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Controlled Ecological Life Support System: Transportation Analysis

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CELSS

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CELSS

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LIST OF ACRONYMS AND ABBREVIATIONS

ARS	Air Revitalization System
CAMS	Continuous Atmosphere Monitoring System
CELSS	Controlled Ecological Life Support System
CM	Centimeter
CO_2	Carbon Dioxide
deg	Degrees (angular)
ECLSS	Environmental Control/Life Support System
ft	Foot
GEO	Geosynchronous Earth Orbit
HEO	High Earth Orbit
HLLV	Heavy Lift Launch Vehicle
HM	Habitat Module
hr	Hour
kg	Kilogram
km	Kilometers
kW	Kilowatt
IOC	Initial Operating Capability
lbf	Pounds Force
LDEF	Long Duration Exposure Facility
LEO	Low Earth Orbit
LiOH	Lithium Hydroxide
LSS	Life Support System
LTV	Lunar Transfer Vehicle
m	Meter
mmHg	Conventional Millimeter of Mercury
MOTV	Manned Orbit Transfer Vehicle
$Ni\text{-}H_2$	Nickel - Hydrogen
O_2	Oxygen
OTV	Orbital Transfer Vehicle
PMSC	Performance and Mass Sequence Calculator
ppm	Parts per Million
SAWD	Solid Amine Water Desorbed
SEPS	Solar Electric Propulsion System

LIST OF ACRONYMS AND ABBREVIATIONS (CONTINUED)

SOC	Space Operations Center
SPS	Solar Power Satellite
STS	Space Shuttle Transportation System
TIMES	Thermoelectric Integrated Membrane Evaporation System
ΔV	Change to Velocity
VCD	Vapor Compression Distallation

1.0 INTRODUCTION

This document is the final report for the Regenerative Life Support Research/ Controlled Ecological Life Support System (RLSR/CELSS) Program Planning Support (Transportation Analysis) study, Contract Number NAS2-11148. Boeing Aerospace Company performed the study for the NASA Ames Research Center in support of the Controlled Ecological Life Support System Program and the Advanced Life Support Program.

1.1 Study Objectives

The study objectives are:

a. To identify future NASA missions that will require CELSS technology based on specific mission models.

b. To develop rationale and justification, and to identify potential cost savings for controlled ecological life support systems based on mission model analysis.

1.2 Background

Certain basic physiological needs (fig. 1-1) must be satisfied in order to sustain man. In the terrestrial environment, these needs are met through the evolution of life forms that effectively use man's waste products in conjunction with energy received from the sun, to produce fresh supplies of food, oxygen, and clean water. Likewise, in the artificial environment of a spacecraft; oxygen, water, and food must be provided, and the waste products that man generates must be removed. The spacecraft environment, however, does not have the capabilities or resources that are supplied by the Earth biosphere to carry out these life-sustaining processes. Artificial methods must be utilized to supply man's needs.

To date, manned spaceflight has used the relatively simple technique of bringing all the necessary sustenance for the duration of the mission and collecting and storing waste products for return to Earth. This is referred to as an open system. It was recognized early, as manned missions became longer and crew size increased, that the weight, volume, and transportation penalties of storing or routinely resupplying consumables

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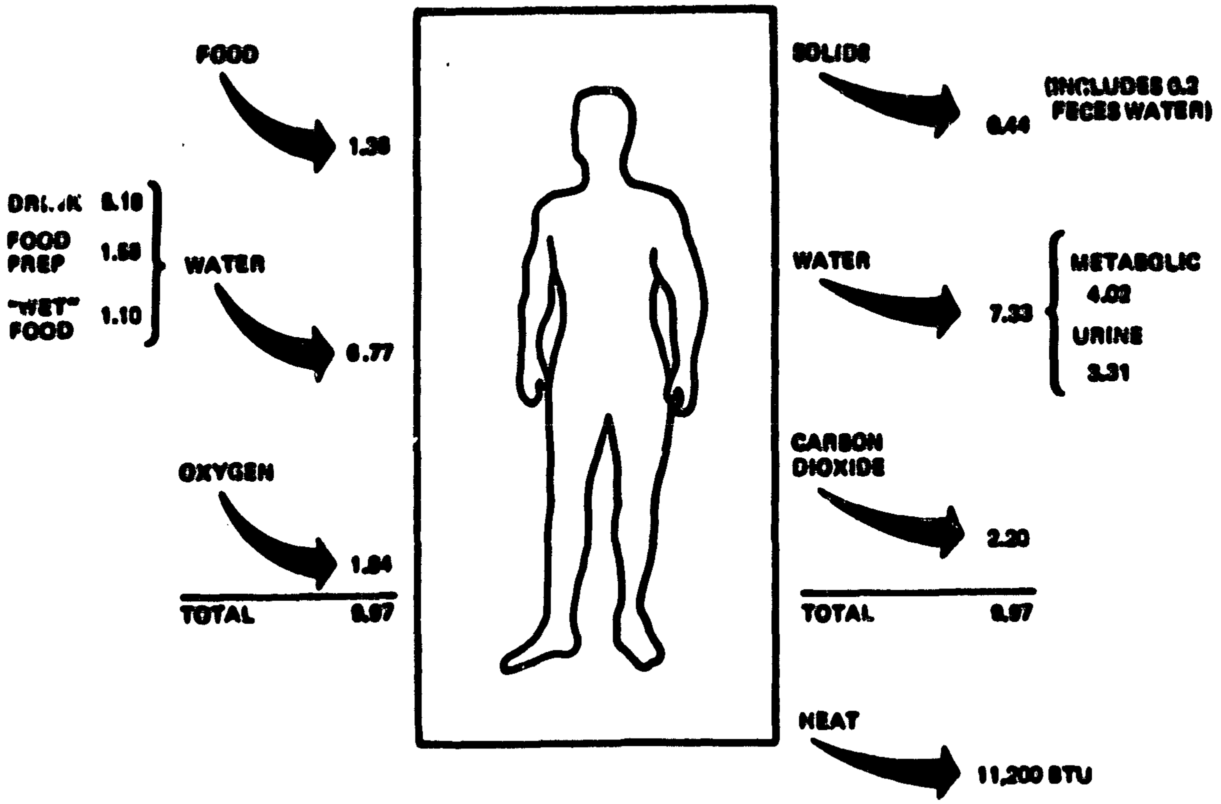

Figure 1-1 Human Metabolic Requirements (Pound/Man-Day)

would at some point become expensive, and that eventually the cost would become prohibitive (refs. 7, 12, 13, 19, 21, 22, 23, 32, 34, 43, 46, 66, and 71). Since the early 1960's, regenerative life support technology has been under development, and there now exists a foundation in both systems definition and subsystem technology to support long-duration manned missions. In many cases this development has reached the engineering prototype stage for many of the physiochemical systems.

