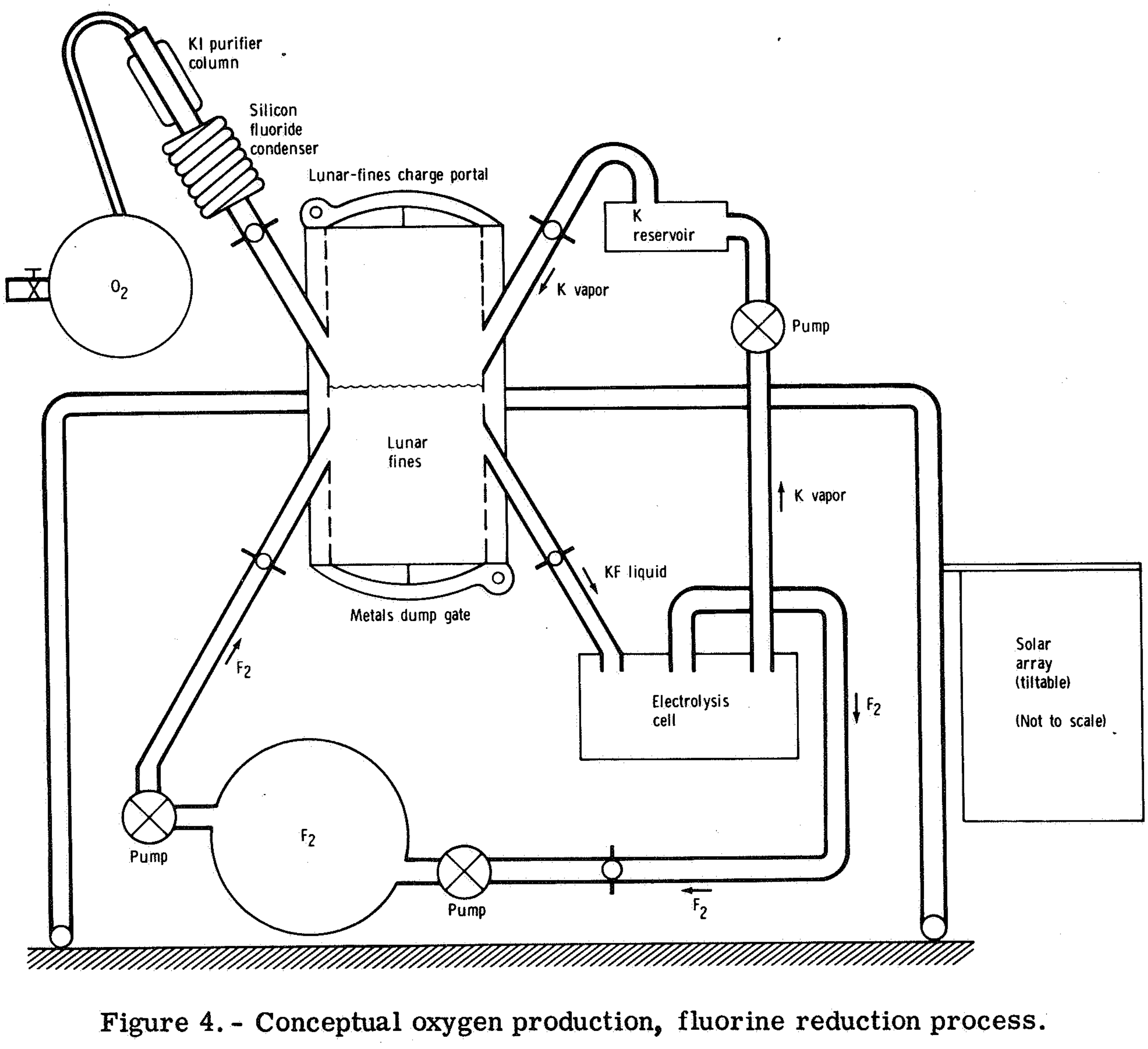


Figure 4. - Conceptual oxygen production, fluorine reduction process.

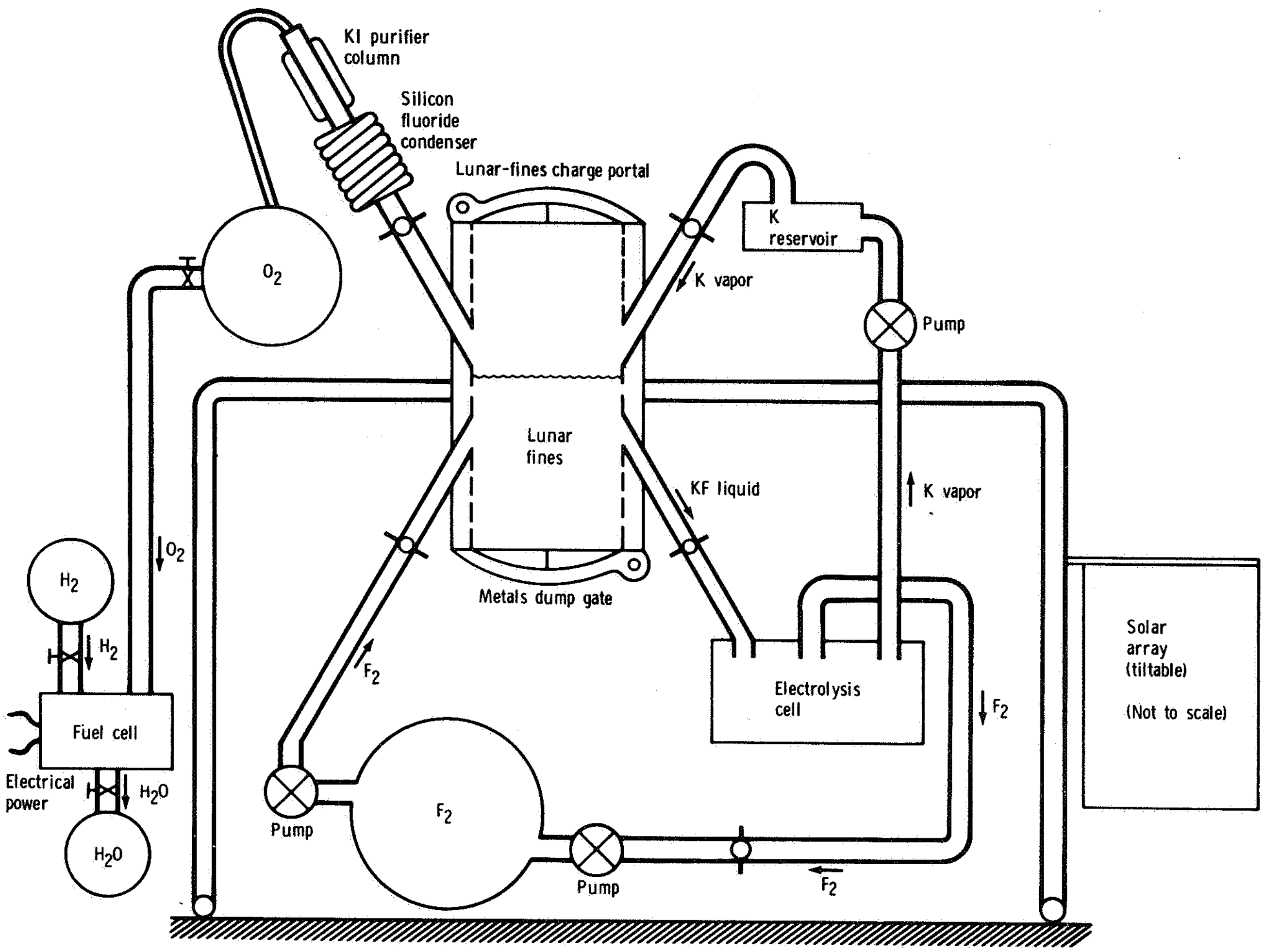


Figure 5. - Conceptual water production, fluorine reduction process.

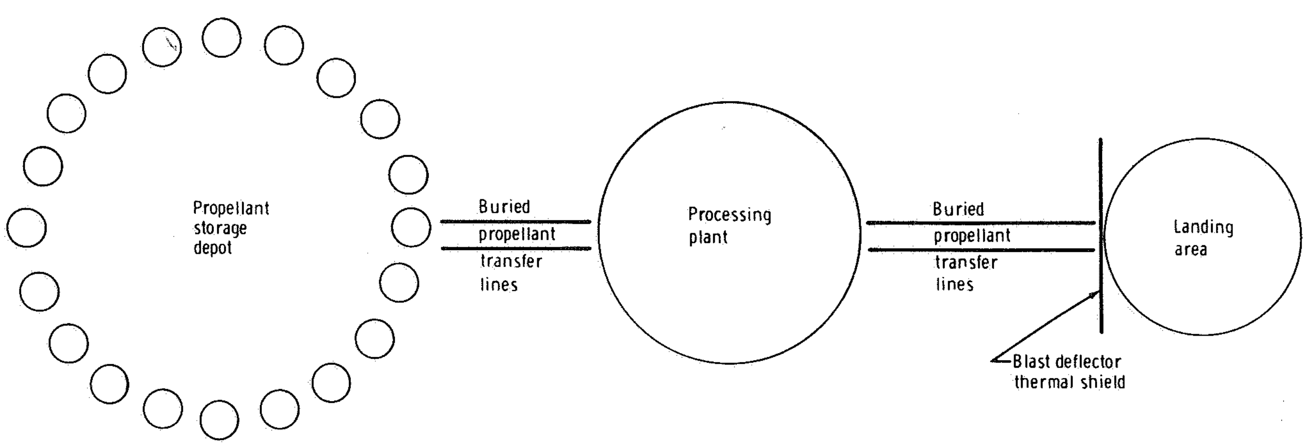


Figure 6. - Lunar-surface oxygen plant — preliminary operational facility concept.

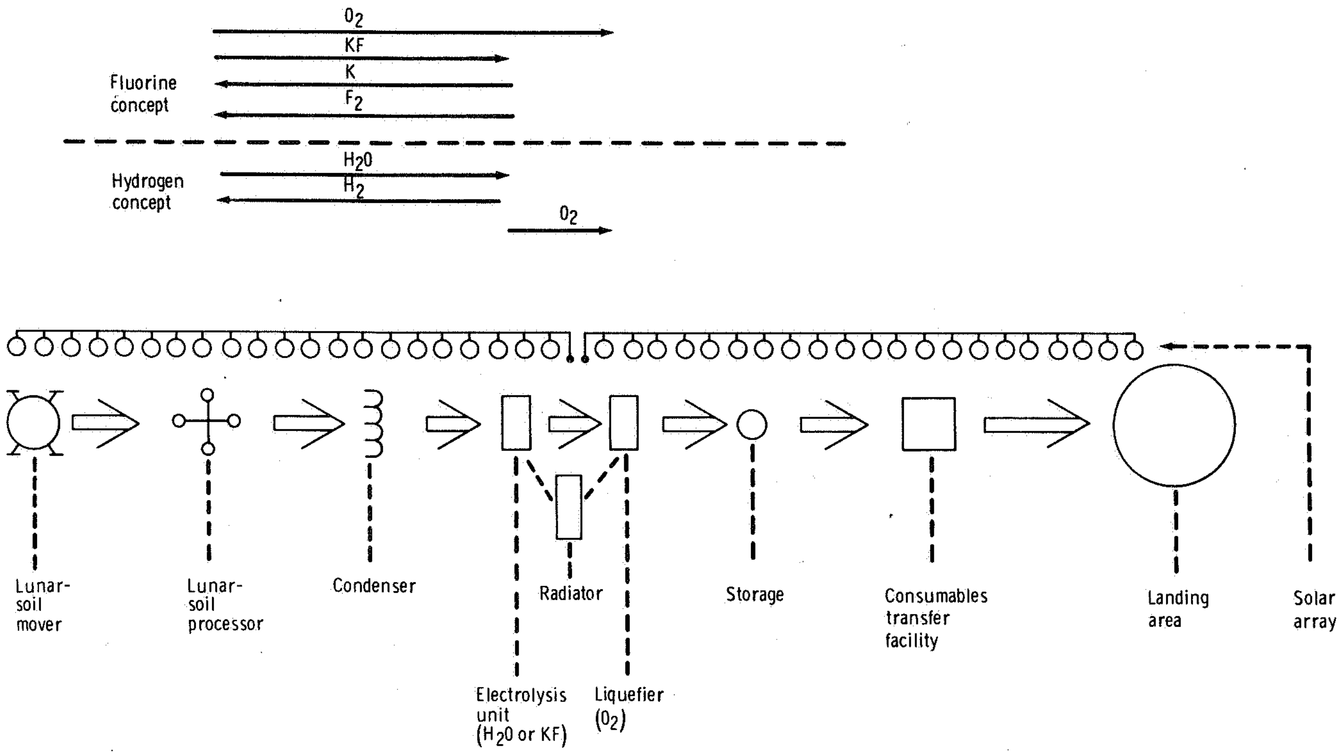


Figure 7. - Lunar-surface oxygen plant functional flow.

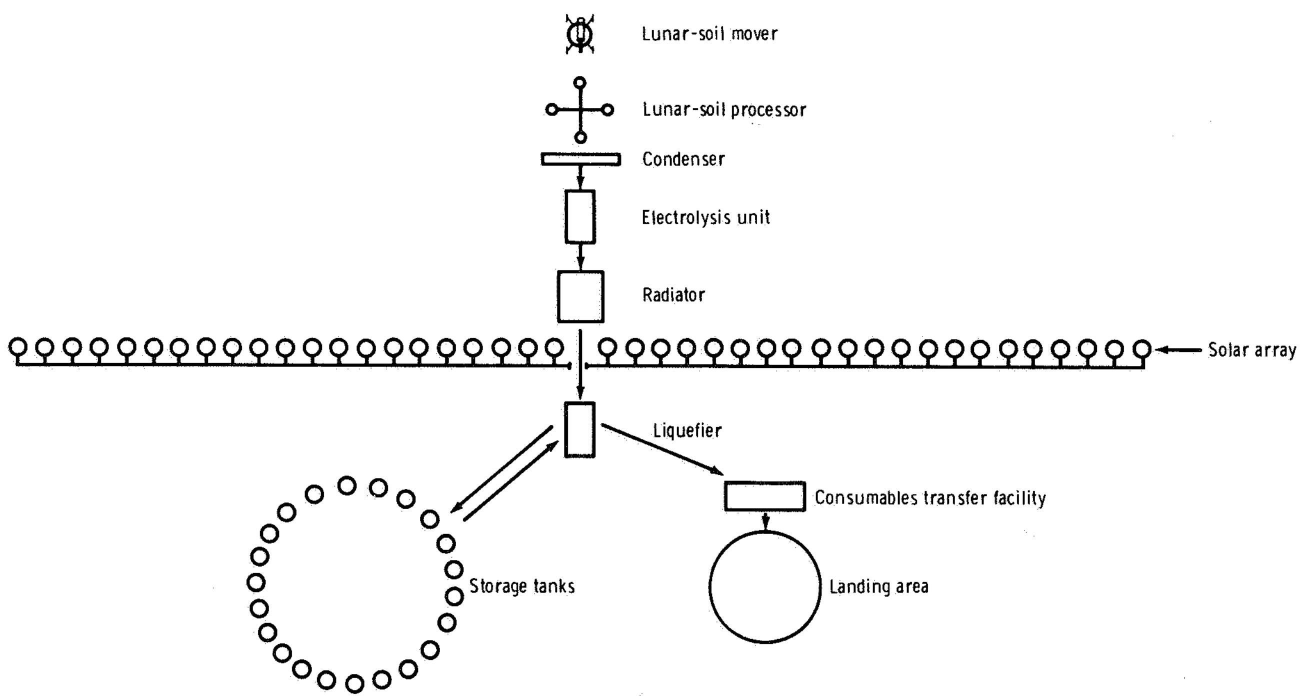


Figure 8. - Conceptual lunar-surface oxygen plant layout.

