CELSS TRANSPORTATION ANALYSIS

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ABSTRACT

Regenerative life support systems based on the use of biological material have been considered for inclusion in manned spacecraft since the early days of the United States space program. These biological life support systems are currently being developed by NASA in the Controlled Ecological Life Support System (CELSS) program. Because of the progress being achieved in the CELSS program, it is time to determine which space missions may profit from use of the developing technology. This paper presents the results of a study that was conducted to estimate where potential transportation cost savings could be anticipated by using CELSS technology for selected future manned space missions.

Six representative missions were selected for study from those included in NASA planning studies. The selected missions ranged from a low Earth orbit mission to those associated with asteroids and a Mars sortie. The crew sizes considered varied from four persons to five thousand. Other study parameters included mission duration and life support closure percentages, with the latter ranging from complete resupply of consumable life support materials to 97% closure of the life support system. The paper presents the analytical study approach and describes the missions and systems considered, together with the benefits derived from CELSS when applicable.

INTRODUCTION

Man's basic requirements for oxygen, water, food, and waste removal must be met by the spacecraft life support system to sustain life and provide an acceptable environment for productive crew activity. To date, these basic requirements have been met on space missions by simply storing the necessary consumable materials on board for use during the mission and returning the waste products to Earth. This "open" life support technique has served well for the relatively short missions that have been flown. As manned missions become longer and crew size increases, the weight, volume, and transportation penalties associated with storing or routinely resupplying consumables will eventually become prohibitively expensive /1/2/3/. This paper reports the results of a study to determine for specific missions when consideration should be given to replacing open life support systems with "closed" systems that recycle metabolic materials.

For over two decades, NASA and its contractors have studied techniques for closing spacecraft environments by using regenerative life support technology. This effort has resulted in an extensive data base for both physical-chemical and biological regenerative systems. The physical-chemical technology has reached a point where a number of prototype subsystems are being tested. The biologically based systems have not reached the same level of advancement; however, the Controlled Ecological Life Support System (CELSS) program is making significant progress toward producing a closed life support system based on biological technology. The CELSS program is primarily directed toward biological systems for food production and environmental control mechanisms /4/5/6/.

The objectives of this study were to identify future NASA missions that will require CELSS technology and to develop cost estimates and comparisons for using controlled ecological life support systems based on selected mission model analyses. The study focused on six manned missions selected from NASA planning forecasts, compared various life support scenarios and transportation systems, and made cost evaluations.

APPROACH AND ASSUMPTIONS

The study was conducted in two separate phases: (1) a space transportation system analysis and (2) a characterization of the environmental control and life support system (EC/LSS). The results of these two phases were combined in the final step of the study to provide the mission cost estimates.

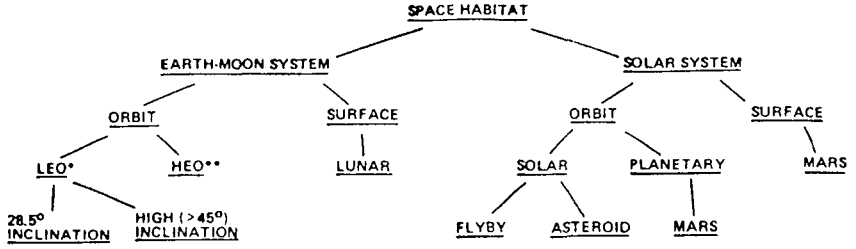
Six missions were selected for study during the transportation analysis. Several EC/LSS's were investigated for estimates of weight, volume, and power requirements. These systems were used in developing life support closure scenarios that, when combined with the transportation analysis, provide mission life support cost estimates.

Certain assumptions and ground rules were required to accomplish the study because in some cases, extensive extrapolations from the current data base were necessary. The assumptions and ground rules follow:

a. Advanced transportation technology projections were used, in conjunction with the specific mission location and mission era, to determine the corresponding costs.
b. Development costs for transportation systems or EC/LSS's were not considered.
c. Full payload manifesting on transportation vehicles was used to determine cost as opposed to providing fractional credits for partial loads. This is similar to airline industry practices whereby individual tickets cost the same regardless of the number of passengers or amount of cargo on each flight.
d. The current data base was used when available to determine EC/LSS and CELSS mass, volume, and power requirements; otherwise, engineering estimates were made.
e. EC/LSS consumables attributed to vehicle leakage and extravehicular activity were not considered.