The NASA CELSS program was initiated as a long term research and development effort to fulfill future needs for recycling and regenerating materials for human consumption during extended NASA space missions. This material recycling is referred to as a closed system. The CELSS program has been primarily directed toward biological and synthetic systems for food production and environmental control mechanisms (refs. 3, 26, 28, 30, 33, 37, 38, 40, 43, 45, 47, 49, 54, 60, 66, 67, 70, and 73).

It was the intent of the RLSR/CELSS Program Planning (Transportation Analysis) study to use a systems analysis approach to determine which generic missions would benefit from CELSS technology. The study focused on manned missions selected from NASA planning forecasts covering the next half century. Comparison of various life support scenarios for the selected missions and characteristics of projected transportation systems provided data for cost evaluations. This approach identified missions that derived benefits from a CELSS, showed the magnitude of potential cost savings, and indicated which system or combination of systems would apply. This report outlines the analytical approach used in the evaluation, describes the missions and systems considered, and sets forth the benefits derived from CELSS when applicable.

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2.0 APPROACH AND ASSUMPTIONS

2.1 Overall Study Approach

The overall approach was to conduct a detailed transportation analysis using an extensive data base from previous programs to evaluate six missions selected for study. The transportation analysis, in conjunction with data derived for mass and volume requirements for several environmental control/life support systems closure scenarios, was used to determine breakeven time and cost for mission closure scenario comparisons. The development of transportation costs as a function of EC/LSS closure gives an estimate of cost savings and provides justification for life support technology advancement. Figure 2-1 shows the interrelationships and tasks used to conduct this study.

2.2 General Assumptions

The assumptions and groundrules employed during the study are listed below.

a. Advanced transportation technology projections were used, in conjunction with the specific mission location and mission era, to determine the corresponding costs.

b. Development and operating (labor, etc.) costs for transportation systems or EC/LS systems 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 a particular 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.

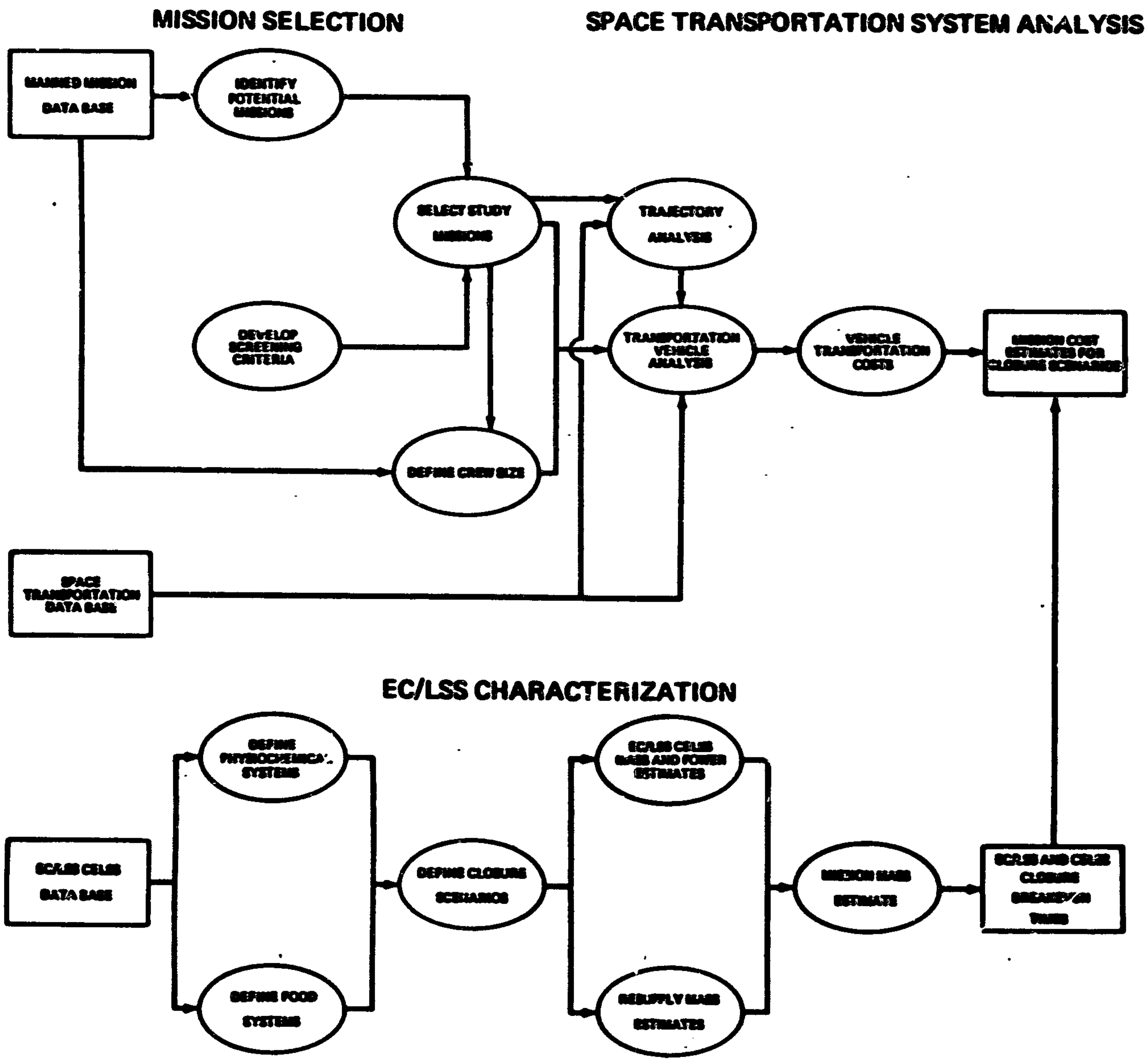


Figure 2-1 Study Logic Flow

f. The EC/LSS volume, including plant growth area, was assumed to have the same radiation protection as required for human habitation.

g. Only commonly used higher plants were considered for food production.

3.0 MISSION DEFINITION

3.1 Identify Potential Missions

Potential manned missions have been identified using information from NASA long range planning documents and from discussions with Air Force Space Division personnel. These missions are categorized by function, and are displayed in figure 3-1. Potential mission locations are diagrammed in figures 3-2 through 3-4. Figure 3-2 shows the potential locations for a CELSS-equipped habitat. Figures 3-3 and 3-4 are pictorial displays of these potential locations. Ceres and Vesta are two of the largest asteroids, with the orbit of Ceres near the outer boundary of the majority of bodies in the asteroid belt. Generic mission descriptions from the mission matrix have been noted under the various mission locations in figure 3-5. The last figure shows the variety of mission locations available for selection of transportation scenarios.