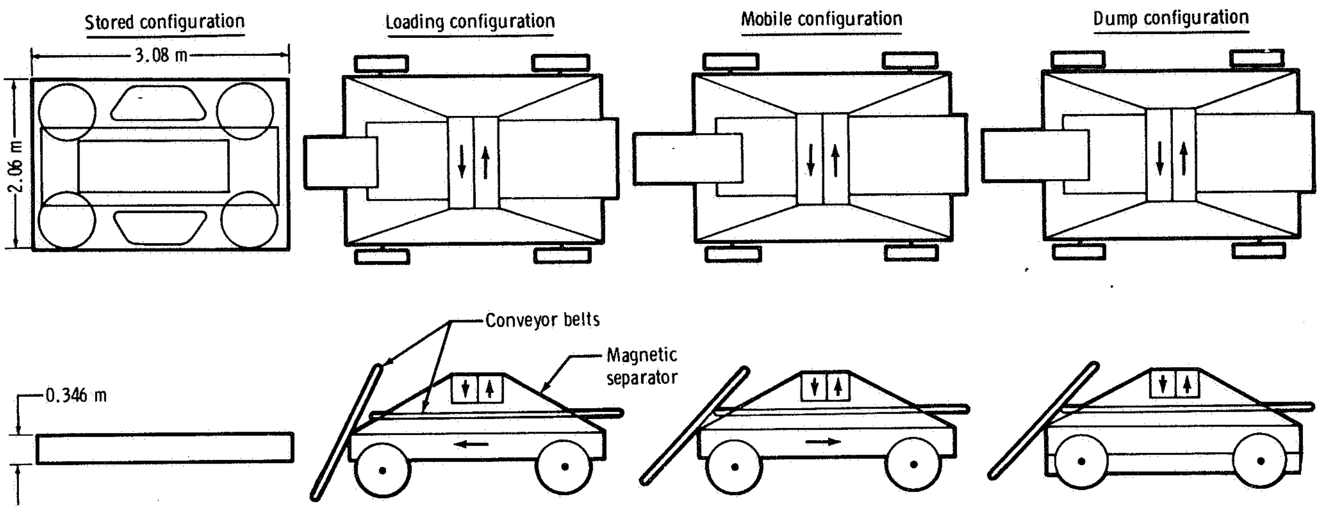
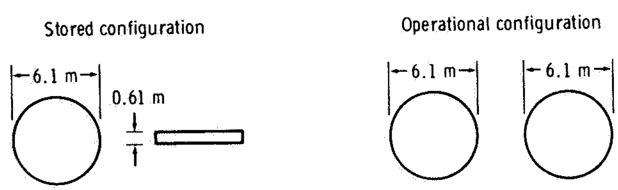


Figure 9. - Lunar-soil mover.



Sphere weight	273 kg
Internal volume	119 m^3
Wall thickness	0.0812 cm
Internal pressure	17 psia
Liquid O_2 density	1140 kg/m^3
Maximum O_2	136 Mg
Liquid H_2 density	72 kg/m^3
Maximum H_2	8.6 Mg

Figure 10. - Hydrogen or oxygen storage spheres.

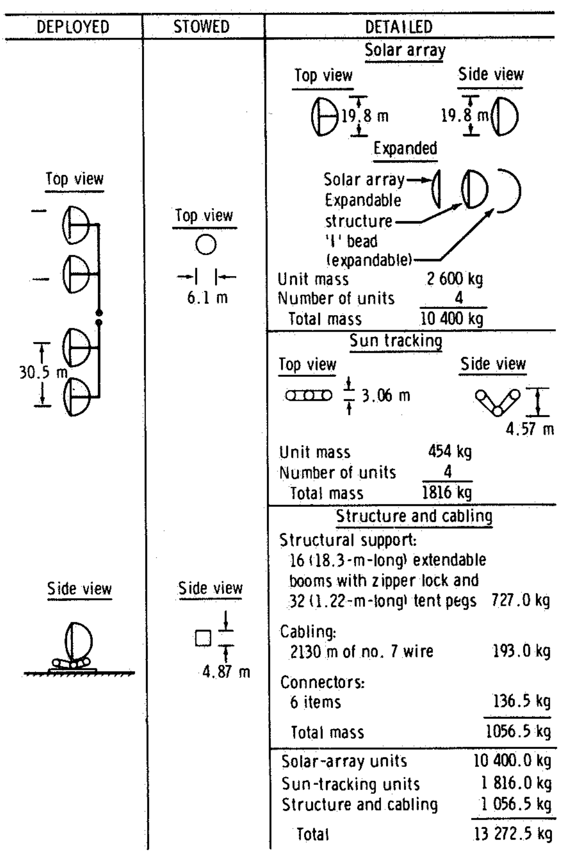


Figure 11. - The 250-kilowatt solar-array (Mariner-type) semiautomatic deployment.

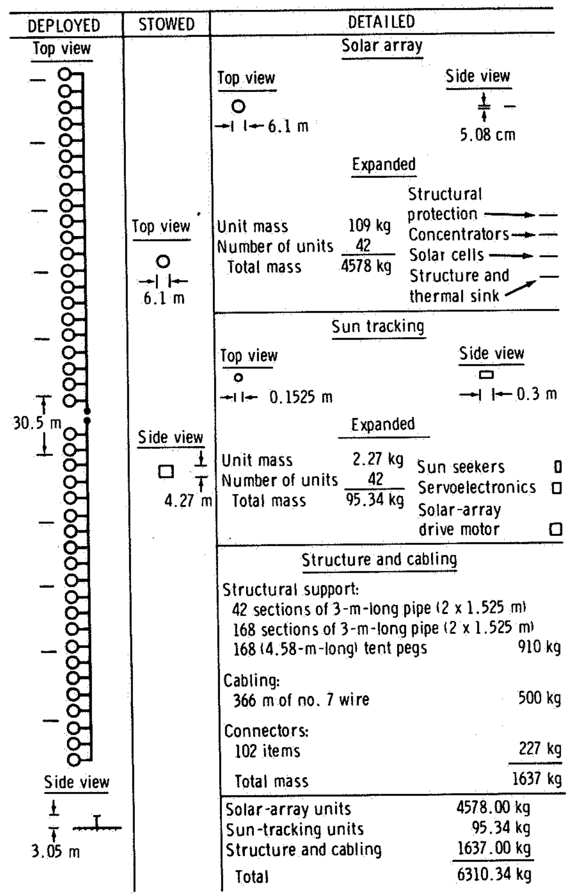
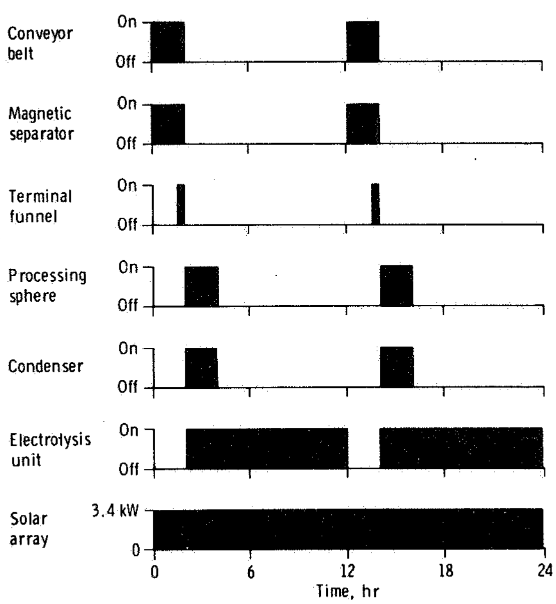


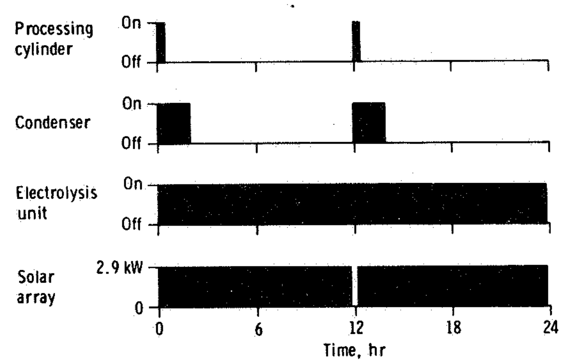
Figure 12. - The 250-kilowatt solar-array (Mariner-type) manual deployment.



NOTES

1. 3.4 kW/hr are required for the electrolysis of ~13.8 kg of H_2O (12.3 kg of O_2, 1.5 kg of H_2) in 20 hr of every 24-hr cycle.
2. 3.4 kW/hr are allocated for the operation of the conveyor belt and magnetic separator for 4 hr of every 24-hr cycle.
3. 0.48 m^3 of lunar soil is moved every 24 hr.
4. 114 kg of magnetically separated soil are processed every 24 hr.
5. The 24-hr cycle shown is repeated continuously for the duration of the lunar daylight portion of the mission.

(a) Hydrogen process.

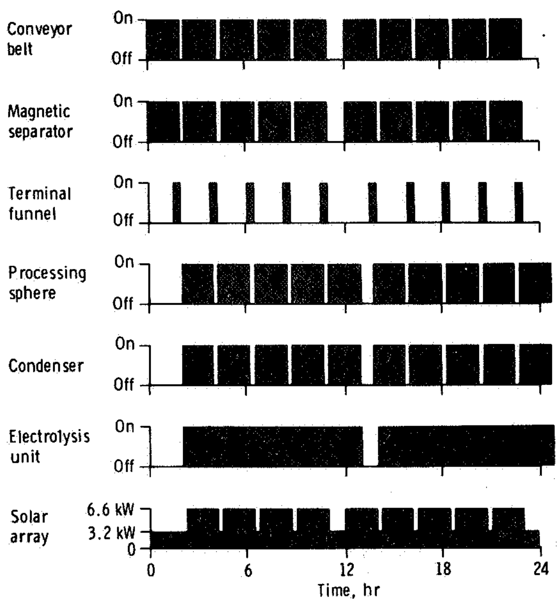


NOTES

1. 2.9 kW/hr are required for the electrolysis of ~39.4 kg of KF (12.1 kg of K, 27.3 kg of F) for 23 hr of every 24-hr cycle.
2. 0.22 m^3 of lunar soil is moved every 24 hr.
3. 30.9 kg of unseparated lunar soil are processed every 24 hr.
4. The 24-hr cycle shown is repeated continuously for the duration of the lunar daylight portion of the mission.

(b) Fluorine process.

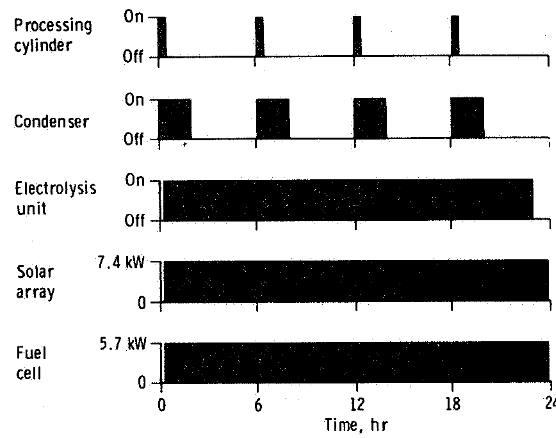
Figure 13. - Level I time line: six-man crew, 14 days, life-support oxygen only (12 kg/day).



NOTES

1. 3.2 kW/hr are required for the electrolysis of ~13.8 kg of H_2O (12.3 kg of O_2, 1.5 kg of H_2) in 21 hr of every 24-hr cycle.
2. 3.4 kW/hr are allocated for the operation of the conveyor belt and magnetic separator for 20 hr of every 24-hr cycle.
3. 2.41 m^3 of lunar soil are moved every 24 hr.
4. 546 kg of magnetically separated soil are processed every 24 hr.
5. The 24-hr cycle shown is repeated continuously for the duration of the lunar daylight portion of the mission.

(a) Hydrogen process.

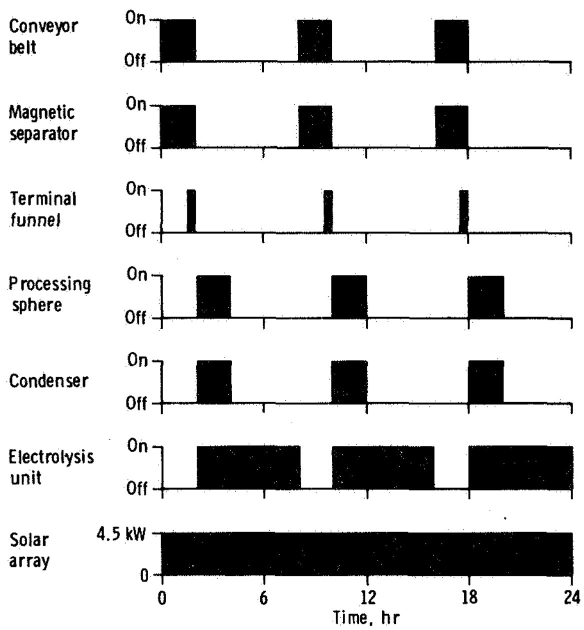


NOTES

1. Electrolysis requirement for O_2 is ~2.4 kW/hr per 0.454 kg of O_2.
2. Fuel-cell power output is ~1.31 kW per 0.454 kg of O_2.
3. Bootstrapping the fuel-cell output to the electrolysis unit input still leaves a solar-array power requirement of 1.09 kW (2.4 kW - 1.31 kW) per 0.454 kg of O_2. For 59.1 kg of O_2, 142 kW are required. On a 24-hr continuous-cycle basis, this is 5.7 kW/hr.
4. 0.087 m^3 of lunar soil is moved every 24 hr.
5. 141 kg of unseparated lunar soil are processed every 24 hr.
6. The electrolysis unit must convert 5 times the amount of KF required for the O_2-only configuration.
7. The 24-hr cycle shown is repeated continuously for the duration of the lunar daylight portion of the mission.

(b) Fluorine process.

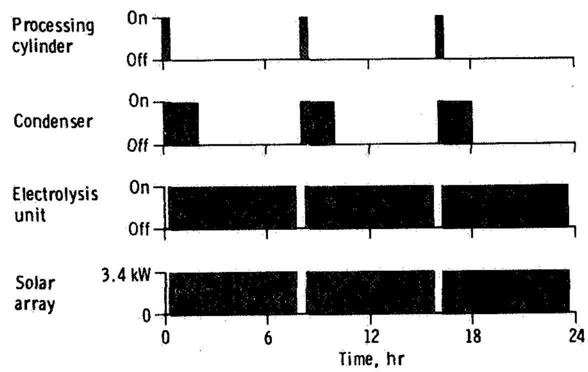
Figure 14. - Level I time line: six-man crew, 14 days, life-support oxygen (12 kg/day) and water (53 kg/day).



NOTES

1. 4.5 kW/hr are required for the electrolysis of ~16.3 kg of H_2O (14.5 kg of O_2, 1.8 kg of H_2) for 18 hr of every 24-hr cycle.
2. 4.5 kW/hr are allocated for the operation of the conveyor belt and magnetic separator for 6 hr of every 24-hr cycle.
3. 0.58 m^3 of lunar soil is moved every 24 hr.
4. 138 kg of magnetically separated soil are processed every 24 hr.
5. The 24-hr cycle shown is repeated continuously for the duration of the lunar daylight portion of the mission.
6. The electrolysis unit capacity is increased 20 percent over the system used for 12.3 kg/hr.

(a) Hydrogen process.

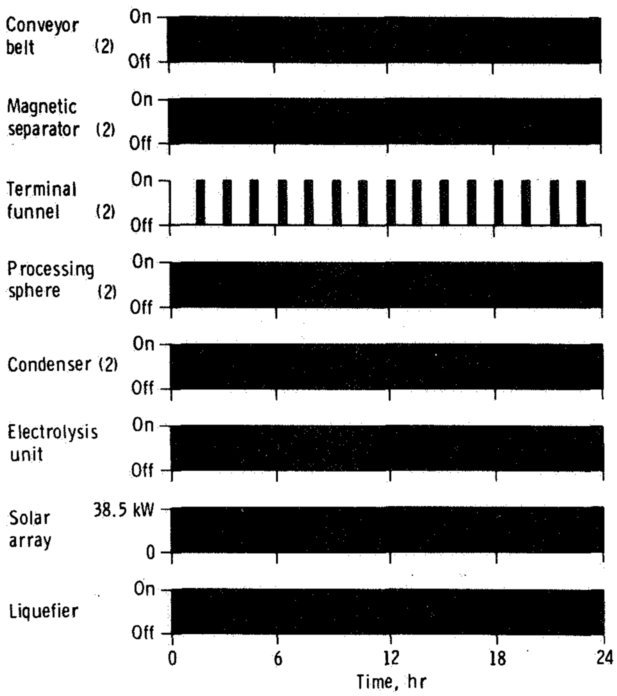


NOTES

1. 3.4 kW/hr are required for the electrolysis of ~46.7 kg of KF (14.3 kg of K, 32.4 kg of F) for 23 hr of every 24-hr cycle.
2. 0.021 m^3 of lunar soil is moved every 24 hr.
3. 34.5 kg of unseparated lunar soil are processed every 24 hr.
4. The 24-hr cycle shown is repeated continuously for the duration of the lunar daylight portion of the mission.