MISSION DEFINITION

The missions selected for study were taken from information provided in NASA long-range planning documentation and from discussions with Air Force Space Division personnel. Potential locations for CELSS-equipped habitats were identified based on the projected missions. Figure 1 shows the locations that were considered.



* LEO = LOW EARTH ORBIT < 1000 KM
** HEO = HIGH EARTH ORBIT > 6000 KM

Fig. 1. Potential habitat locations

The two-step screening process used to select the missions for study is shown in Figure 2. This screening method was used to reduce approximately 34 candidate missions to the final 6 that were analyzed. The selected missions included the five resupply missions and the one sortie mission listed in Figure 3, along with the crew size range, crew rotation period, and resupply periods used in the analysis of each mission.

PHASE I TRANSPORTATION ANALYSIS

The transportation analysis was conducted in two parts: a trajectory analysis to determine the route of travel and a vehicle analysis to determine the rocket or combination of rockets

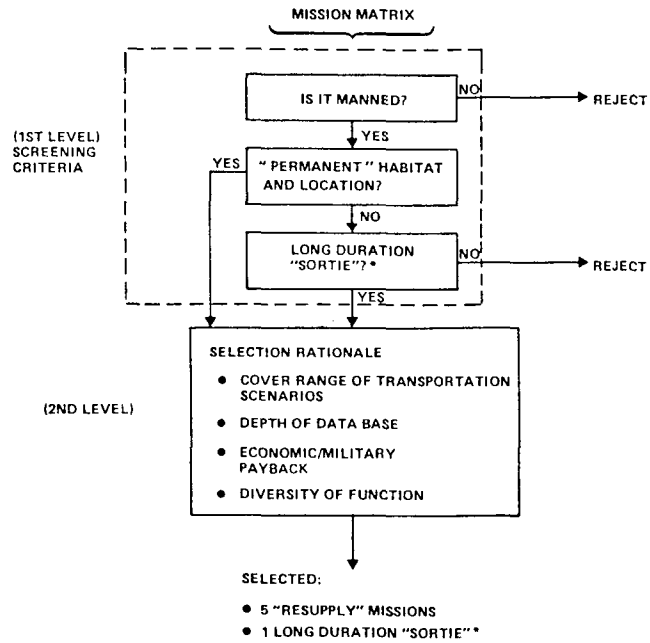


Fig. 2. Mission selection schematic

MISSION	CREW SIZE RANGE	CREW ROTATION PERIOD	RESUPPLY PERIOD
		DAYS	DAYS
OPERATIONS CENTER	4 - 12	90	90
MONITORING BASE	4	90	90
COMMAND POST	4 - 24	180	180
LUNAR BASE	12 - 48	180	90
ASTEROID MISSION	5000	1856	928
MARS SORTIE	8	944	NONE

Fig. 3. Crew size and rotation

needed to efficiently accomplish the mission. The trajectory analysis was accomplished using the standard orbital mechanics relationships, which determine time line and velocity change data. The vehicle analysis was performed using the vehicle data base compiled by Boeing, which includes inputs on mission trajectory data, mission-technology era, and approximate payload mass estimates. The results of these studies determined the optimum vehicle types required, their size, and estimated cost per kg to transport payloads from Earth to the respective space base.

LEO-Low Inclination

The low Earth orbit (LEO) operations center is located at a circular Earth orbit altitude of 370 km with an inclination of 28.5 deg. The center is serviced directly by the shuttle orbiter from an eastern test range (Kennedy Space Center) launch. In 1990, an unmodified shuttle launched to the operations center can carry approximately 65,000 lb (29,480 kg).

The operations center orbits the Earth beneath the Van Allen belts to minimize solar array degradation and radiation shielding requirements. However, the power system is quite massive due to the fact that one-third of the 90-min orbit period is in darkness requiring storage batteries for power.

LEO-High Inclination

The monitoring station mission is very much like the LEO operations base, in that it can be directly serviced by the shuttle orbiter. The station is located in low Earth orbit at an altitude of 450 km and a sun-synchronous inclination of 97.5 deg. Because of the high orbit inclination, this mission requires a launch from the western test range at Vandenburg AFB, California. The higher altitude requires that some of the orbiter payload bay area is used for fuel tanks, which are needed to extend the shuttle range. The high inclination and altitude of the station lowers the payload capacity of the shuttle to 40,000 lb (18,144 kg). The high inclination of the orbit might expose the station to a greater amount of solar proton flux, although it was determined that no additional shielding was required to protect station personnel. The sun-synchronous orbit of this station ensures that the solar arrays will be in continuous sunlight; therefore, batteries for energy storage are not required.