3.2 Selection Procedure

The missions to be studied were selected in the manner shown in figure 3-6. The first level rejects all missions for which CELSS is obviously unlikely—such as unmanned missions, or Apollo-type short duration sorties. Those missions that passed the initial screening process were subjected to the selection rationale to identify a number of realistic missions that are diverse both in function and location. This desire for diversity motivated the inclusion of an additional mission, the long-duration sortie. This variety of mission function and location covers a wide range of transportation scenarios, and provides a broader perspective on the indication of cost breakeven for CELSS.

3.3 Selected Study Missions

The six missions chosen include four in the earth-moon system, and two farther out in the solar system. The local environment—radiation, solar flux, usable materials— of each mission varies greatly because each mission has a distinct location. The mission location has a significant impact on the final design of the space base as well as on the transportation methods designed to get to that base. For example, low earth orbit stations that fly beneath the Van Allen belts do not require the large amounts of radiation shielding necessary in other missions, although heavy Ni-H_2 batteries are needed to store solar energy (for use when flying in the earth's shadow 16 times per day). The values for

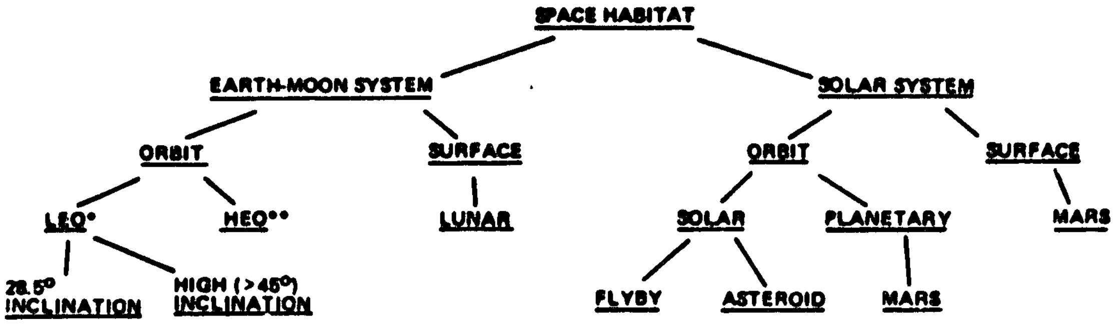
SPACE INDUSTRIALIZATION			SOLAR SYSTEM			SPACE SCIENCE	EARTH SERVICING	
MANUFACTURING BASIC MATERIALS	MANUFACTURING FAB & ASSY	RESOURCE EXTRACTION (SPACE MINING)	LUNAR EXPLORATION AND EXPLOITATION	PLANETARY EXPLORATION	SOLAR EXPLORATION AND MONITORING	ASTRONOMY–SETI*	EARTH MONITORING	POWER

• LDEF, SPACELAB
• ELECTROPHORETIC SEPARATION OF BIOLOGICALS
  • ENZYMES
  • HORMONES
10^5–10^8 \$/lb
• HIGH VALUE MAT'LS
  • SPS SOLAR CELLS
  • HYPER-ALLOYS
  • SINGLE FILAMENTS
  • ON ORBIT ELECTROLYSIS OF PROPELLANT
10^1–10^2 \$/lb
• SPACE MFG OF
  • STEEL
  • ALUMINUM
  • PLASTICS
  • GLASS
  • FOAM METALS
10^{-1}–10^0 \$/lb
	• ON-ORBIT ASSY DEMONSTRATIONS
	• ON-ORBIT INTEGRATION + SIMPLE ASSY OPS (GEO PLATFORM, S.O.C.)
	• COMMERCIAL ON-ORBIT SERVICING OF LEO SATELLITES
	• COMMERCIAL ON-ORBIT SERVICING: GEO SATELLITES
	• ON-ORBIT FAB OF STRUCT ELEMENTS; COMPLEX ASSY OPS
	  • SPS
	  • KM APERTURE ANTENNA
	• FACTORY FAB; LIGHT INDUSTRY
	  • ALUMINUM
	  • PROCESS IND.
	    –CHEMICALS
	    –PLASTICS
	• LARGE SCALE EXTRACTION OF OXYGEN, HYDROGEN ORGANICS FROM ASTEROID FEEDSTOCKS
	• SPACE HEAVY INDUSTRY
	  • STEEL, METALS
	  • LARGE SCALE PROCESS IND.
	  • FAB SPACE COLONIES
		• EXTENSIVE LUNAR AND ASTEROID RECONNAISSANCE
		• LUNAR SOIL FOR RAD SHIELDING, EXTRACTION OF SILICON, OXYGEN, ALUMINUM FROM LUNAR SOIL FOR SPS
		• EXTENSIVE PRIVATELY FINANCED ASTEROID "PROSPECTING"
		• ASTEROID MAT'L FROM LOW ΔV ASTEROIDS
		  • OXYGEN
		  • WATER
		  • ORGANICS
		• EXTENSIVE RECOVERY OF IRON, NICKEL, ETC., FROM ASTEROID BELT, ASTEROID HABITATS
			• LUNAR ORBIT S.O.C. MANNED LANDING LONG STAY WITH ROVERS, SAMPLE RETURN (USSR)
			• EXTENSIVE LUNAR PROSPECTING
			• PERMANENT MANNED BASE, LUNAR RESOURCE EXTRACTION, LUNAR CATAPULT (LUNATRON)
			• LUNAR CITY (IES) EXTENSIVE RESOURCE EXPLOITATION TOURISM
			• TERRAFORM AND COLONIZE
				• MANNED ASTEROID RENDEZVOUS & SAMPLE RETURN FROM LOW ΔV "LOCAL" ASTEROID
				• MANNED MARS EXPLORATION
				• MARS TOURISM
					• COMPREHENSIVE SOLAR MONITORING PROGRAM
					–SUN SYNCH OBS PLATFORM (MANNED)
						• HIGH ORBIT OBSERVATORY (MANNED)
						–SERVICES: OPTICAL, RADIO, X-RAY, TELESCOPES
						⇩
						MODULAR EXPANSION TO MATURE ASTRONOMICAL CAPABILITY
							• LOW POLAR ORBIT EARTH MONITOR PLATFORM(3-6), INTERMITTENT MANNED
							• HIGH INCLINATION LOW EARTH ORBIT (MILITARY)
							• HIGH ORBIT (>3 X GEO) MILITARY
								• SPS PRECURSOR
								• SPS IOC
								• SPS IOC
								• SPS SERVICE TO MOBILE USERS
								–LPTS
								–AIRCRAFT
								–SPACECRAFT
								⇩
								MATURE SPACE POWER CAPABILITY

SPACE HABITATION			
• STS/SPACELAB	**(7)	• SCI + APP PLATFORMS	(10^2)
• SOC/LEO	(10)	• LUNAR BASE	(10^2)
• SPS PRECURSOR + CONST. BASE	(10^2)	• LUNAR CITIES	(10^3)
• LEO SPACE BASE	(60)	• ASTEROID HABITAT	(10^3)
• GEO SOC	(10)	• ASTEROID CITIES	(10^4)
• SPS CONST.	(10^3)	• SPACE COLONIES	(10^5)