(b) Fluorine process.

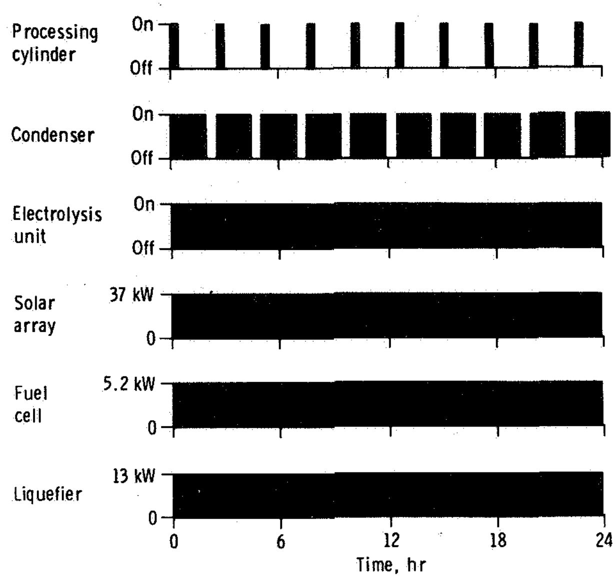
Figure 15. - Level I time line: three-man crew, 28 days, life-support oxygen only (14.6 kg/day).



NOTES

1. 13 kW/hr are required for the electrolysis of ~67.7 kg of H_2O (56.4 kg of O_2, 11.3 kg of H_2) for 24 hr of every 24-hr cycle.
2. 5 kW/hr are allocated for the operation of the conveyor belts and magnetic separators for 24 hr of every 24-hr cycle.
3. 13 kW/hr are allocated for the liquefier for 24 hr of every 24-hr cycle.
4. 2.29 m^3 of lunar soil are moved every 24 hr.
5. 536 kg of magnetically separated soil are processed every 24 hr.
6. The 24-hr cycle shown is repeated continuously for the duration of the lunar daylight portion of the mission.
7. Fuel cells provide lunar night electrical power; they do not operate during the lunar day.
8. The daylight power requirement for the life-support system is 5 kW/hr.

(a) Hydrogen process.



NOTES

1. 22.7 kW/hr are required for the electrolysis of ~333 kg of KF (102 kg of K, 231 kg of F) for 24 hr of every 24-hr cycle.
2. Bootstrapping the fuel-cell output to the electrolysis unit input still leaves a solar-array power requirement of 1.09 kW (2.4 kW - 1.31 kW) per 0.45 kg of H_2O. For 53.21 kg of H_2O, ~124 kW (2.4 kW - On a 24-hr continuous-cycle basis, this is 5.2 kW/hr.
3. The daylight power requirement for the life-support system is 5 kW/hr.
4. 13 kW/hr are allocated for the liquefier for 24 hr of every 24-hr cycle.
5. 0.154 m^3 of lunar soil is moved every 24 hr.
6. 247 kg of lunar soil are moved every 24 hr.
7. The 24-hr cycle shown is repeated continuously for the duration of the lunar daylight portion of the mission.
8. ~5.9 kg of H_2 per day are required for fuel-cell daylight operation, 5 kg for nighttime operation.

(b) Fluorine process.

Figure 16. - Level I time line: three-man crew, 28 days, life-support oxygen (14.6 kg/day), water (53 kg/day), and lunar-night electricity (5 kW/hr, 41.7 kg/day).

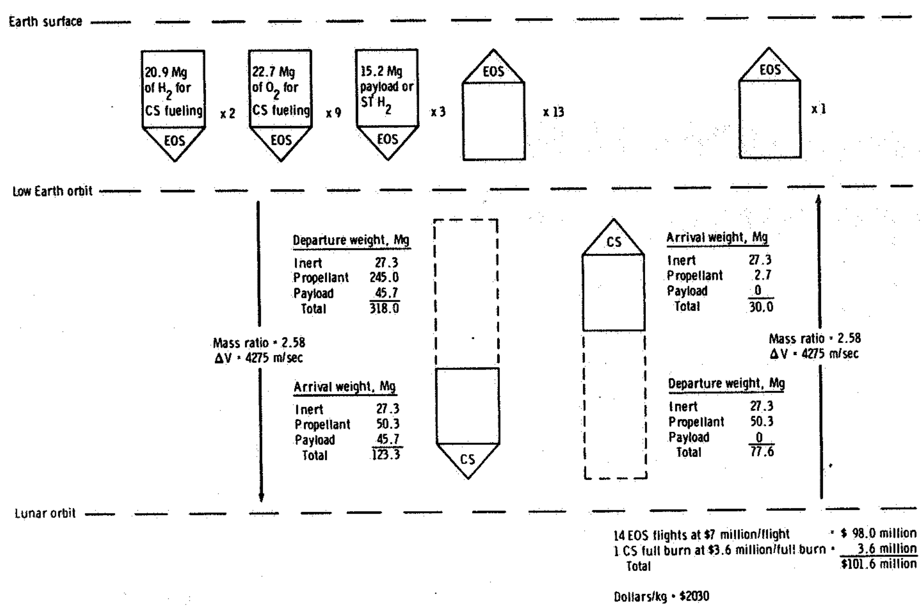


Figure 17. - Earth logistic sequence.

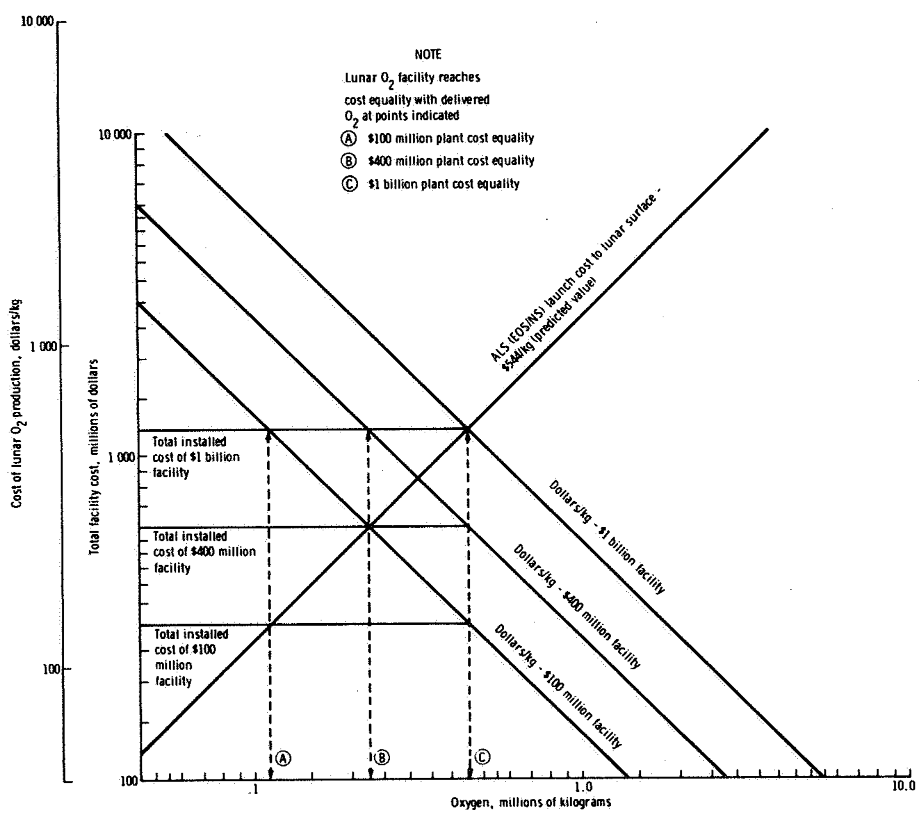


Figure 18. - Lunar-surface oxygen production cost comparison.

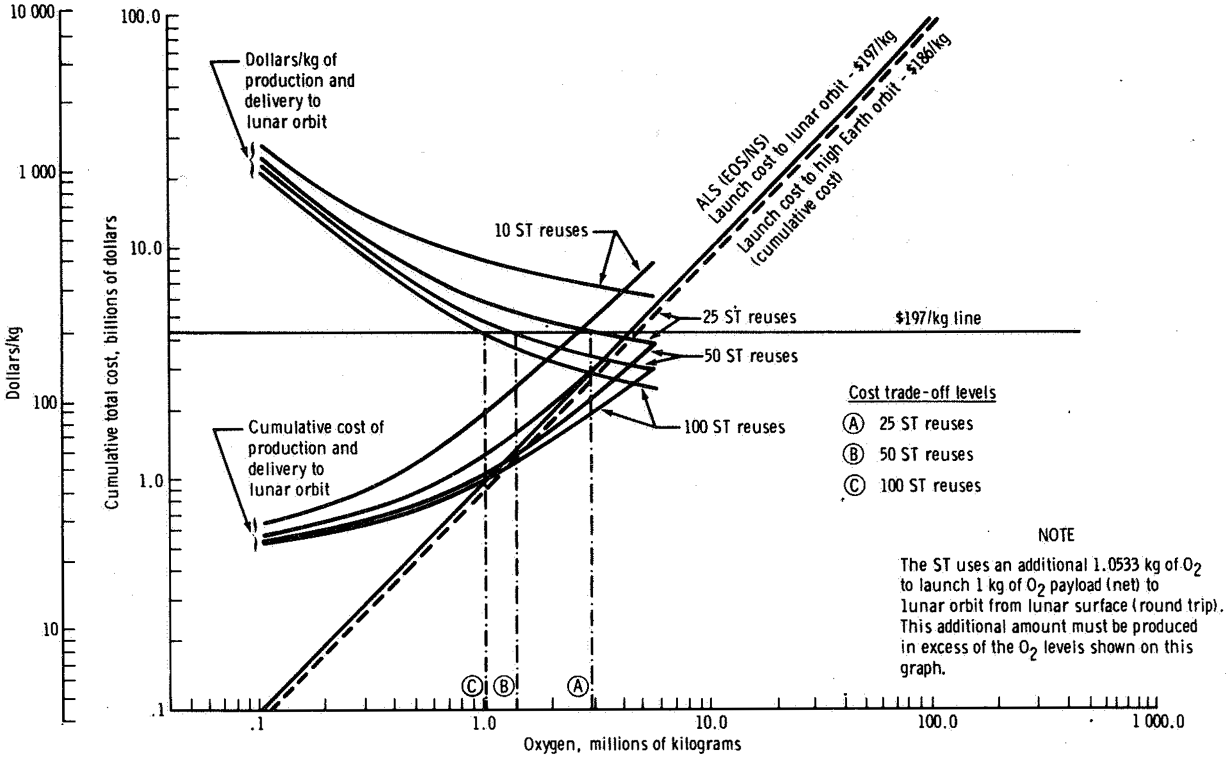


Figure 19. - Lunar-orbit oxygen supply economic feasibility analysis ($100 million lunar-surface production facility).

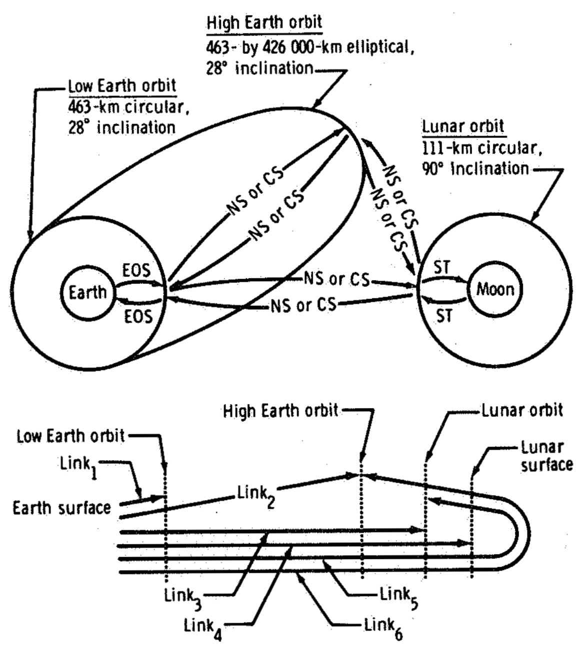


Figure 20. - Transportation links.

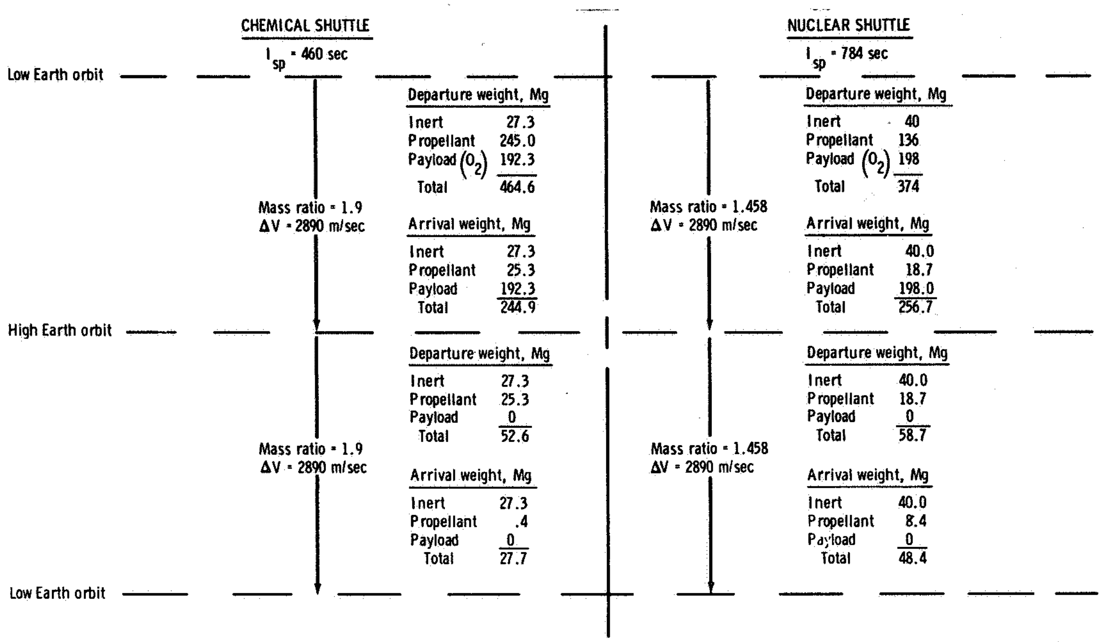


Figure 21. - Reference figure 1: low-Earth-orbit to high-Earth-orbit to low-Earth-orbit CS and NS performance characteristics.