6 X GEO

The 6 X GEO command post is not directly accessible by the shuttle orbiter; therefore, payloads must first be brought to a LEO operations base by a shuttle orbiter. Once at the base, the payload is mated to an orbital transfer vehicle (OTV) that flies to and from the command post. The mission sequence is straightforward: a single revolution in phasing orbit establishes the correct longitude for moving into the command post orbit, followed by propulsion into transfer orbit and coast to altitude. Circularization and plane change is followed by rendezvous with the command post. After the transfer operations are completed at the command post, the manned OTV executes a plane change burn and moves into the transfer ellipse. The braking ballute (a special inflatable balloon stored on the front of the vehicle) is inflated several minutes before perigee passage through the Earth's upper atmosphere. The ballute provides controlled aerodynamic drag to decelerate the vehicle for moving into phasing orbit. The ballute is jettisoned at the apogee of the phasing orbit, followed by propulsion of the OTV into a 160-nmi orbit for rendezvous and recovery by the orbiter. The high-Earth-orbit location causes the solar array to be exposed to sunlight at all times; no energy storage system is necessary. However, the increased orbit altitude places the station above the Van Allen belts and exposes it to direct proton flux radiation. This severe radiation environment causes greater array degradation and increased module shielding weights.

Lunar Base

The lunar base mission requires three types of transportation vehicles: (1) a shuttle orbiter to raise payload from the Earth to an LEO operations center, (2) an OTV that takes payloads from LEO to lunar orbit and back, and (3) a lunar transfer vehicle (LTV) that ferries payloads from lunar orbit to the lunar surface.

The shuttle orbiter must bring the payload to an operations center where it is mated to an OTV. The OTV then propels the payload, the resupply module, into lunar orbit. After circularizing in low lunar orbit, the manned OTV module rendezvous with an LTV that was launched from the lunar surface into orbit. Crew, supplies, and propellant for the LTV are exchanged in orbit, after which the LTV descends to the lunar surface base. The manned OTV executes a plane change burn and moves into the transfer orbit where it will coast until ballute deployment and LEO aerobrake maneuver. The long lunar night precludes the use of a solar array for energy production. A SPAR-type nuclear reactor was determined to be the most mass efficient energy producing system for this mission. Both the nuclear reactor and the manned habitats use lunar soil for shielding.

Asteroid Base

The asteroid mission assumes an asteroid mining operation with a 5000 person habitat. The complex transportation scenario for this advanced mission involves four different vehicles and three separate space bases. Payload and propellant are launched from the Earth's surface by a heavy lift launch vehicle to a LEO staging base (operations center). The LEO base serves as a staging area for all personnel, cargo, and propellant enroute to the final fusion rocket assembly area in geosynchronous orbit. At the LEO base, the cargo and propellant are loaded onto a solar electric powered transfer vehicle. The personnel and any

priority cargo are transported on an enlarged version of an aerobraked OTV for a faster trip to the GEO assembly base.

The GEO base serves as the final assembly area for the large fusion rocket system used to propel payloads out to the asteroids. The complex fusion propulsion system is assembled at the GEO base with the fusion power core, propellant tanks, large thermal radiators, and the personnel and priority cargo modules. The resulting vehicle, can transport 1250 passengers and 150 metric tons of priority cargo to the asteroids. The habitat power is derived from solar arrays that assume 1990 technology. In this case, the power mass factor is necessarily conservative, as projecting solar cell performance 70 years into the future is speculative at best.

Mars Surface Exploration

The Mars sortie spacecraft is first assembled at a LEO base from individual modules brought up by the shuttle orbiter. The Mars mission vehicle consists of one stage for Mars transfer orbit injection, one stage for Earth transfer orbit injection, an enroute habitation module, and a Mars landing and ascent vehicle. Additionally, when the vehicle intercepts Mars it must be configured for aerobraking maneuvers (such as disposable nosecone and correct lift-drag) in order to dump excess velocity. The returning Earth-intercept module must also carry an aerobraking ballute. The Mars mission was included as the most realistic long-duration sortie. The technology for this mission is available today. Mission design involves two power systems: a solar array for the transit and orbiting period of the mission, and a small nuclear reactor for Mars surface exploration using Martian soil for the reactor radiation shielding.