*SEARCH FOR EXTRATERRESTRIAL INTELLIGENCE (SETI).
**( ) ESTIMATED CREW SIZE

Figure 3-1 Projected Manned Space Missions



* LEO = LOW EARTH ORBIT < 1000 KM

** HEO = HIGH EARTH ORBIT > 6000 KM

Figure 3-2 Potential Habitat Locations

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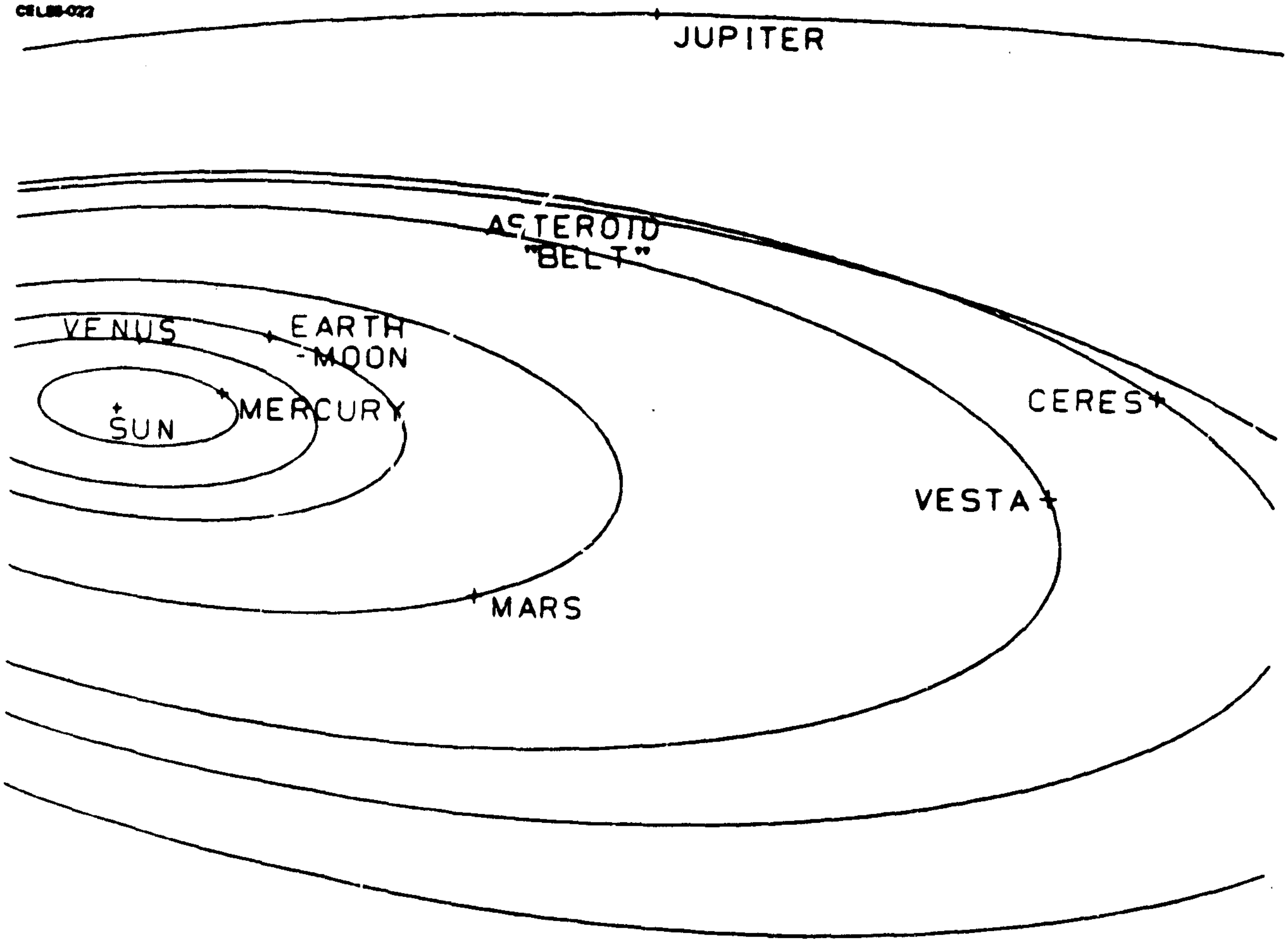
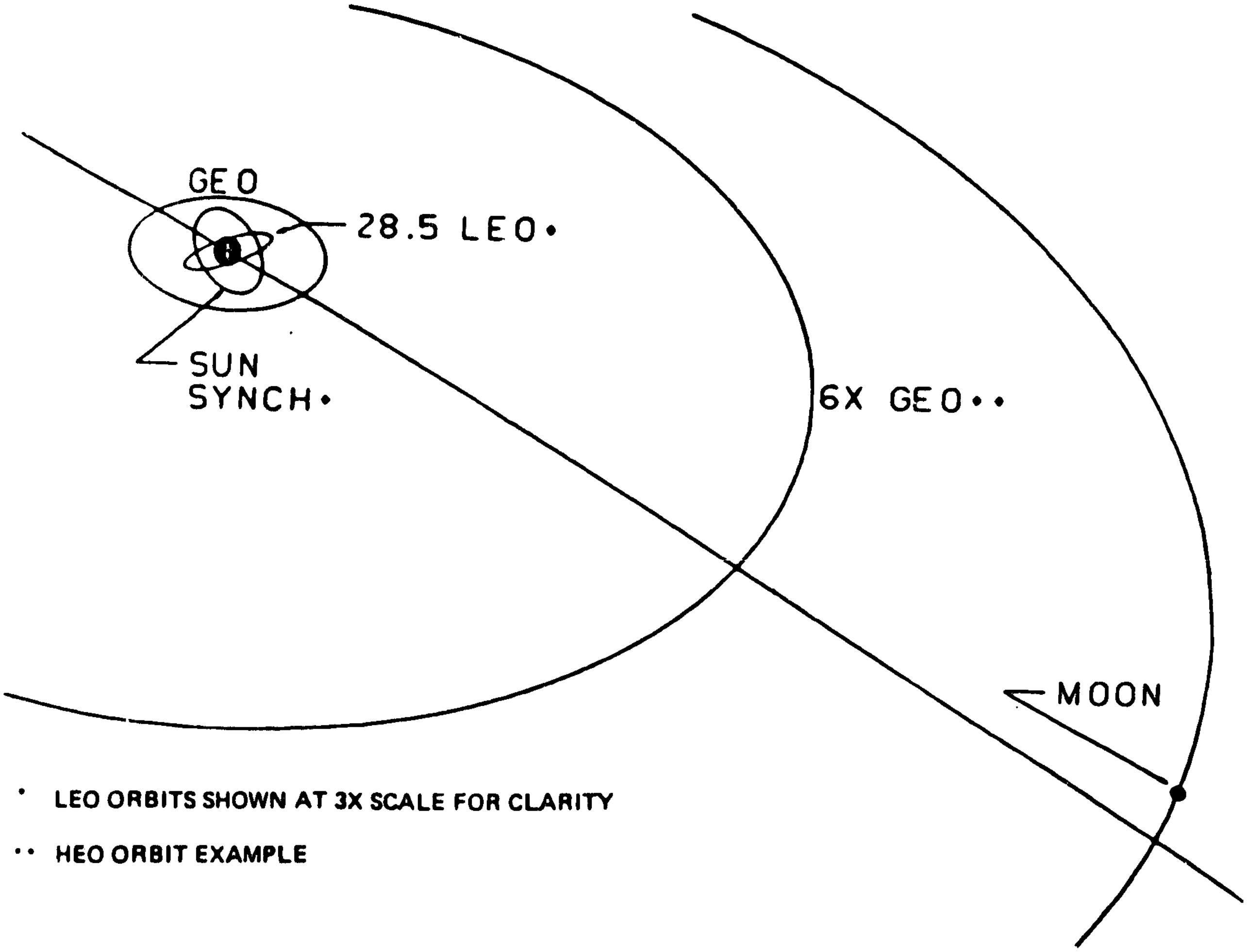