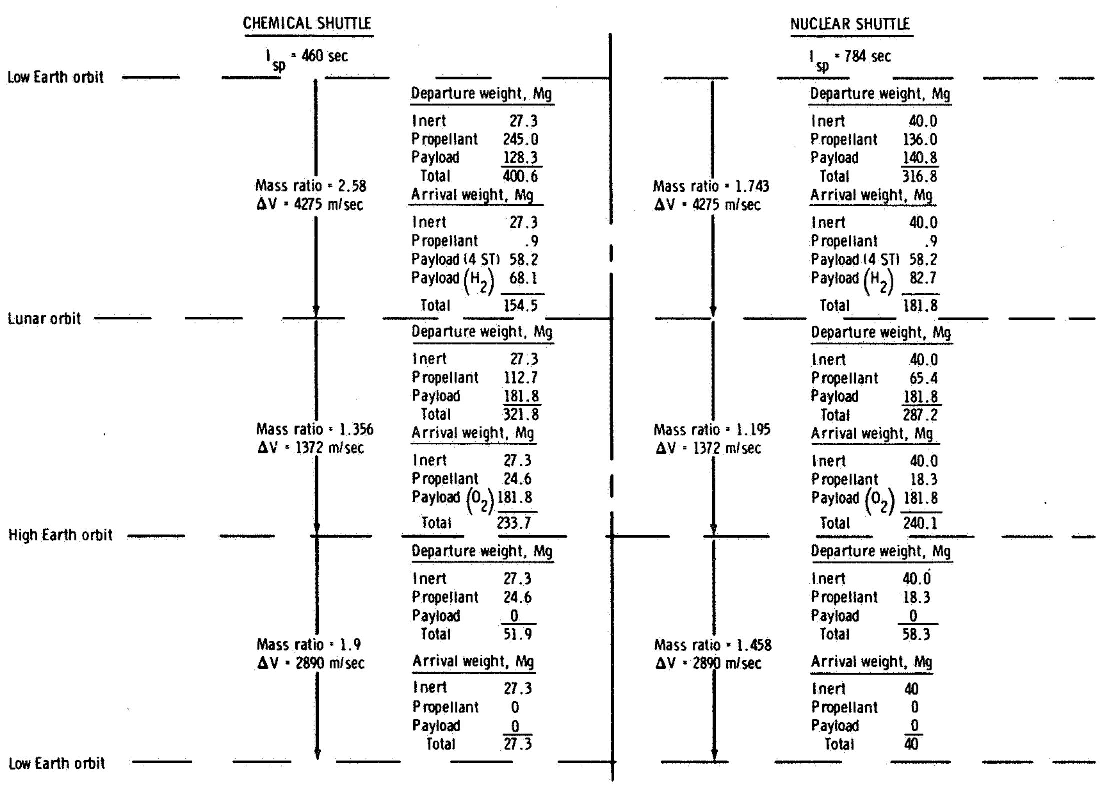


Figure 22. - Reference figure 2: low-Earth-orbit to lunar-orbit to high-Earth-orbit to low-Earth-orbit CS and NS performance characteristics.

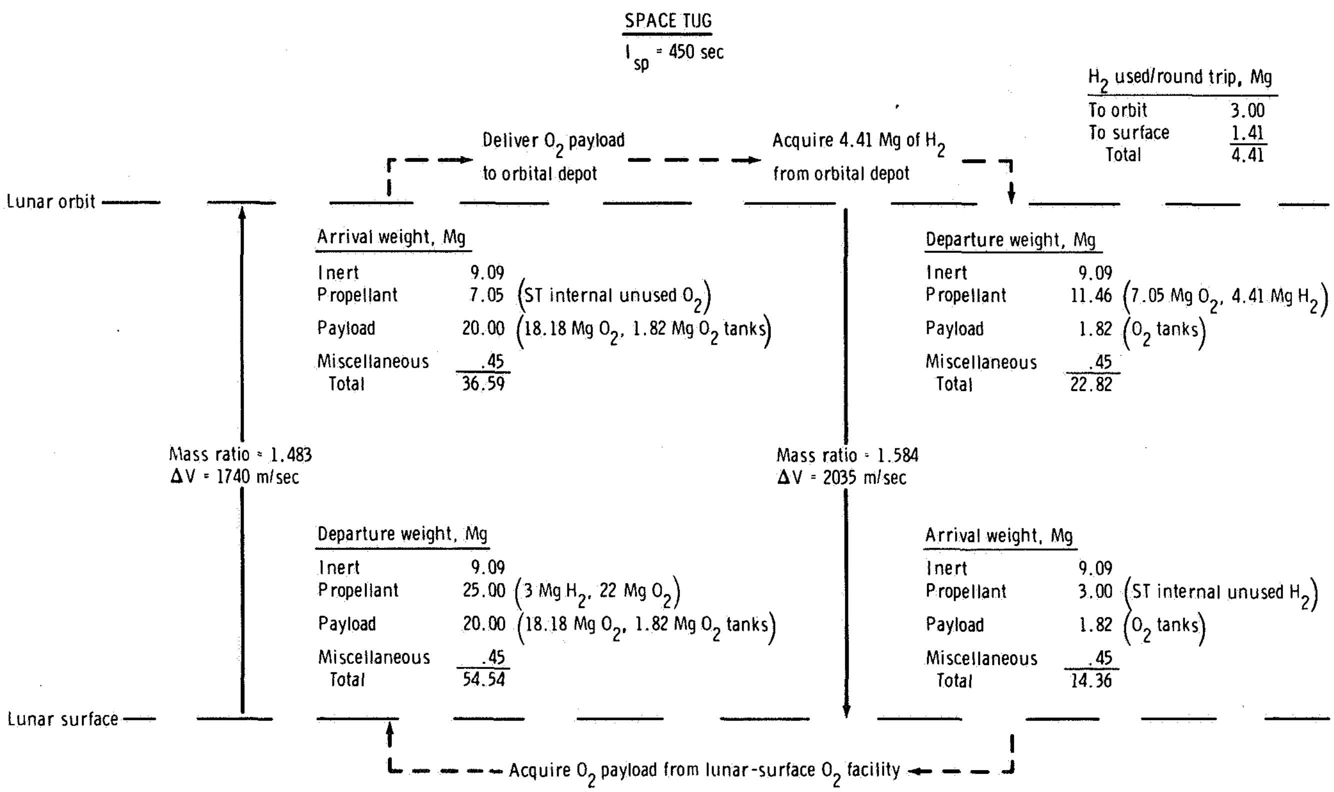
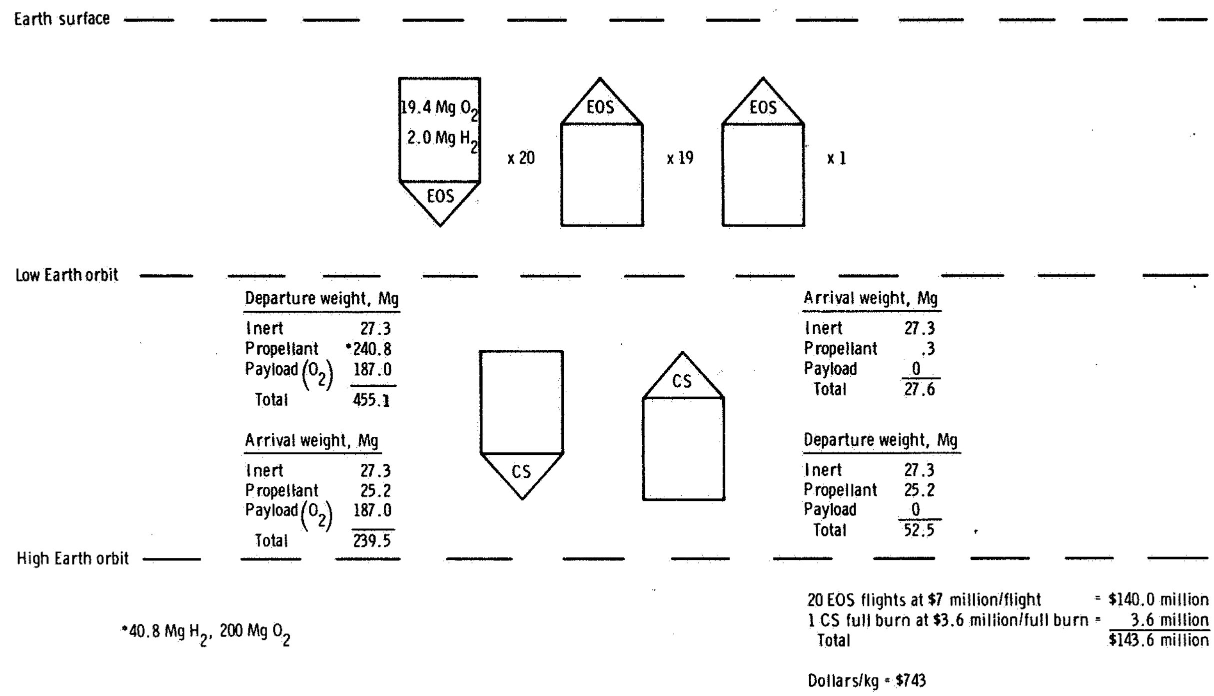
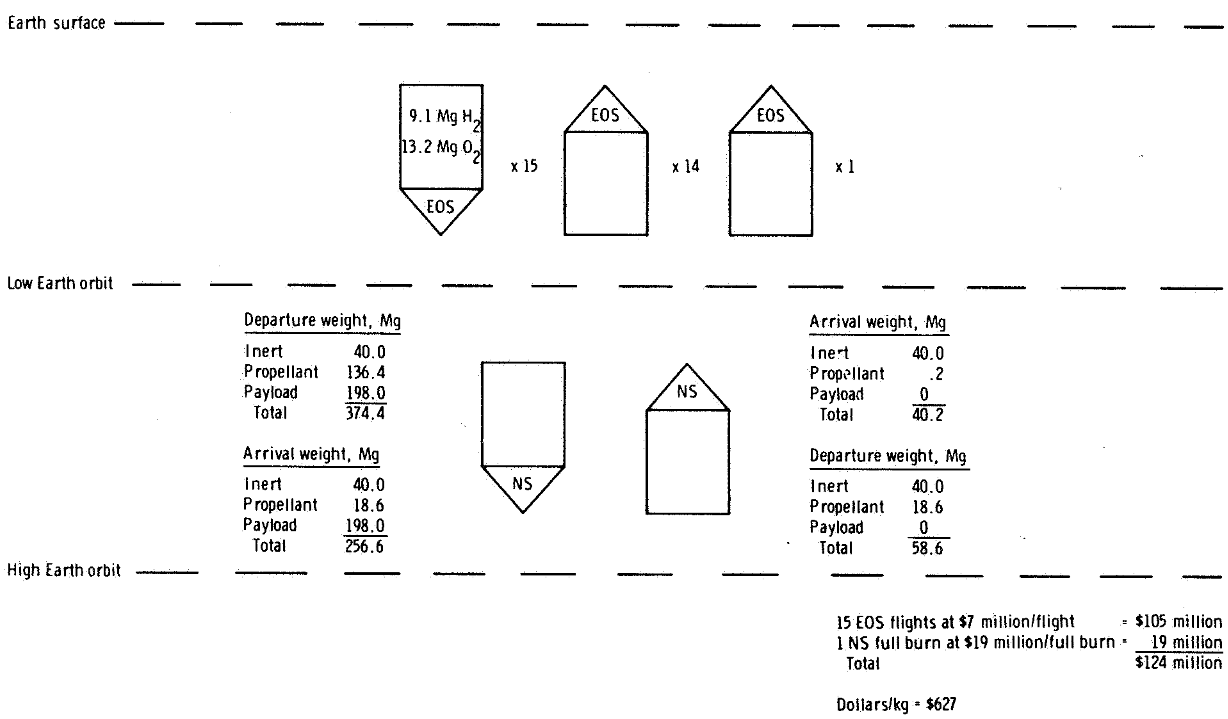


Figure 23. - Reference figure 3: lunar surface-to-orbit-to-surface cycle and ST performance characteristics.



(a) Chemical stage.



(b) Nuclear stage.

Figure 24. - Basic building block 1: Earth-surface to low-Earth-orbit to high-Earth-orbit and return sequence, EOS and CS/NS performance.

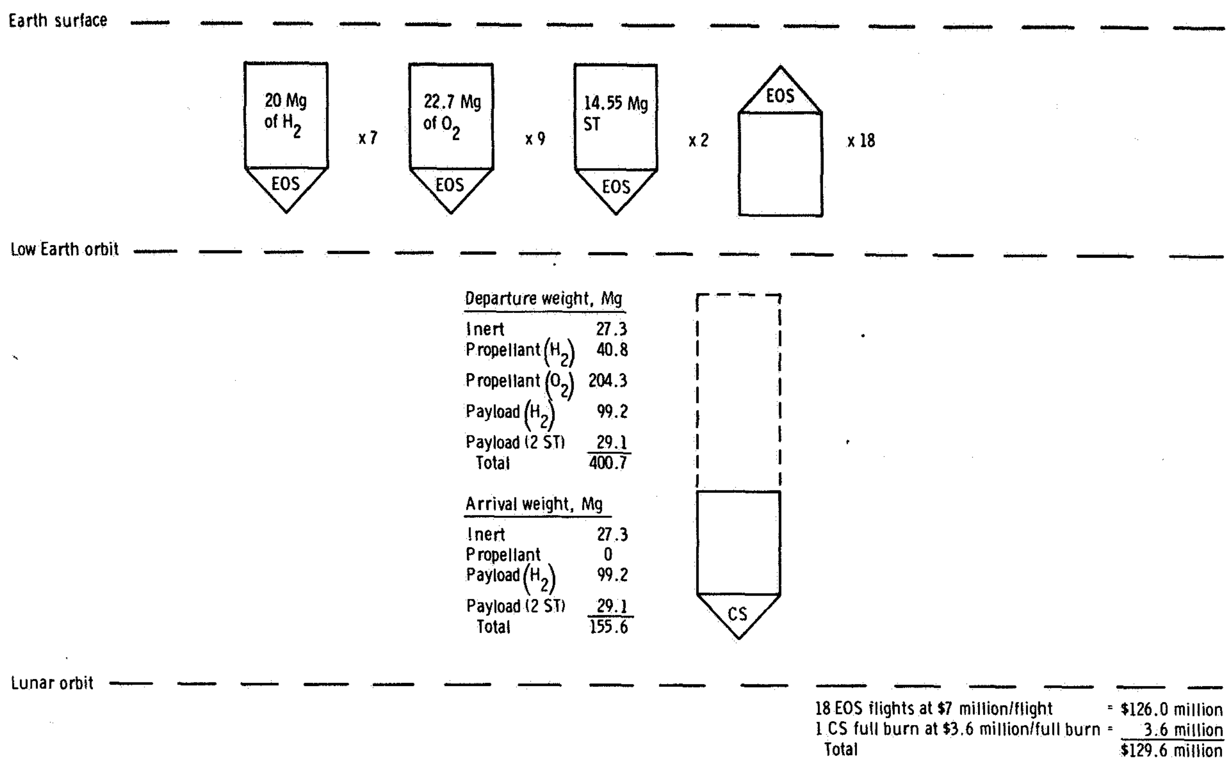


Figure 25. - Basic building block 2: Earth-surface to low-Earth-orbit to lunar-orbit sequence (two space tugs and 99.2 megagrams of hydrogen delivered), EOS and CS performance.

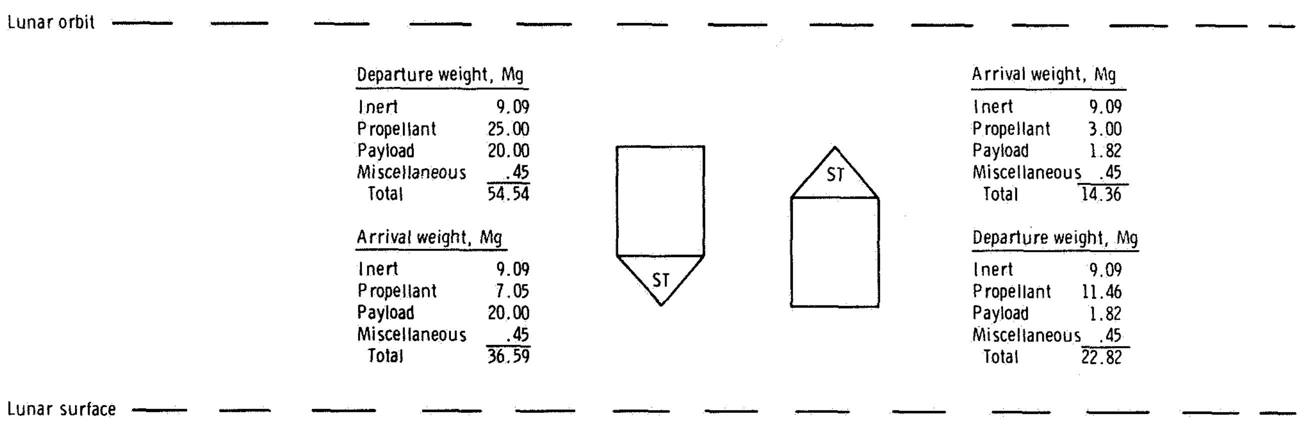


Figure 26. - Basic building block 3: lunar surface-to-orbit-to-surface cycle used in conjunction with table XIX for ST performance.