PHASE II LIFE SUPPORT SYSTEMS CHARACTERIZATION

The life support systems characterization was based on estimating the total mass of equipment and system elements required to supply man's needs by using either an open or closed system or some combination of the two. When a system is open, the basic elements are storage containers and resupply. When a system is closed, recycling equipment must be provided in lieu of the resupply process. Trade studies were conducted based on the total weight of each type of system to determine the optimum combinations of supplying materials. Total weight was determined by the sum of the weight of the following elements: (1) required materials such as water, oxygen, food; (2) appropriate storage containers; (3) recycling equipment; (4) pressure vessel to house the elements, based on a weight penalty of the volume occupied by the system elements; and (5) the resupply module, based on the volume of material to be resupplied. Power requirements were also determined for each system type. Figure 4 shows the logic flow used to derive the weight, volume, and power estimates.

The following paragraphs summarize the data that were derived for the water, air, waste, and food systems considered in the study. Weight, volume, and power were estimated for open and recycle conditions for each system. For the food system, three food growing scenarios (i.e. food growth comprising 3%, 50%, and 97% of the total diets) in addition to the 100% food resupply scenario, were considered and are shown in Figure 5.

A four-man crew segment was used as a basic module size for developing the weight, volume, and power estimates. The rationale for the four-man module baseline selection follows:

a. It fits the range identified in the mission crew size analysis with the exception of the asteroid mission, which was handled separately.
b. It provides a generic baseline for mass, volume, and power estimates.
c. It eliminates the necessity for a detailed EC/LSS design for each mission and closure scenario, which was outside the scope of this study.
d. It is the module size on which the most current data base for the physical-chemical systems is based (Space Operations Center).

Closure Scenarios

Seven closure scenarios were selected to enable the comparison of an entirely open system with various physical-chemical system closures and the comparison of a closed physical-chemical system with three food-growing scenarios. Figure 6 defines these seven closure scenarios using codes A through G assigned to each case respectively. The initial total mass, resupply mass, and power requirements are also summarized for each closure scenario.

Plant growth systems provide advantages in addition to supplying fresh food. The water that passes through plants in the transpiration process is purified. This phenomenon can be used

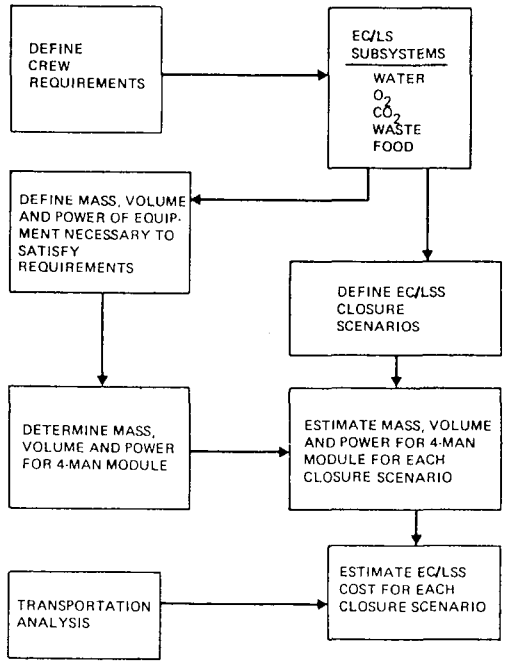


Fig. 4. Approach to life support systems characterization

PLANT SPECIES (% OF DIET)		
3%	50%	97%
LETTUCE	DRY BEANS	SOYBEAN
TOMATO	PEANUTS	POTATO
CARROT	CABBAGE	MUSTARD GREENS
	CARROT	PEANUTS
	TOMATO	RICE
	POTATO	PEA POD
	GREEN BEANS	SPLIT PEA
	LETTUCE	CORN
	MELONS	KALE
	PEAS	DRY BEANS
	WHEAT	WHEAT
		TURNIP GREENS
		CHICKPEA
		OATS
		BROCCOLI

Fig. 5. Plant species for projected diets

to advantage if water purification equipment can be reduced in the total system. This study assumed that no water purification equipment would be necessary if the daily water requirement for the crew could be met by the growing plants. It was further assumed that waste products removed from the water by the plants during transpiration are later removed from the inedible plant material during waste processing. The other important advantage offered by plant systems is the removal of carbon dioxide and the generation of oxygen by the plants. Again, this is an advantage to the total system based on estimated quantities of CO_2 removed and O_2 generated.