Figure 3-3 Solar System



• LEO ORBITS SHOWN AT 3X SCALE FOR CLARITY

•• HEO ORBIT EXAMPLE

Figure 3-4 Earth-Moon System

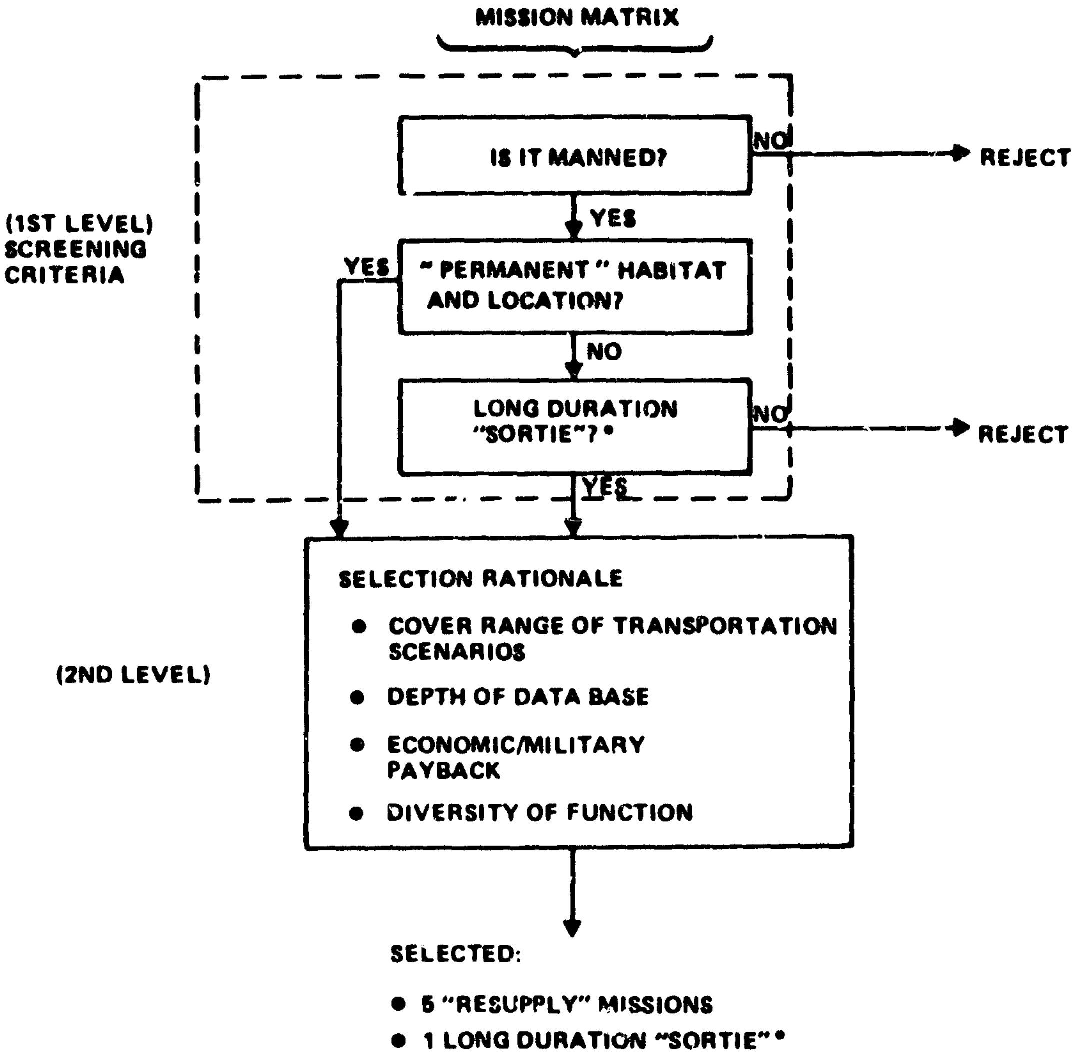
EARTH–MOON SYSTEM

28.5° LEO	>60° LEO	HEO	LUNAR SURFACE
OPERATIONS CENTER	MILITARY	GEO OPS CENTER	RESOURCE RECON.
SPS PRECURSOR	EARTH/SUN MONITORING IN SUN	DEEP MILITARY	OXYGEN PLANT
CONSTR. BASE	SYNCHRONOUS ORBIT	HIGH ORBIT OBSERVATORY	MINERAL MINING
SPACE FACTORY		LUNAR ORBIT	LUNAR CITY

SOLAR SYSTEM

ASTEROID ORBIT	FLYBYS	MARS ORBIT	MARS SURFACE
RESOURCE RECON	MARS	SURVEY	EXPLORATION
RESOURCE EXTR.	VENUS–MERCURY		MARS COLONY
ASTEROID RETURN			

Figure 3-5 Missions with Habitat Locations



* A "SORTIE" IS DEFINED HERE AS AN IMPERMANENT MISSION FOR WHICH IT IS IMPRACTICAL TO RESUPPLY, SUCH AS A PLANETARY FLYBY

Figure 3-6 Mission Selection Schematic radiation shielding and power mass factor are given for each mission in table 3-1 (refs. 63 and 90.)

In this regenerative life support system analysis, each level of closure will have different power and volume requirements. Table 3-1 provides the mass penalties that must be assessed to a mission for each closure level. In the final analysis, the total system mass (and resupply mass) will determine the optimal closure level for each mission. The following paragraphs provide a description of each mission, and give the rationale for the power and shielding values presented in table 3-1.

a. **LEO—Low Inclination.** This mission is a permanently manned operations center in low earth orbit at an inclination of 28.5 deg. The four- to twelve-person center would be responsible for assembly and construction of complex spacecraft, service and basing of upper stages, and service of free-flying satellites.