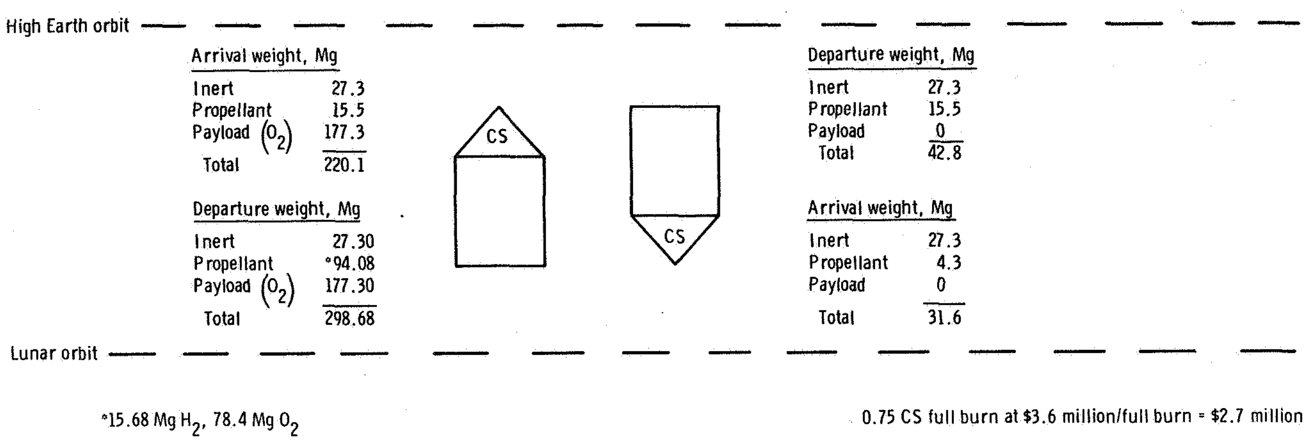


Figure 27. - Basic building block 4: lunar-orbit to high-Earth-orbit (177.3 megagrams of lunar oxygen delivered) and return sequence, CS performance.

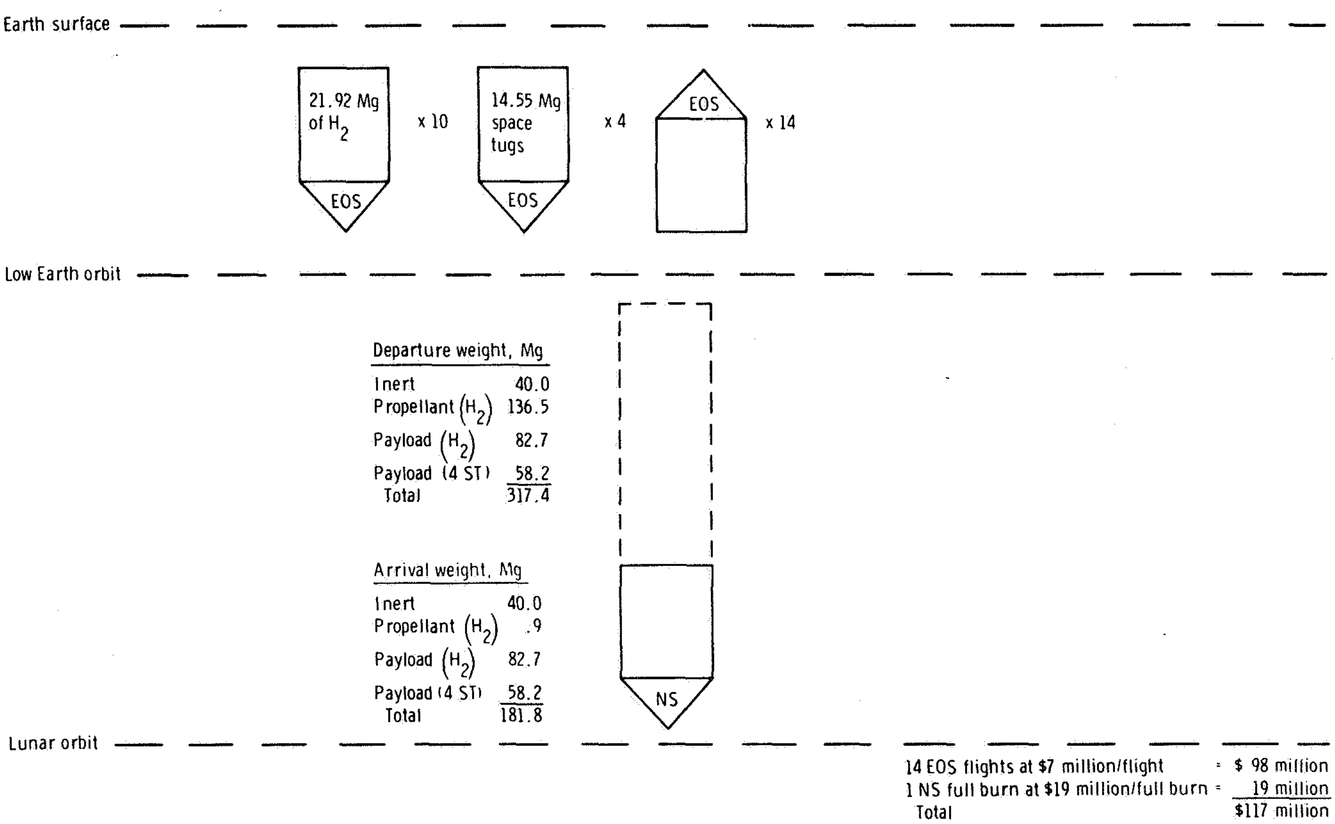


Figure 28. - Basic building block 5: Earth-surface to low-Earth-orbit to lunar-orbit sequence (four space tugs and 82.7 megagrams of hydrogen delivered), EOS and NS performance.

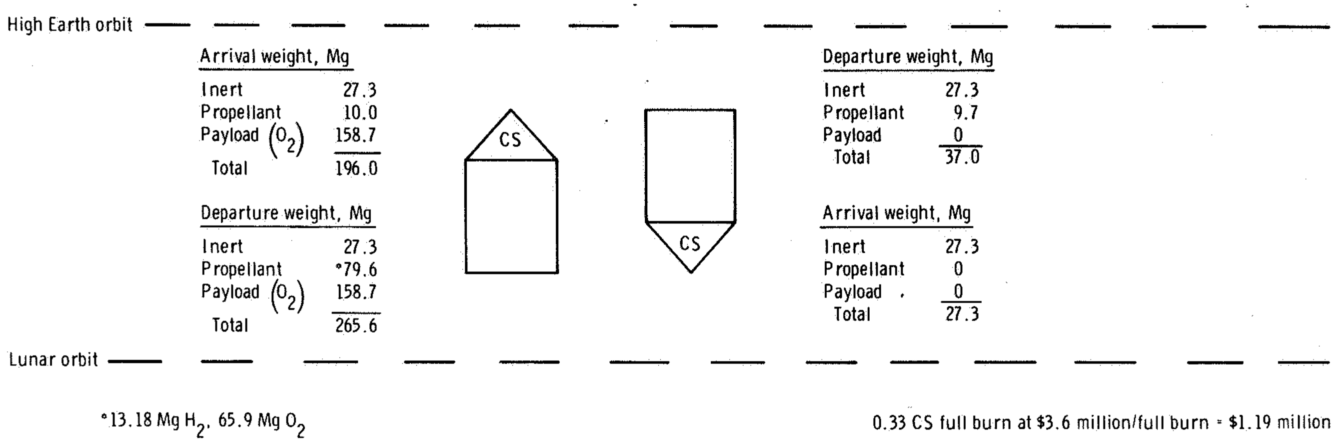


Figure 29. - Basic building block 6: lunar-orbit to high-Earth-orbit (158.7 megagrams of oxygen delivered) and return sequence, CS performance.

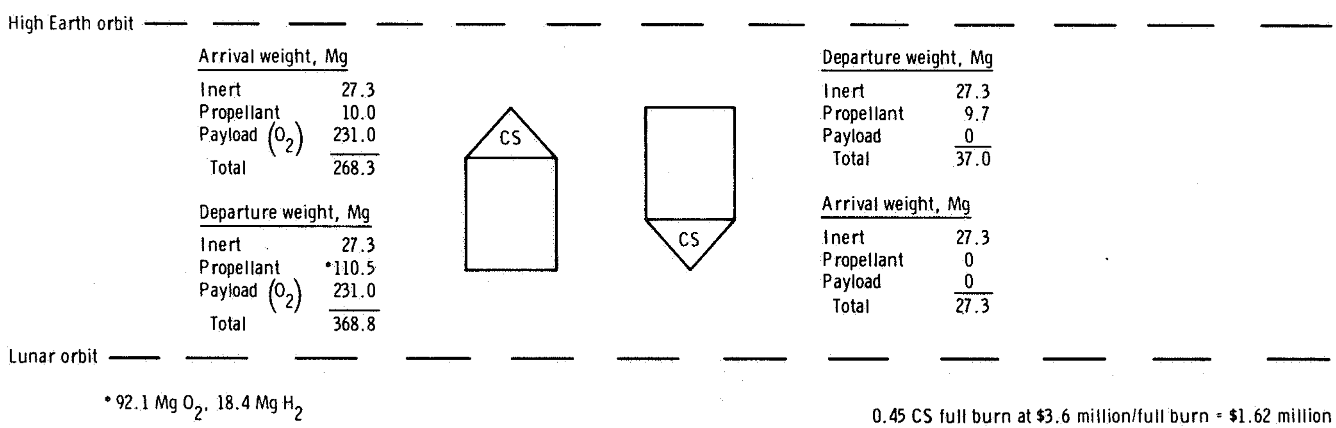


Figure 30. - Basic building block 7: lunar-orbit to high-Earth-orbit (231 megagrams of oxygen delivered) and return sequence, CS performance.

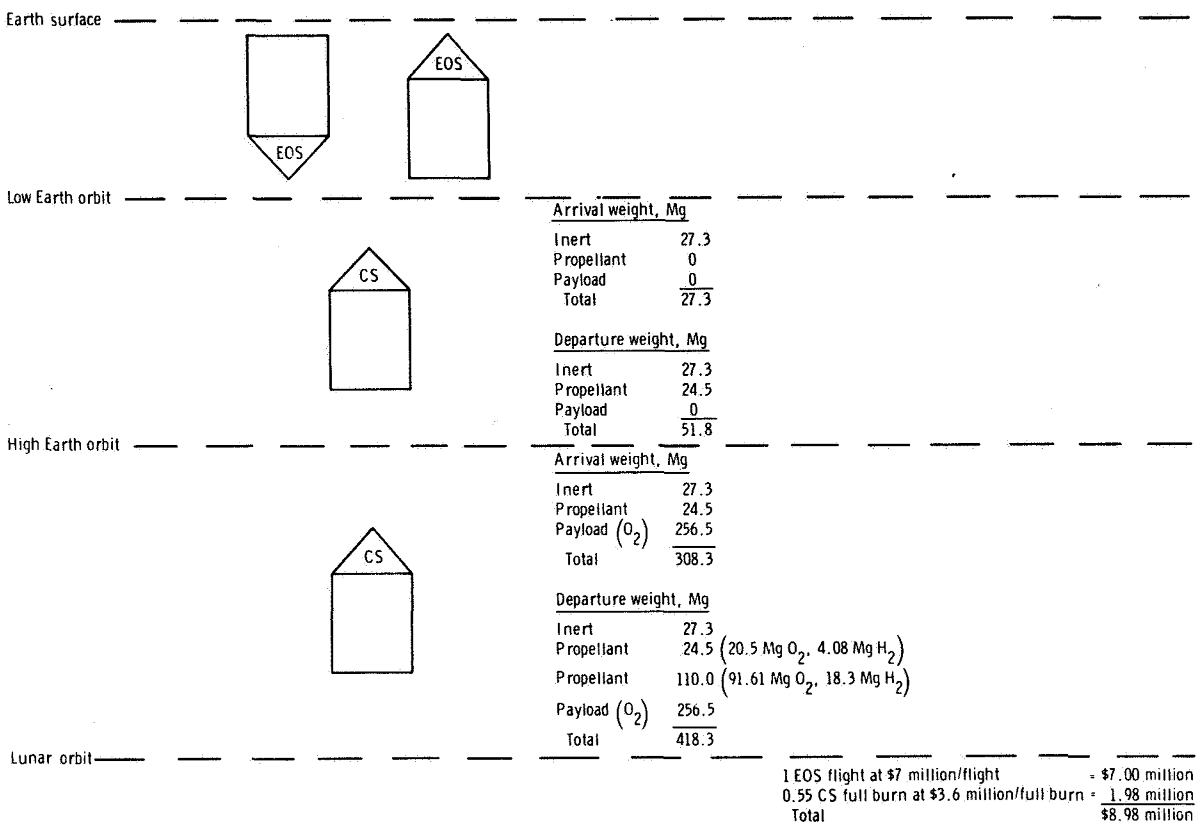


Figure 31. - Basic building block 8: lunar-orbit to high-Earth-orbit (256.5 megagrams of oxygen delivered) to low-Earth-orbit to Earth-surface sequence, CS performance.

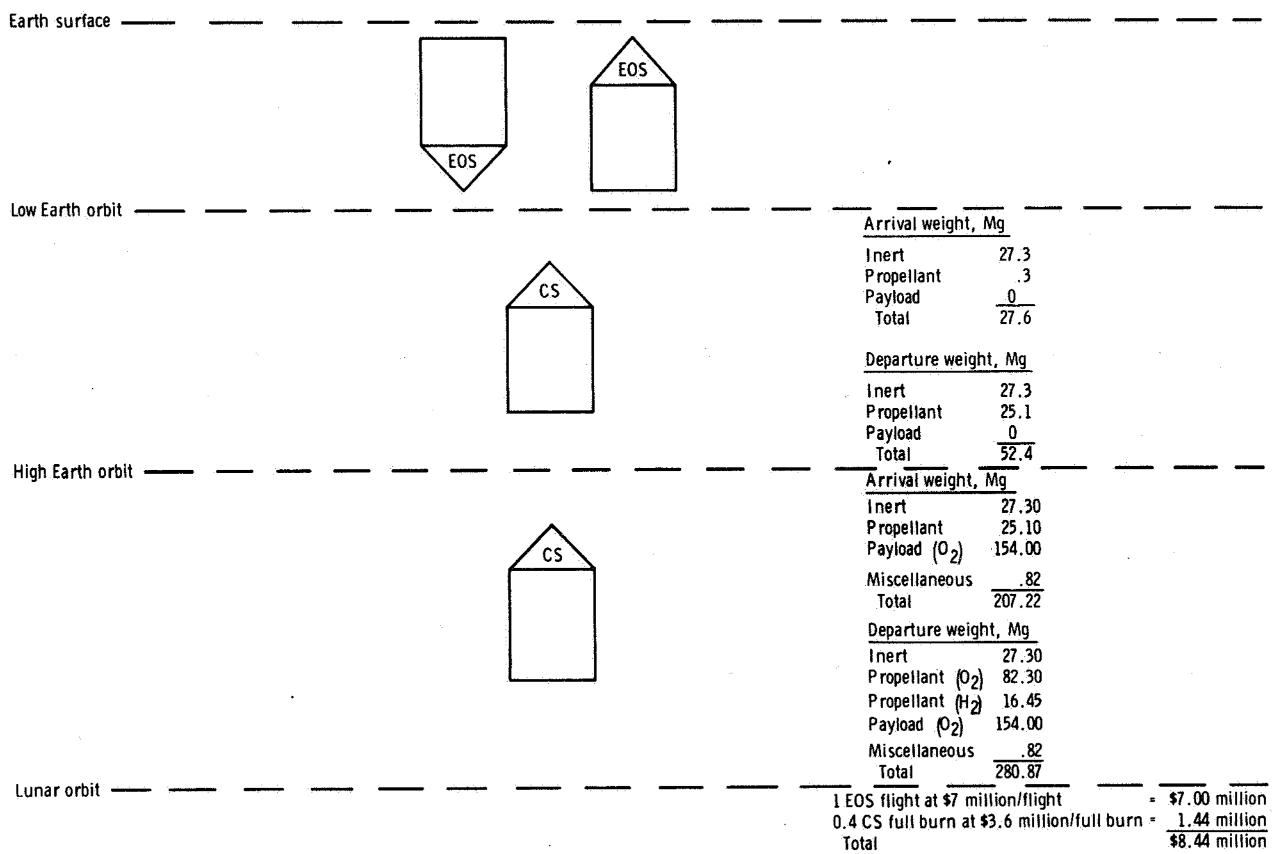


Figure 32. - Basic building block 9: lunar-orbit to high-Earth-orbit (154 megagrams of oxygen delivered) to low-Earth-orbit to Earth-surface sequence, CS performance.