When credits for water and oxygen generation and carbon dioxide removal are applied to the total system characterizations, the weight, volume, and power system requirements are affected. For the 3% plant growth scenario, the percentage credits are 19% for water, 6% for oxygen, and 5% for CO_2. Because percentages in this case are relatively low, no credit was given the 3% scenarios. In the case of growing 50% of the required food, the water requirement is clearly met with 180% and the oxygen and carbon dioxide credits are approximately 50%. Credits given for the 97% food growth scenario were assumed to be 100% for all three materials, even though the CO_2 removal was shown to be only 85% of the requirement. It was assumed that 100% CO_2 removal could be easily achieved by adjusting the plant species in the diet. The number derived for CO_2 removal in this study was averaged from several plant species; numbers for individual species vary widely.

Other factors to be considered in estimating the total closure scenario weights are (1) a pressure vessel module to house the equipment in the space environment and (2) a resupply module to provide protection for transporting supplies. To determine a first-order estimate of the weight of these modules, a density factor of module weight-to-volume was applied. The density factors for both modules were derived from Space Operations Center (SOC) data /7/. The habitat module from the SOC study was used as a baseline to estimate the housing module for CELSS equipment. The SOC resupply module was used as the baseline for transporting CELSS resupply materials. The derived weight-to-volume factor of 44.0 kg/m^3 was used for the CELSS module and 27.8 kg/m^3 was used for the resupply module.

Mission and Scenario Comparisons

The total mass and power estimates developed for each of the closure scenarios, shown in Figure 6, were used to generate two sets of comparisons. The first set compares the mass data for the open system, closure scenario A, with each of the physical-chemical system closures, scenarios B, C, and D. The second set compares the closed physical-chemical system, D, with each of the food closure scenarios, E, F, and G. These two sets of comparisons are based strictly on the mass and power estimates that were developed for each of the closure scenarios and do not include any transportation considerations. The transportation analysis is used in combination with the closure mass estimates to derive potential cost savings that can be available by closing the food system. The mass comparisons for each closure scenario must be worked separately for each mission because the factors for converting power to mass and the radiation shielding factors are different for each mission.

Closure Scenario	Initial Total Mass, kg	90-Day Resupply Mass, kg	Nominal Power, Watts
A - Open	17,895	13,552	1,140
B - H_2O Closed	5,814	2,102	1,907
C - Air Closed	16,216	12,523	5,399
D - H_2O and Air Closed	4,135	1,069	6,166
E - 3% Diet	5,785	1,064	7,762
F - 50% Diet	15,389	549	17,445
G - 97% Diet	27,002	237	26,740

Fig. 6. Summary of mass and power estimates for closure scenarios (4-man module, 90-day resupply)

In the comparisons that follow, closure scenario E (3% food closure, salad plants) is not considered. Due to the small amount of oxygen generated and carbon dioxide removed by these plants, the physical-chemical systems must be used to the full extent to satisfy the requirements; therefore, no savings would be realized. Scenario E could provide psychological advantages but it is not considered significant from a life support system viewpoint.

LEO-low inclination mission. For this mission the power penalty factor is 113 kg/kW and includes the weight of the solar array and batteries necessary for power in the near Earth

orbit. Radiation shielding is not required for this mission because the orbit is below the Van Allen radiation belt and the pressure vessel wall of the module provides adequate protection.

The curves drawn in Figure 7 show the weight and cost advantages of closing the physical-chemical systems. All closures show an immediate advantage over the open system, although the combined water and air systems closure provide the greatest savings. The physical-chemical system closure comparisons follow this pattern for other missions as well. Because of the tremendous weight saving from closing the water and air systems, it does not appear reasonable to consider open water and air systems for long-term missions, especially those beyond the Earth-Moon system. For these reasons, the other five mission comparisons for physical-chemical systems are not reported.

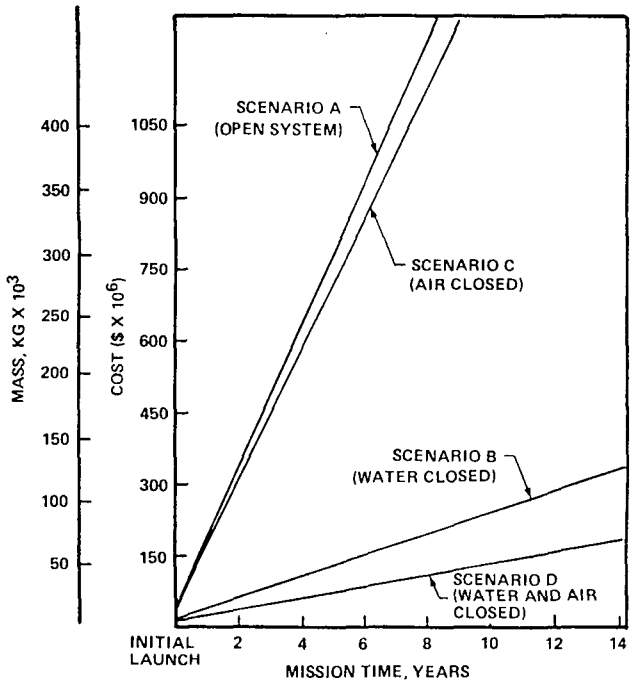


Fig. 7. Mass and cost comparison of physical-chemical systems mission: LEO—low inclination