   This mission is likely to be implemented before the year 2000, with technology and manufacturing constraints placing initial operating capability after 1989.

   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 still quite massive due to the fact that one third of the 90 minute orbit period is in darkness.

b. **LEO—High Inclination.** This scientific station will be located in a sun-synchronous low earth orbit at an inclination of approximately 97 deg. The four-person station will be concerned with scientific investigation of various aspects of the earth and sun. This mission was selected because the location of a high inclination orbit will necessitate an additional LEO transportation scenario. The technology and manufacturing constraints are essentially the same as the operations center, but the scientific rather than commercial thrust of the mission places initial operation after 1995.

   The high inclination of the orbit may 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

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Table 3-1 Mission Dependent Masses

	SOLAR ARRAY			NUCLEAR		SOLAR ARRAY	
	LEO LOW INCL	LEO HIGH INCL	6X GEO	LUNAR BASE	MARS SURFACE	SOLAR MARS TRANSIT	ASTEROID SOLAR
ELECTRICAL POWER ARRAY/REACTOR	630 KG	630	630	1,395	1,280	1,400	4,200
SHIELDING				380	360		
POWER CONDITIONING	200	200	200	400	300	200	200
NI H_2 BATTERIES	1,941	-0-	-0-	-0-	-0-	-0-	-0-
NI H_2 EMERGENCY BATTERIES	50	50	50	100	100	100	50
AUTO POWER SYSTEM MANAGEMENT	50	50	50	50	50	50	50
MAIN CABLES	168	168	168	300	200	168	400
WIRE HARNESSES	500	500	500	1,000	800	500	1,000
BUSES	200	200	200	400	300	200	500
OTHER	200	200	200	800	250	200	200
TOTAL MASS	3,939 KG	1,998	1,998	4,825	3,640	2,818	6,600
AVERAGE POWER LOAD *	35 KW	62.5 KW	55 KW	100 KW	75 KW	76 KW	70 KW
POWER MASS FACTOR	113 KG/ KW	32 KG/ KW	36 KG/ KW	48.3 KG/ KW	48.5 KG/ KW	37 KG/ KW	94.3 KG/ KW
RADIATION SHIELDING	NOT REQ'D	PROBABLY NOT REQ'D	10g/CM^2	NOT REQ'D (LUNAR SOIL)	NOT REQ'D (ATMOS & SOIL)	N/A (NO PLANT GROWTH)	2g/CM^2

* INCLUDES SHADOWING EFFECTS (BATTERY CHARGING LOADS) AND DEGRADATION RATES – DESIGNED FOR END OF LIFE POWER AVAILABILITY

solar arrays will be in continuous sunlight, therefore batteries for energy storage are not required.

c. **6 X GEO.** A military command post will be modeled in a typical 6 X GEO circular orbit. The station will support 4 to 24 men with infrequent resupply. This mission was selected because of the unique military aspects involved, in addition to the high earth orbit location. These military aspects motivated the 1995 initial operation date.

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. A nuclear reactor was examined as a potential energy source, but was rejected because of operational uncertainties and reactor shielding weight penalties.

d. **Lunar Base.** A habitat will be located on the lunar surface to support 12 to 48 personnel who are primarily concerned with transporting lunar soil to lunar orbit for use in construction and manufacturing missions. The lunar location of this mission and potential economic return motivated its selection.

The need for lunar material for space construction projects is not anticipated before the end of this century. The mission model indicates this requirement, and the necessary technology, in the year 2010.

The long lunar night precluded 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.

e. **Asteroid Base.** A mining mission to extract minerals from an asteroid in the asteroid belt will be modeled at a manning level of 5000 personnel. The asteroid mission was chosen because it is the only mission outside of the earth-moon system with potential economic return. This mission is projected 70 years in the future, and anticipates development of advanced technology such as fusion-drive propulsion systems and heavy-lift launch vehicles.

The habitat power is derived from solar arrays that assume 1990 technology. In this case the power mass factor is seen to be necessarily conservative, as projecting solar cell performance 70 years into the future is speculative at best. Habitat radiation shielding is accomplished using asteroidal materials.

f. **Mars Surface Exploration.** This long-duration sortie mission will involve extensive travel time (approximately 1000 days) and a manning commitment of 8 personnel. The Mars mission was included as the most realistic long duration sortie. The technology for this mission is available today, although the need has not yet been identified, nor have all the necessary support systems been designed. The designated use of a shuttle-derived launch vehicle, and a unique Earth-Mars transportation system compelled a 2010 mission date. Transportation vehicles necessary for the various missions will be described in the following section.

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. An advanced solar array with a regenerative fuel cell energy storage system was examined for use upon the surface, however using Martian soil for the reactor radiation shielding provided a lower power-to-weight penalty for the nuclear system.

3.4 Crew Size Definition

The crew size, crew rotation period, and the base resupply period have been determined for each mission (table 3-2). The values for crew size are particularly sensitive to the selected mission description; for example, the lunar mining base is modeled at a level of 12 to 48 personnel because a lunar mining operation need not require more personnel. The crew size numbers may be extrapolated, with the understanding that the mission definition will change—and with it the transportation analysis, vehicles, and cost.

Table 3-2 Crew Size and Rotation

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

4.0 TRANSPORTATION ANALYSIS

Analyzing the methods and vehicles used to transport personnel and materials from the earth's surface to the mission location will provide the study with a sound transportation cost for each mission. These mission-dependent transportation costs will be used to determine the cost savings (or penalties) incurred by each level of closure.

The transportation analysis comprises two parts; a trajectory analysis to determine the route of travel, and a vehicle analysis to determine what rocket or combination of rockets can accomplish the mission most efficiently. The following paragraphs describe the trajectory analysis and vehicle analysis for each mission. The trajectory analysis was accomplished using the standard orbital mechanics relationships, which determine timeline and velocity change data and a descriptive illustration for each mission. The illustration has been included with each transportation description. The vehicle analysis was performed using the vehicle data base compiled by Boeing. Inputs to this analysis were mission trajectory analysis data, mission-technology era, and approximate payload mass estimates. The analysis determined optimum types of vehicles necessary, their sizes, and approximate cost per kg to transport personnel and material from earth to the space base.

4.1 LEO—Low Inclination

This mission has the most straightforward transportation analysis, in addition to being the most specifically defined mission studied. The 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 (Cape Kennedy) launch. In 1990, an unmodified shuttle launched to the operations center can carry approximately 65,000 lb (29,480 kg). Figure 4-1 illustrates the shuttle trajectory from Cape Kennedy to the LEO operations center.