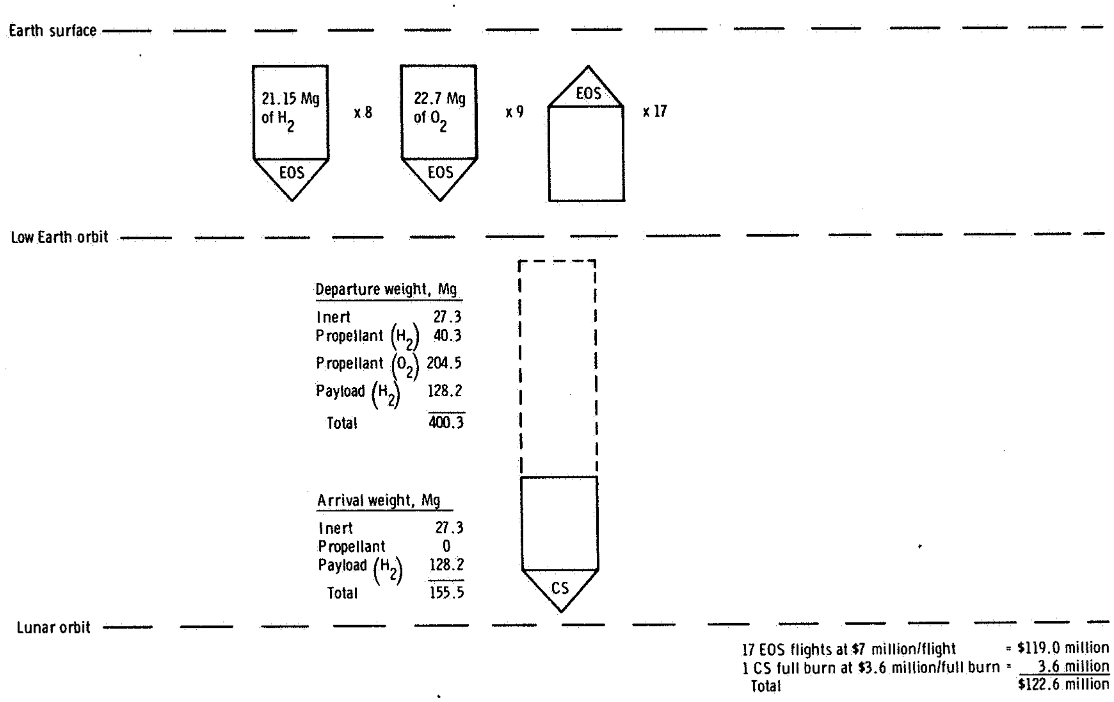


Figure 33. - Basic building block 10: Earth-surface to low-Earth-orbit to lunar-orbit sequence (four space tugs and 70 megagrams of hydrogen delivered), EOS and CS performance.

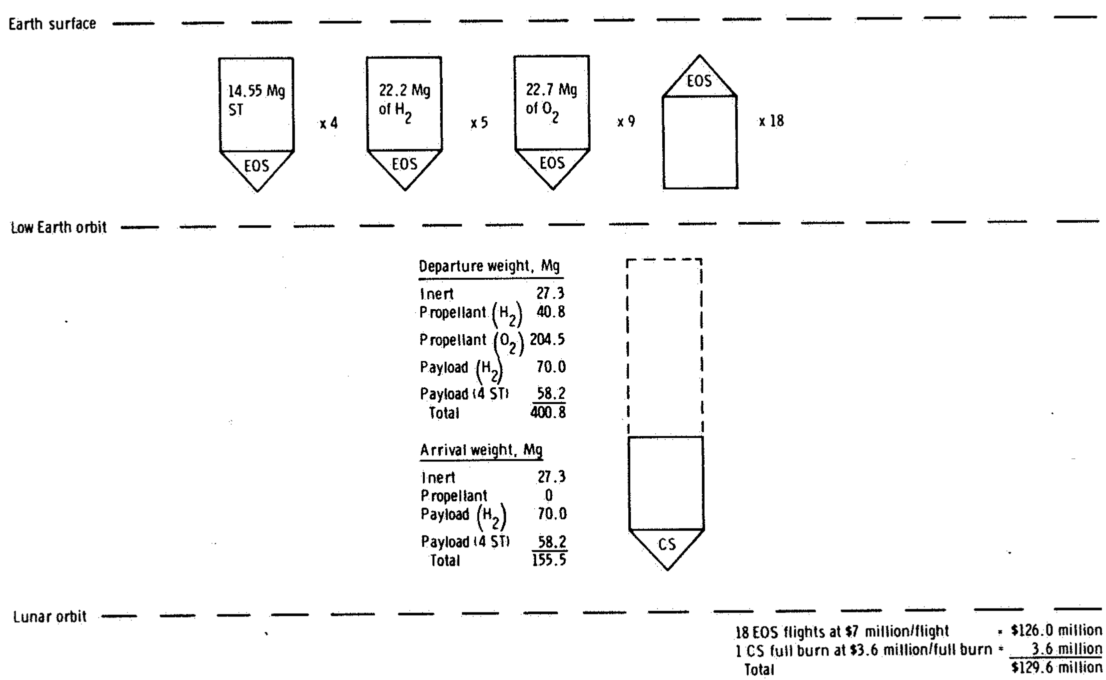


Figure 34. - Basic building block 11: Earth-surface to low-Earth-orbit to lunar-orbit sequence (128.2 megagrams of hydrogen delivered), EOS and CS performance.

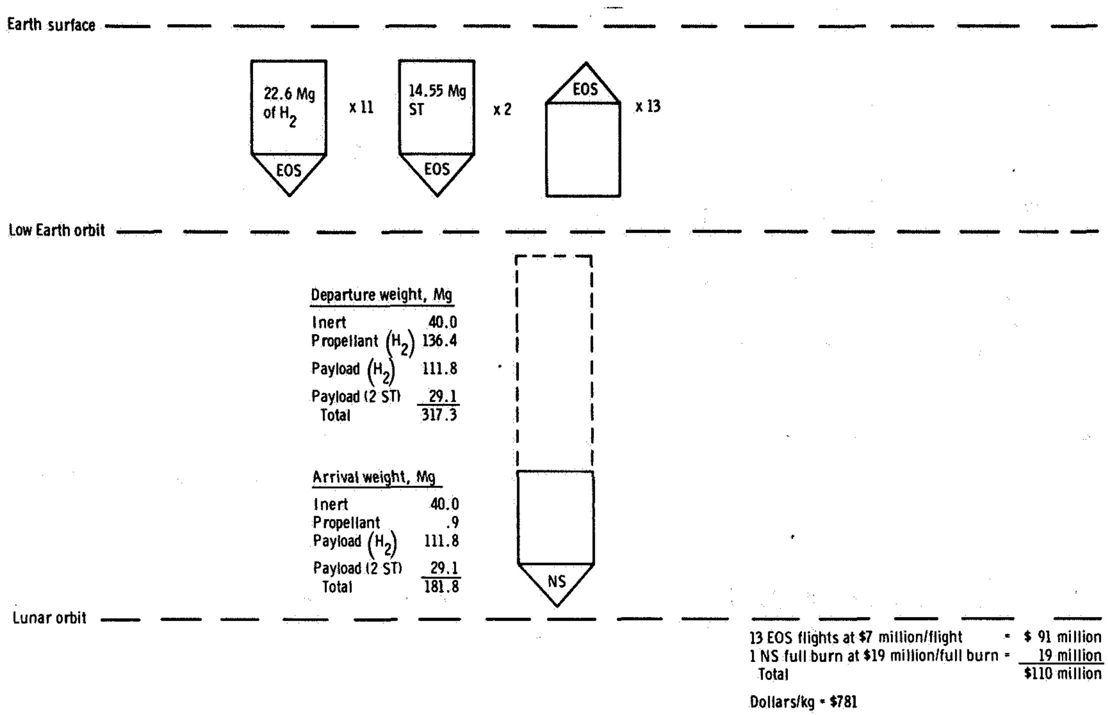


Figure 35. - Basic building block 12: Earth-surface to low-Earth-orbit to lunar-orbit sequence (two space tugs and 111.8 megagrams of hydrogen delivered), EOS and NS performance.

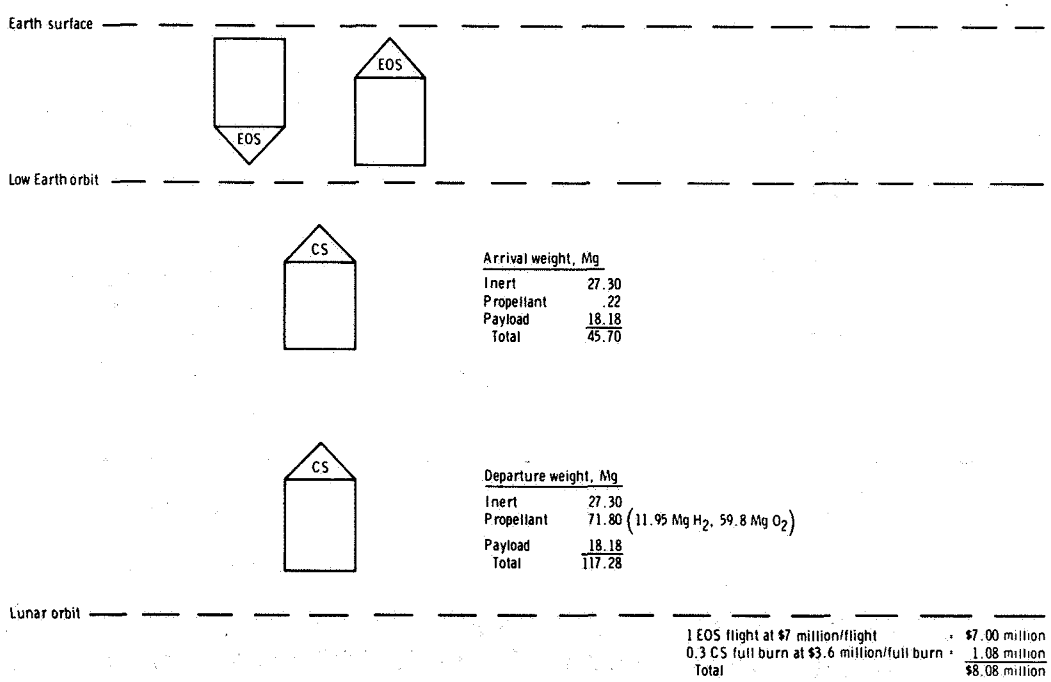
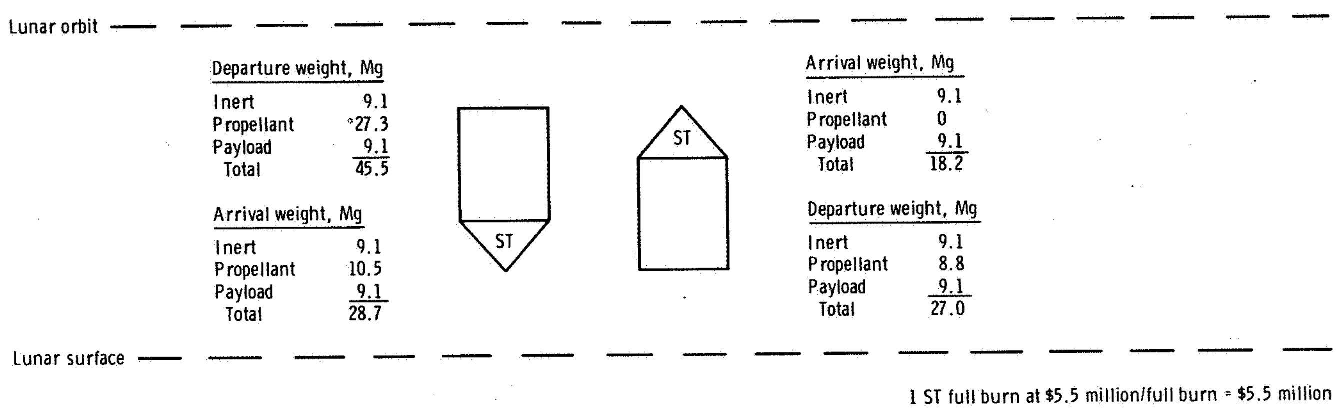


Figure 36. - Basic building block 13: lunar-orbit to low-Earth-orbit to Earth-surface sequence (18.18 megagrams of payload delivered), CS and EOS performance.



*4.54 Mg H_2, 22.7 Mg O_2

Figure 37. - Basic building block 14: lunar orbit-to-surface-to-orbit sortie flights (9.1 megagrams of round-trip payload), ST performance.

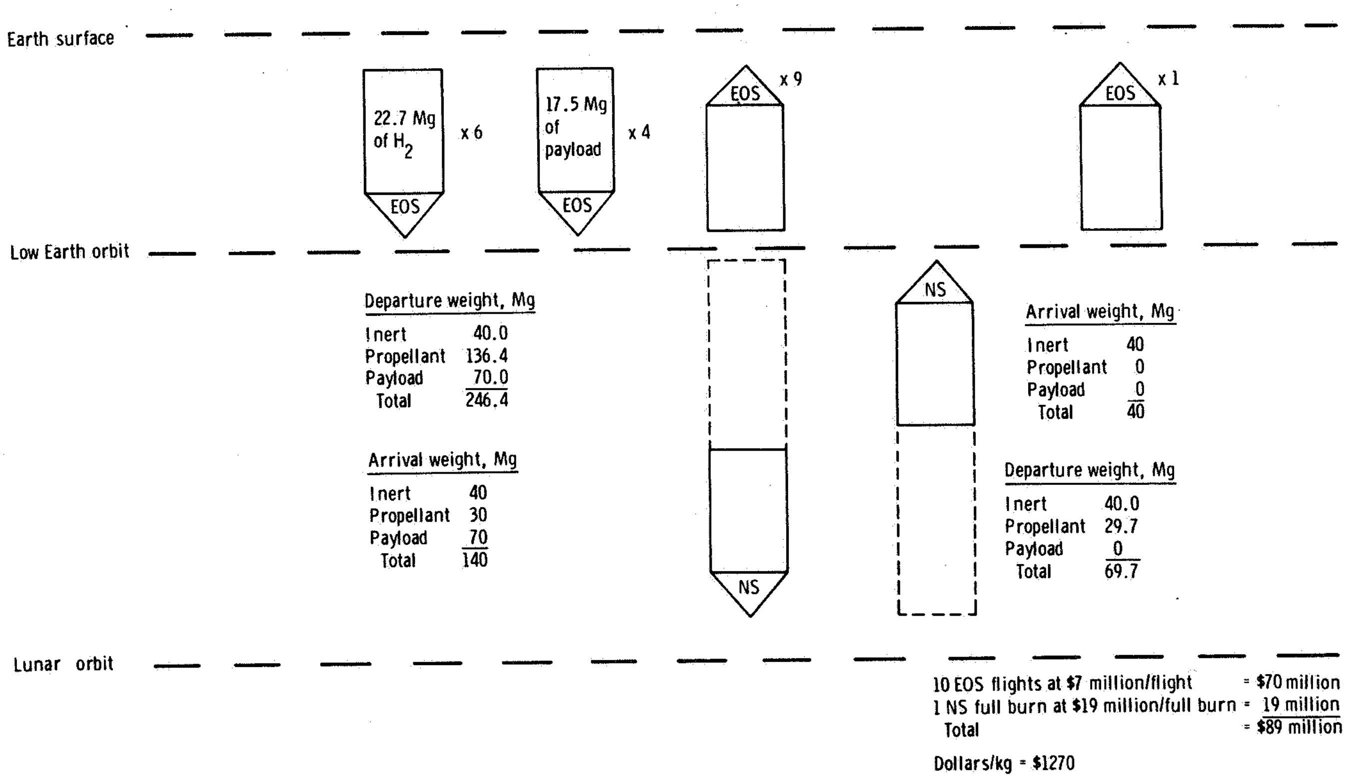


Figure 38. - Basic building block 15: Earth-surface to low-Earth-orbit to lunar-orbit sequence (70 megagrams of payload delivered), EOS and NS performance.