Mass estimate data used for comparing food system closures, scenarios F and G, with the closed physical-chemical system, scenario D, were used to draw the curves in Figure 8. The mass penalties for power and radiation shielding are the same as discussed previously for this mission. Breakeven times for the LEO-low inclination mission are shown at the intersecting points of the curves for scenarios F and G with the curve of scenario D. Breakeven times for the mission are approximately 5.9 and 7.5 years for closure scenarios F and G respectively. These numbers indicate that at least some growing plants could be beneficial, especially if mission life is 10 or more years.

Comparing the cumulative cost data for the first 6 years of operation, the physical-chemical scenario D is the least expensive system. If station life is expected to be between 6 and 10 years, scenario F, which is the 50% food closure, is the minimum cost system. For an expected station life greater than 10 years, 97% CELSS closure is the most cost-effective system. After 15 years of operation, a 97% CELSS closure would save approximately 68 million dollars when compared with a physical-chemical system—or almost one-half of the cumulative transportation cost of the system.

Comparisons similar to these just described for the LEO-low inclination orbit were made for each of the remaining five missions selected for study. The results of these cost comparisons are shown in Figure 9. These data show that significant potential cost savings may be achieved in five of the missions by using a CELSS. The Mars sortie mission was the only mission that did not show a benefit by using a CELSS over a 15 year period. A complete derivation of results is presented in the study final report /8/.

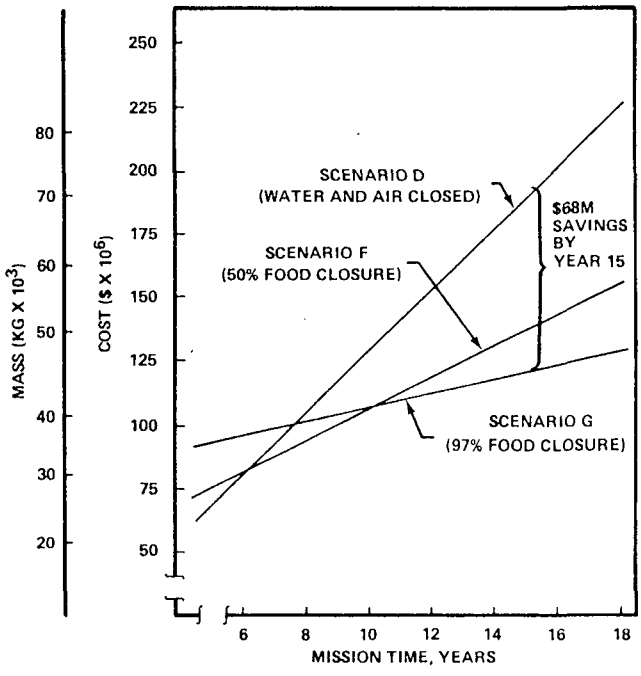


Fig. 8. Cumulative mass and cost savings with CELSS mission: LEO—low inclination

MISSIONS	BREAKEVEN TIME YEARS *		DOLLAR SAVINGS AT 15 YEARS
	50% CELSS DIET (F)	97% CELSS DIET (G)	
LEO - LOW INCLINATION	5.9	7.5	68M
LEO - HIGH INCLINATION	5.6	7.1	260M
6 X GEO	10.5	12.9	30M
LUNAR BASE	5.7	7.2	455M
ASTEROID	1	1.8	25.5B
MARS SURFACE	N/A	N/A	-0-

* NOTE: COMPARED TO CLOSURE SCENARIO D (WATER AND AIR CLOSED)

Fig. 9. Mission breakeven time and cost savings summary

While a great deal of development work will be required to develop operational, reliable CELSS hardware, large benefits can be achieved. The analysis shows that small manned space stations in the Earth-Moon system can derive significant benefits from CELSS while large manned bases beyond the Earth-Moon system will require CELSS technology if these bases are to be established.

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