4.2 LEO—High Inclination

The monitoring station mission is very much like the LEO operations base, in that it may 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

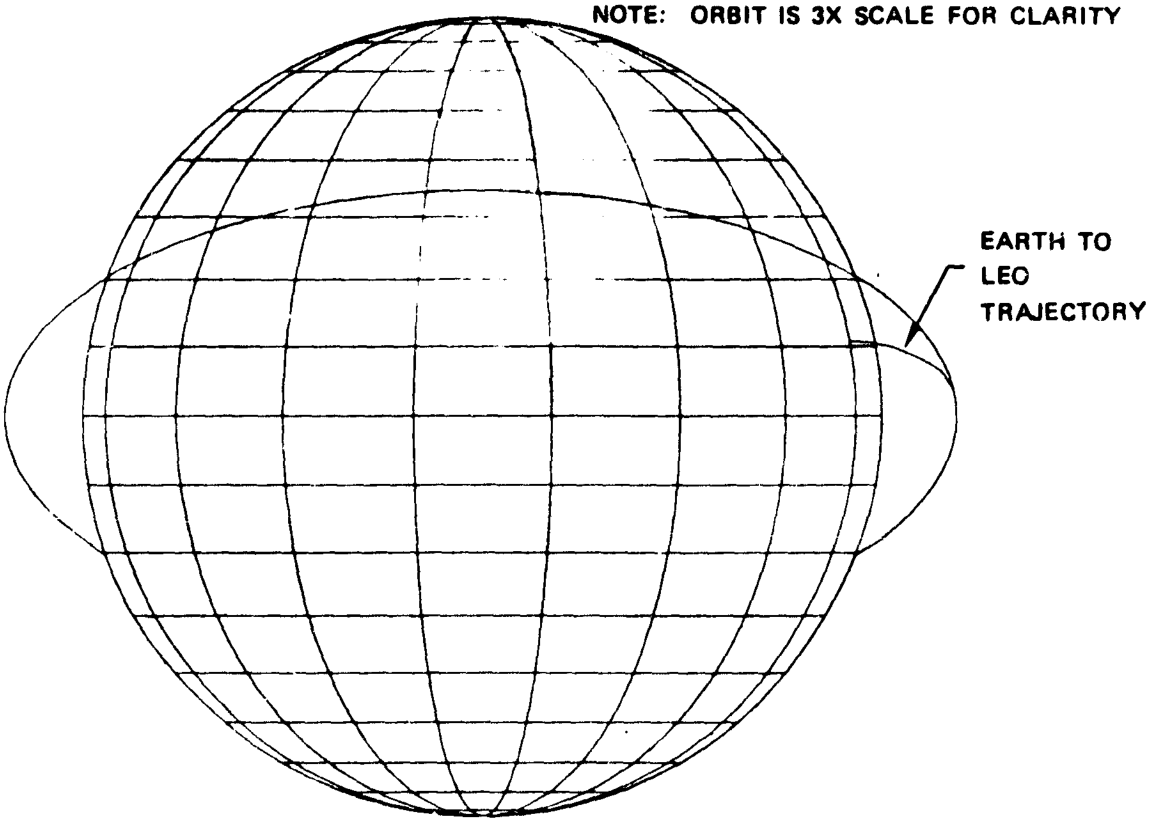

Figure 4-1 LEO – Low Inclination Mission Trajectory

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 lower the payload capacity of the shuttle to 40,000 lb (18,144 kg). The shuttle trajectory from Vandenberg AFB to the space station is illustrated in figure 4-2.

4.3 6 X GEO

The trajectory illustrated in figure 4-3 is used to establish resupply and crew rotation for a military command post in a circular orbit of six times geosynchronous orbit.

Since the command post is not directly accessible by the shuttle orbiter, a payload 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. A conceptual drawing of the OTV can be seen in figure 4-4. The mission sequence is straightforward, with a single revolution in phasing orbit establishing 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 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 Boeing performance and mass sequencer calculator (PMSC) computer code was used to determine the payload capacity of the reusable, aerobraked OTV, which is a projected system with a significant parametric data base (refs. 85 and 87). Figure 4-5 shows the final output from the PMSC program, and lists the vehicle resupply payload capacity at 18,290 lb (8,300 kg).

4.4 Lunar Base

The lunar base resupply trajectory is illustrated in figure 4-6. The low Earth orbit operations are essentially identical to the command post trajectory analysis. The position