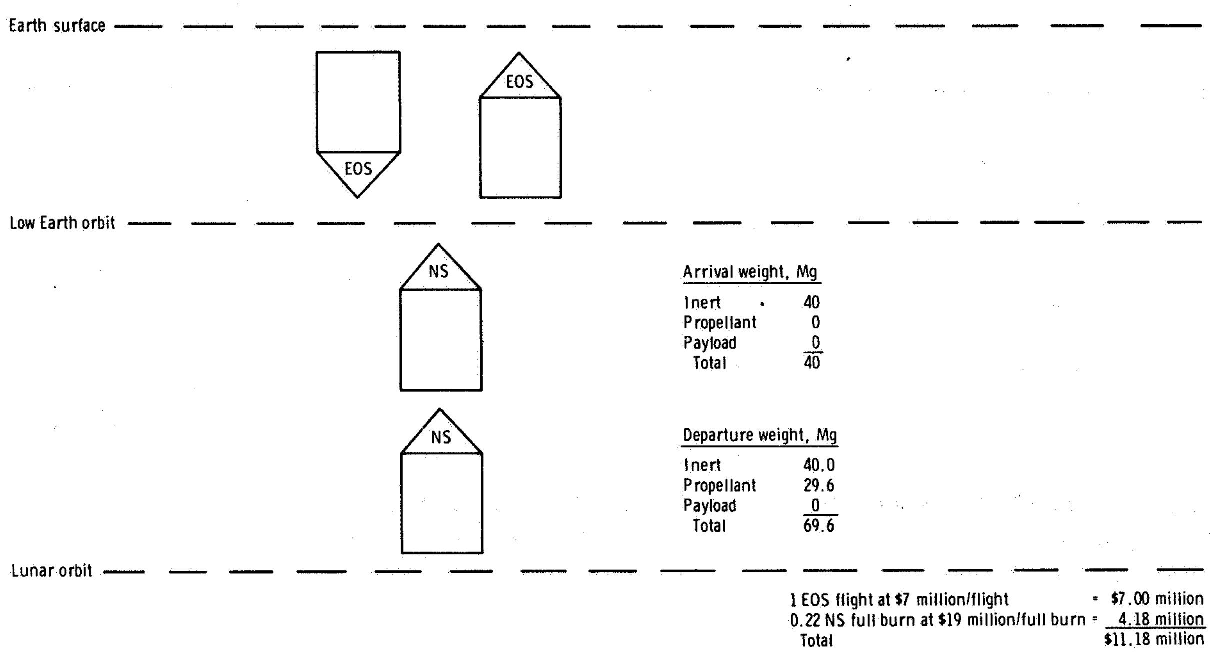


Figure 39. - Basic building block 16: lunar-orbit to low-Earth-orbit to Earth-surface sequence, NS and EOS performance.

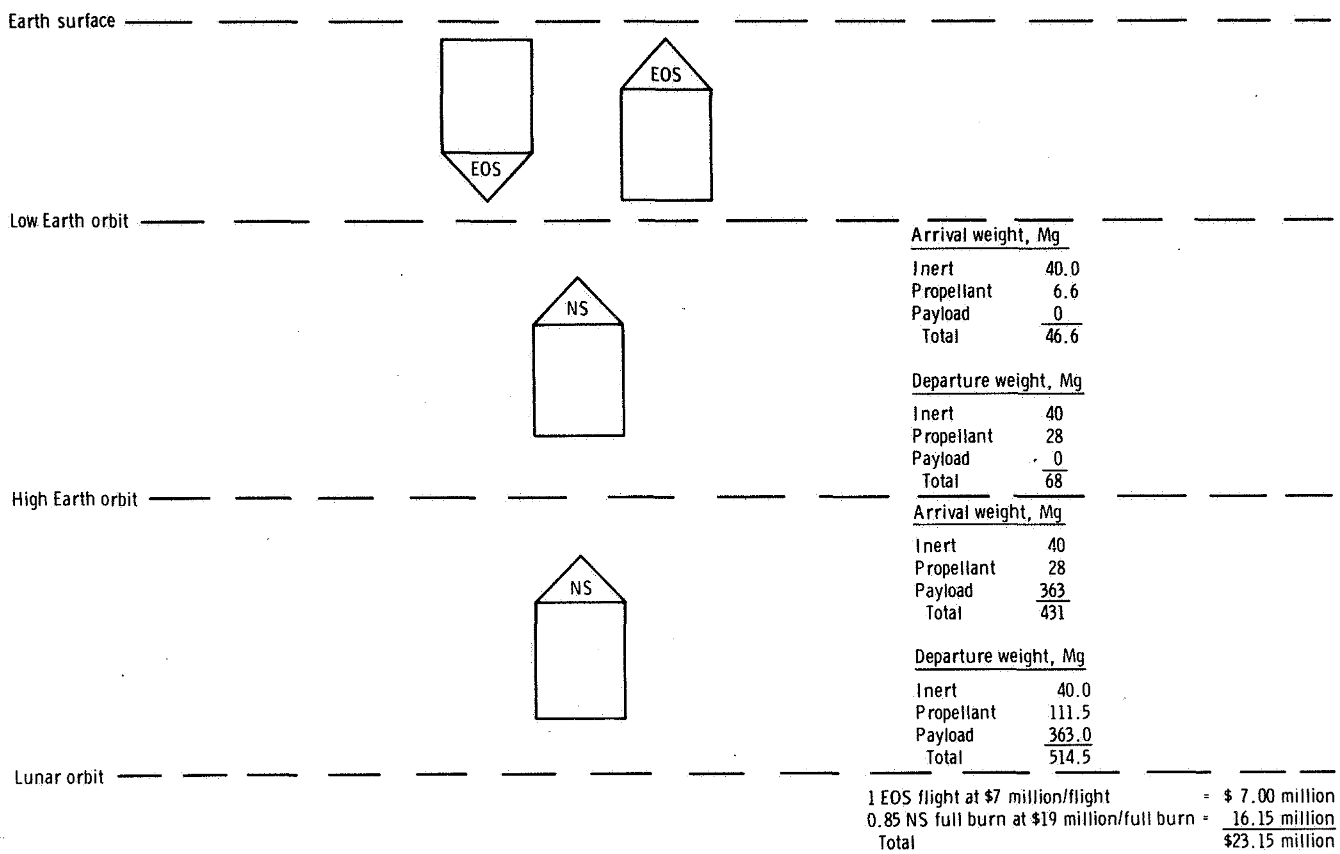


Figure 40. - Basic building block 17: lunar-orbit to high-Earth-orbit (363 megagrams of oxygen delivered) to low-Earth-orbit to Earth-surface sequence, NS and EOS performance.

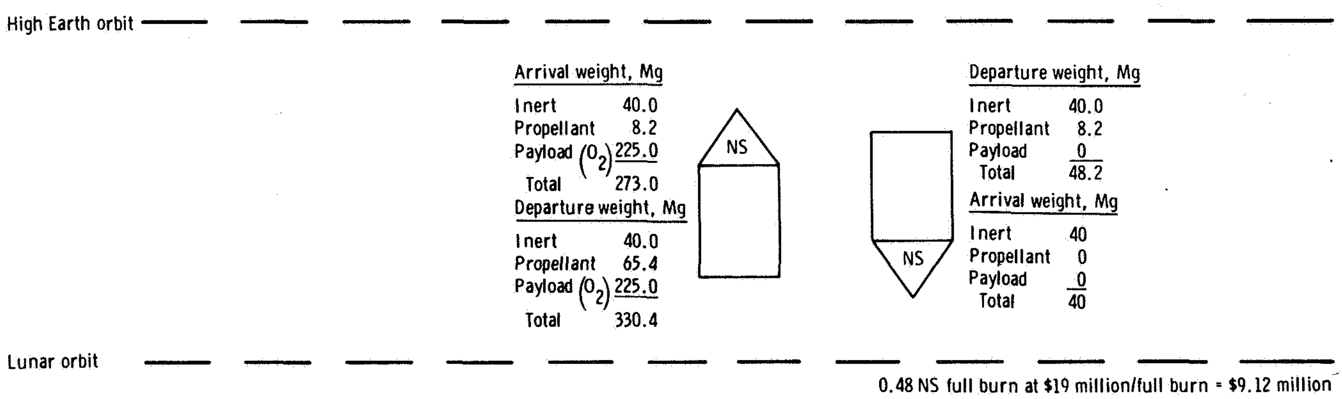


Figure 41. - Basic building block 18: Lunar-orbit to high-Earth-orbit (225 megagrams of oxygen delivered) and return sequence, NS performance.

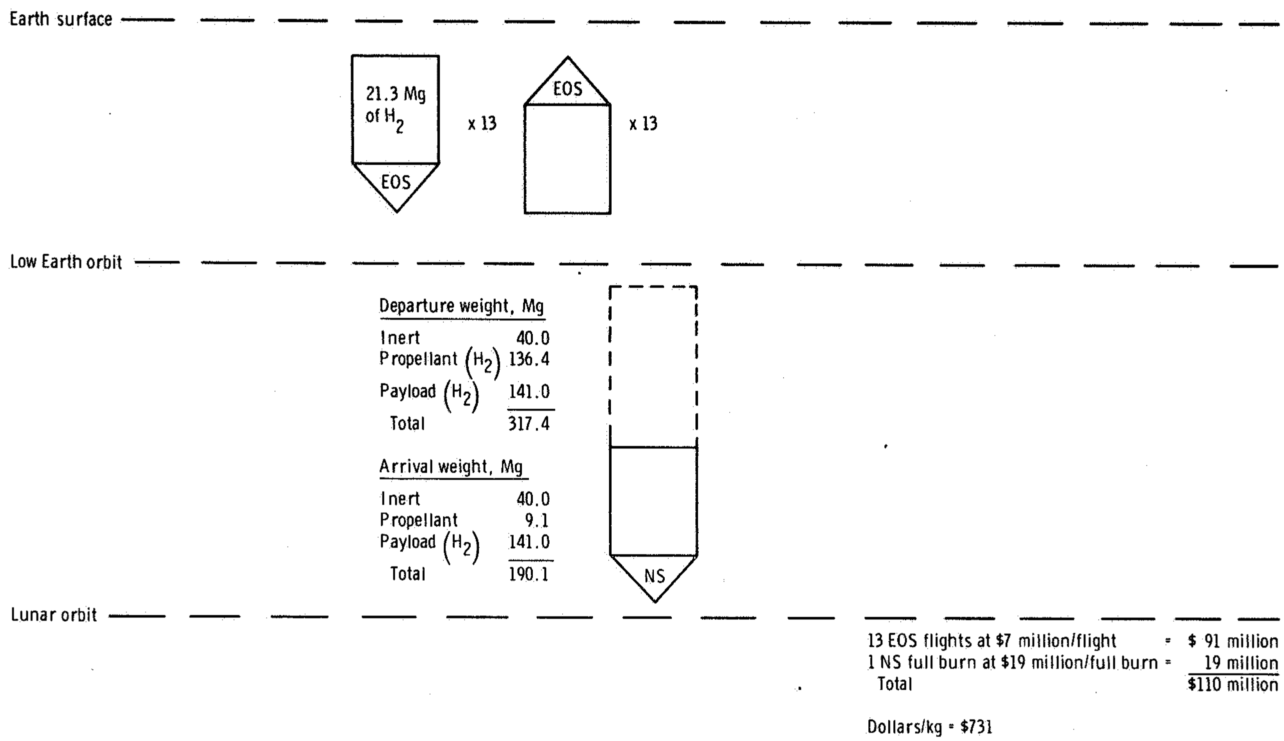


Figure 42. - Basic building block 19: Earth-surface to low-Earth-orbit to lunar-orbit sequence (141 megagrams of hydrogen delivered), EOS and NS performance.

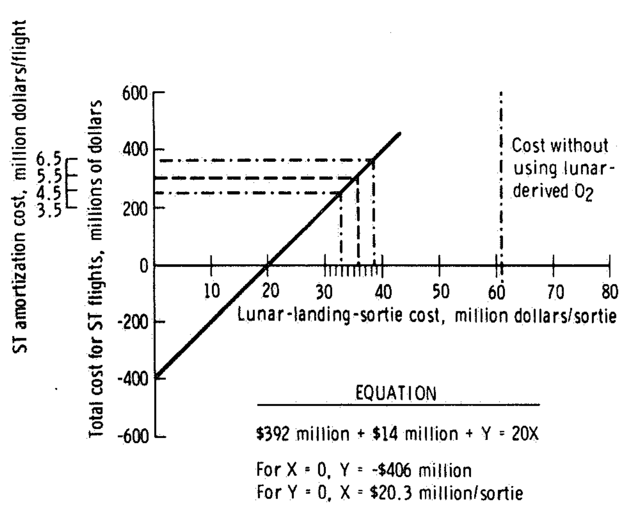


Figure 43. - Sensitivity graph for profile 1 — lunar-orbit support, 20 surface sorties, CS, 10-full-burn ST at $5.5 million/burn.

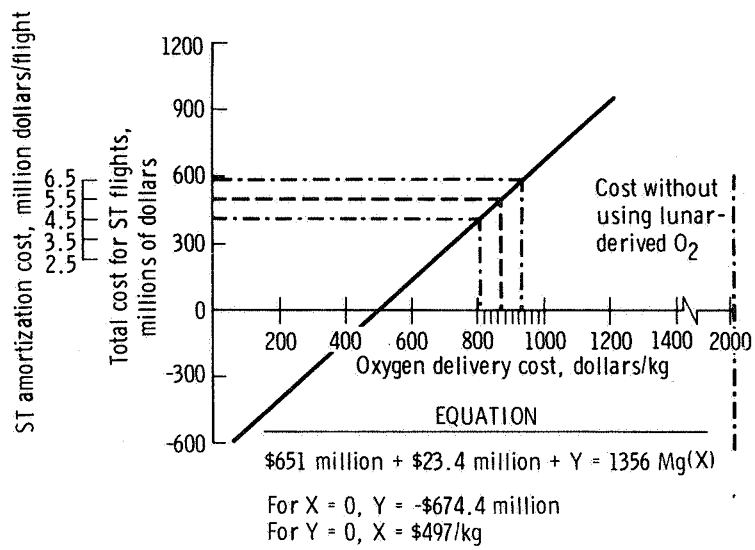


Figure 44. - Sensitivity graph for profile 2 — lunar-orbit support, CS, 10-full-burn ST at \$5.5 million/burn.

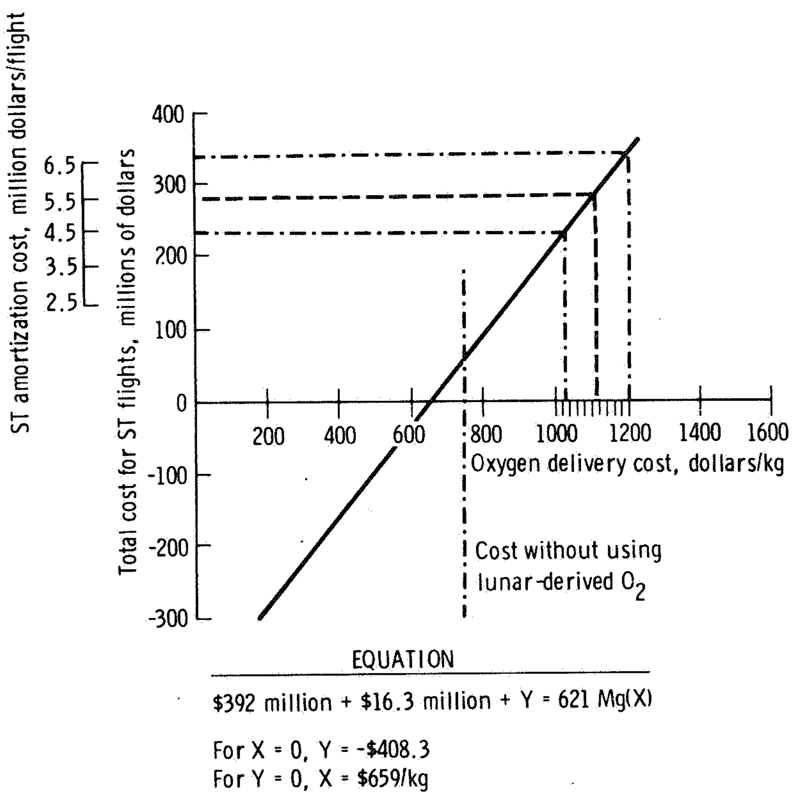


Figure 45. - Sensitivity graph for profile 3 — planetary support, CS, 10-full-burn ST at \$5.5 million/burn.

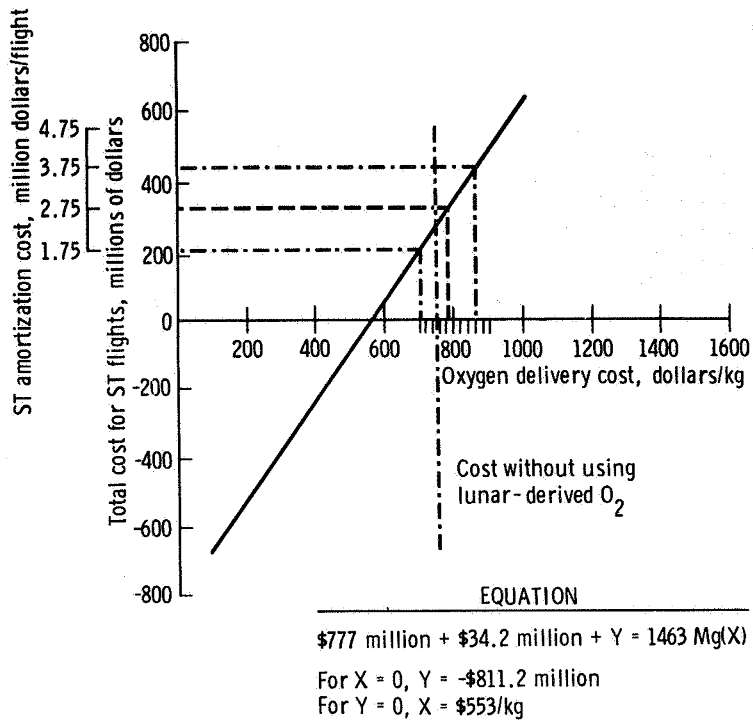


Figure 46. - Sensitivity graph for profile 4 — planetary support, CS, 20-full-burn ST at \$2.75 million/burn.

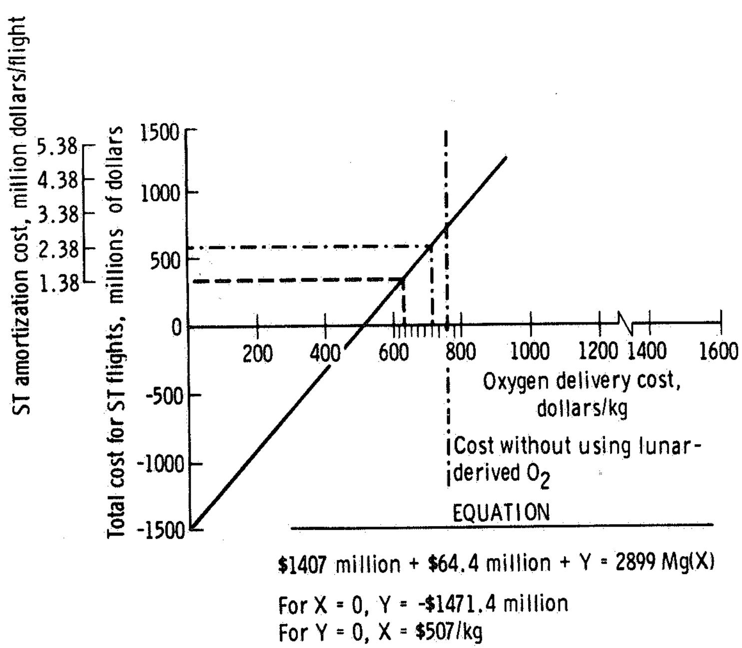
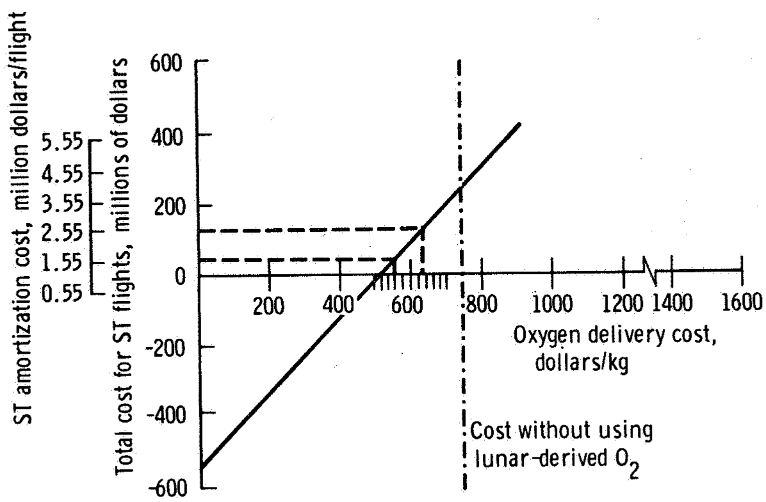


Figure 47. - Sensitivity graph for profile 5 — planetary support, CS, 40-full-burn ST at \$1.38 million/burn.

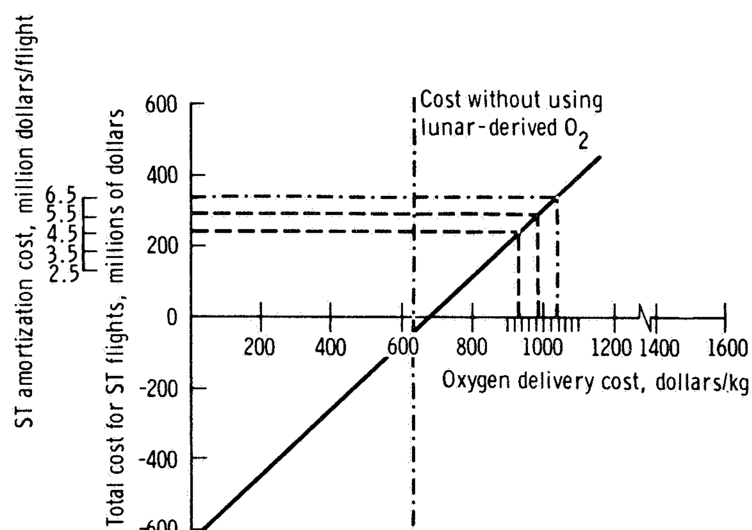


EQUATION

\$511 million + \$23.4 million + Y = 1052 Mg(X)

For X = 0, Y = -\$534.4 million
For Y = 0, X = \$507/kg

Figure 48. - Sensitivity graph for profile 6 — planetary support, CS, 100-full-burn ST at \$0.55 million/burn.



EQUATION

\$490 million + \$149.5 million + Y = 946 Mg(X)

For X = 0, Y = -\$639.5 million
For Y = 0, X = \$676/kg

Figure 49. - Sensitivity graph for profile 7 — planetary support, NS, 10-full-burn ST at \$5.5 million/burn.

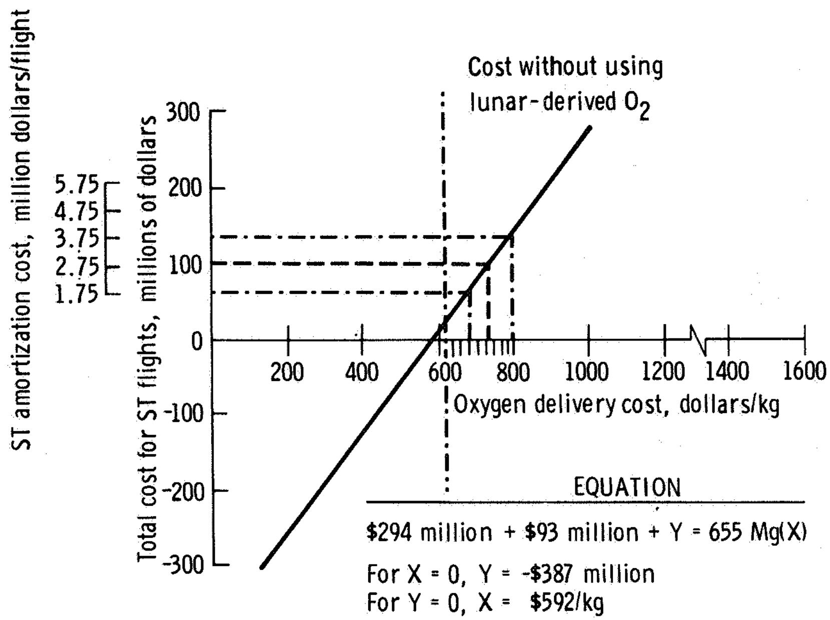


Figure 50. - Sensitivity graph for profile 8 — planetary support, NS, 20-full-burn ST at \$2.75 million/burn.

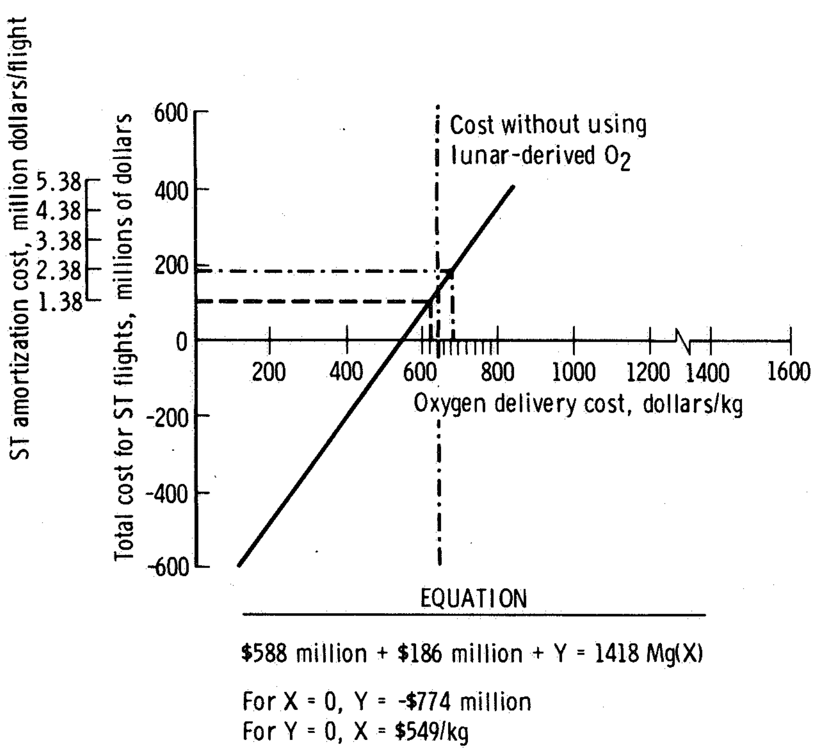


Figure 51. - Sensitivity graph for profile 9 — planetary support, NS, 40-full-burn ST at \$1.38 million/burn.

APPENDIX

ACKNOWLEDGMENTS

Contributor and organization	Date of contribution	Contribution
Andre J. Meyer,[3] Manager Lunar Exploration Project Office Advanced Missions Program Office MSC	October 1969 March 1971	Management and guidance of total activity
Dr. P. Robin Brett, Chief Geochemistry Branch Planetary and Earth Sciences Division Science and Applications Directorate MSC	Continuous	Scientific/chemical system consultation; magnetic separation concept
Dr. David S. McKay Geochemistry Branch Planetary and Earth Sciences Division Science and Applications Directorate MSC	October 1969	Initial scientific facts and concepts, hydrogen extraction concept, chairman of geoscience discussions for the hydrogen process
Edward T. Chimenti, Head Thermal Analysis Section Structures and Mechanics Division Engineering and Development Directorate MSC	October 1969	Thermal aspects consultation for the hydrogen process
Norman H. Chaffee Auxiliary Propulsion and Pyrotechnics Branch, Propulsion and Power Division Engineering and Development Directorate MSC	October 1969 June 1970	Chemical engineering consultation and design for the hydrogen process
Dr. P. Butler, Jr. Office of the Curator Lunar Receiving Laboratory Science and Applications Directorate MSC	October 1969	Provided the $FeTiO_3 + H_2 \rightarrow Fe + H_2O\uparrow + TiO_2$ reaction for the hydrogen concept
Dr. Everett K. Gibson Geochemistry Branch Planetary and Earth Sciences Division Science and Applications Directorate MSC	October 1969	Performed the theoretical calculations verifying the chemical reactions of the hydrogen concept
Hoyt McBryar Power Generation Branch Propulsion and Power Division Engineering and Development Directorate MSC	October 1969 June 1970	Provided the electrolysis unit preliminary design and programmatic details
Dr. Robert L. Golden Physics Branch Planetary and Earth Sciences Division Science and Applications Directorate MSC	October 1969 June 1970	Provided the magnetic separator unit conceptual design and programmatic details
Dr. W. Richard Downs, Technical Assistant for Advanced Systems Structures and Mechanics Division Engineering and Development Directorate MSC	January 1970	Provided all aspects of the fluorine concept and programmatic details
Humboldt C. Mandell, Jr., Chief Operations Analysis Branch Program Support Division Administration and Program Support Directorate, MSC	May 1970	Preliminary economic feasibility
Rinaldo J. Brun Launch Vehicles Division LeRC	May 1970	Propulsion system consultation

[3]Now with Structures and Mechanics Division.

Contributor and organization	Date of contribution	Contribution
F. Hujsak Convair Division General Dynamics	May 1970	Propulsion system consultation
Merlyn F. Lausten Primary Propulsion Branch Propulsion and Power Division Engineering and Development Directorate MSC	May 1970	Propulsion system consultation
Richard K. McSheehy Program Management Representative Marshall Space Flight Center	May 1970	Propulsion system consultation
William E. Goette Launch Vehicles Division LeRC	May 1970	Propulsion system consultation
Tony E. Redding Power Generation Branch Propulsion and Power Division Engineering and Development Directorate MSC	June 1970	Electrical systems consultation
Donald C. Guentert Space Power Systems Division LeRC	June 1970	Electrical systems consultation
Owen G. Morris, Manager for LM Office of Program Manager Apollo Spacecraft Program Office MSC	June 1970	Radiator system consultation
Harry M. Cameron Space Power Systems Division LeRC	June 1970	Electrical systems consultation
J. Leisenring TRW	June 1970	Electrical systems consultation
W. Breckenridge A. D. Little, Inc.	June 1970	Liquefication system consultation
Patricia M. O'Donnell Direct Energy Conversion Division LeRC	January 1971	Laboratory verification of fluorine reaction
Dennis E. Fielder, Manager Program Planning Office Future Programs Division Engineering and Development Directorate MSC	March 1971 Continuing	Management and guidance of total activity
Gus R. Babb Advanced Mission Design Branch Mission Planning and Analysis Division Flight Operations Directorate MSC	December 1971	Mission planning and analysis consultation