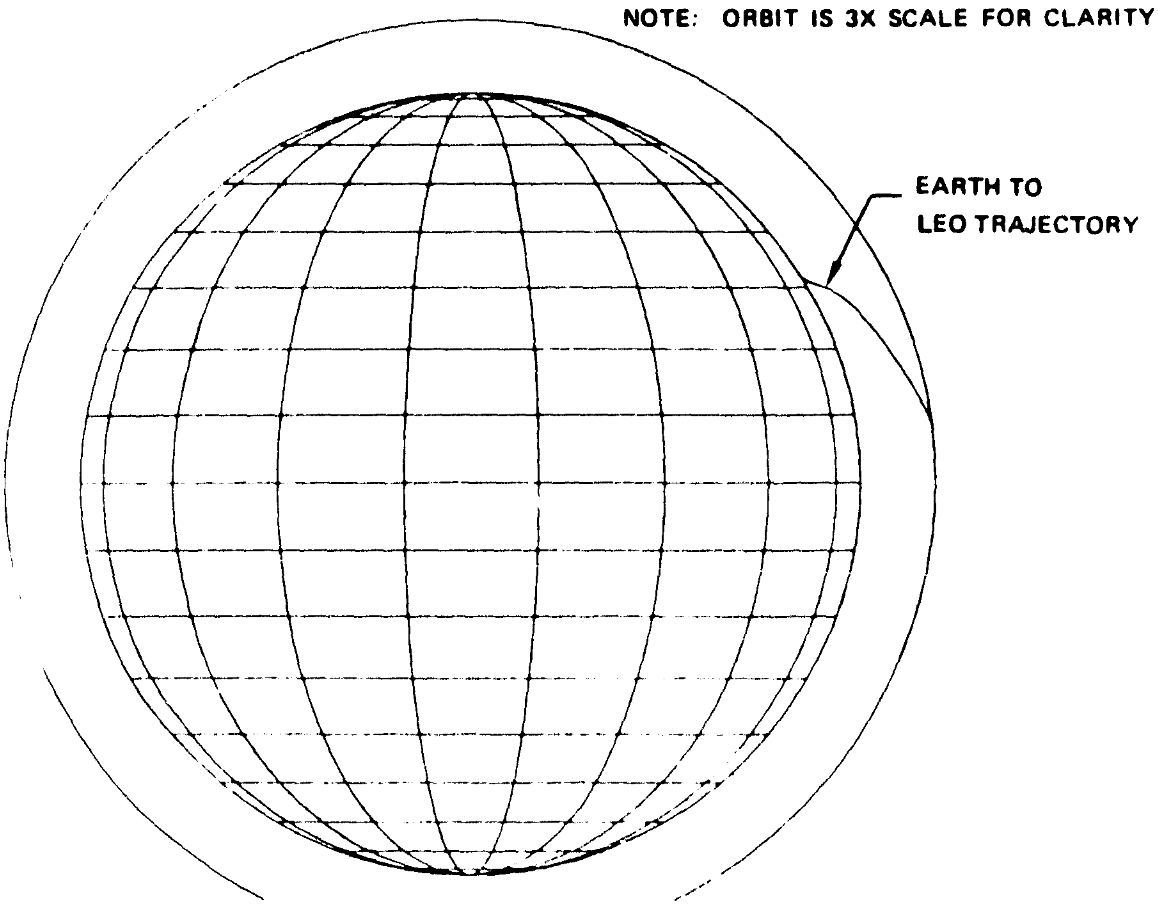

Figure 4-2 LEO – High Inclination Mission Trajectory

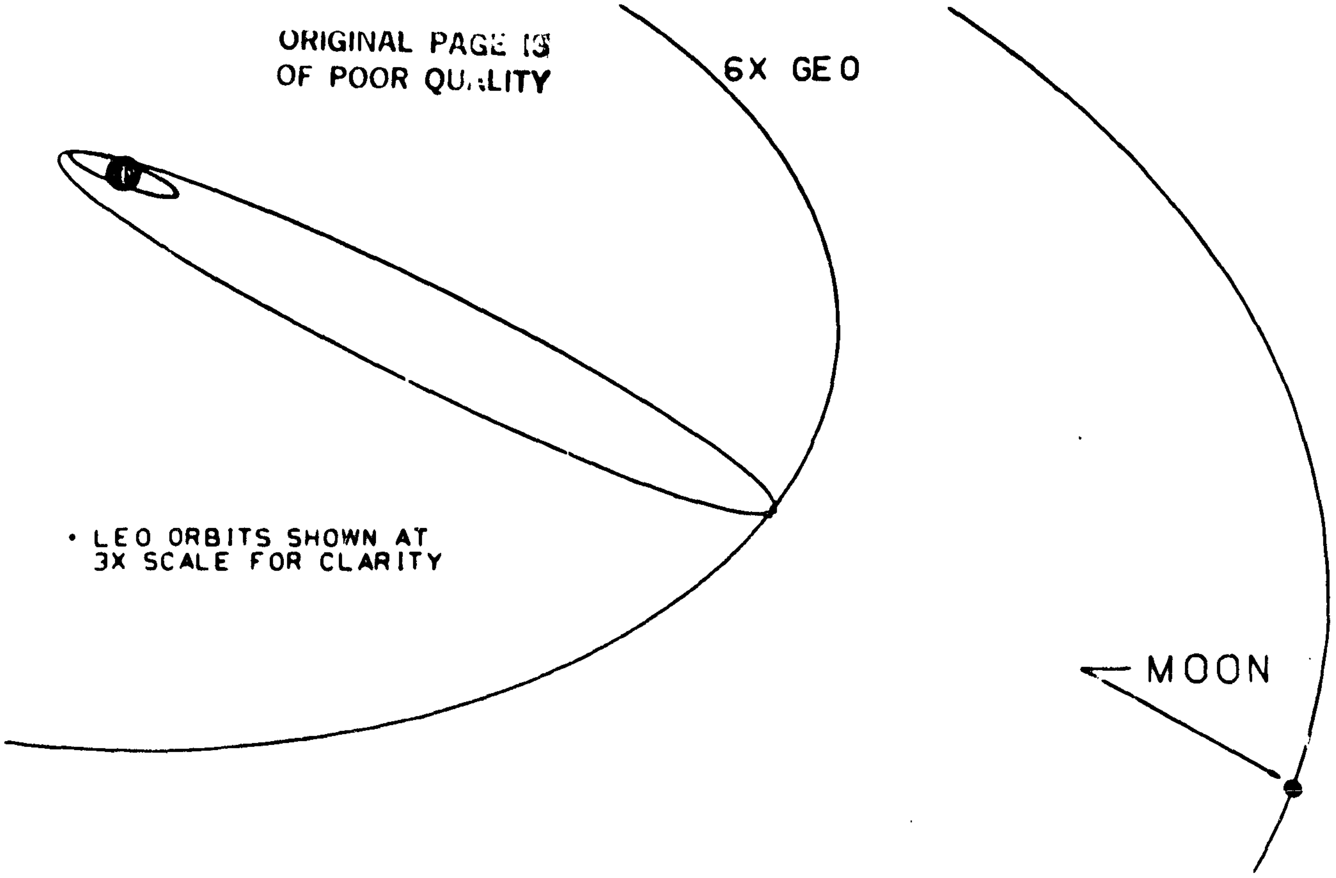

Figure 4-3 6 X GEO Trajectory

CELSS-174

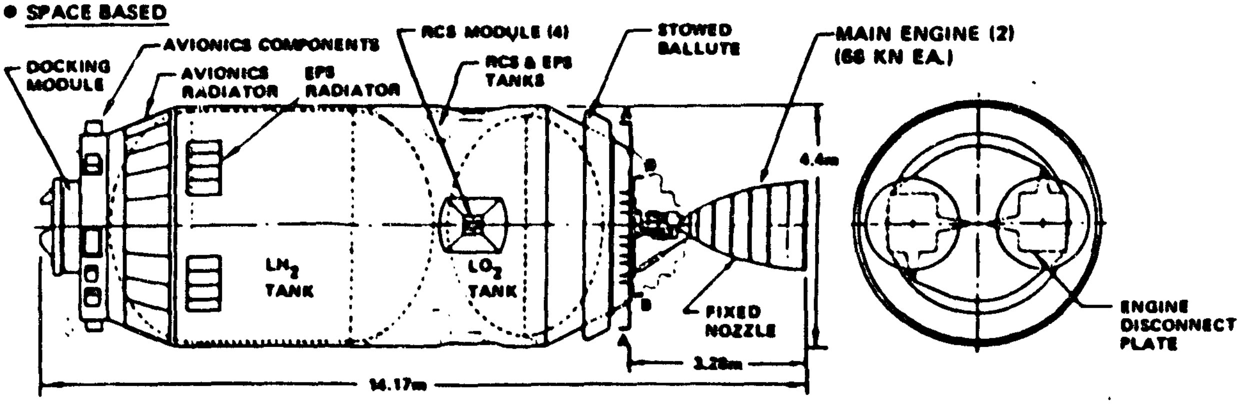

Figure 4-4 LO$_2$/LH$_2$ OTV Configurations

OTV MANNED 6 X GEO RESUPPLY MISSION

	lb
USABLE MAIN PROP. MASS	73700
NOMINAL BURNOUT MASS	9828
START MISSION MASS	115530
ROUNDTRIP PAYLOAD MASS	11000
RESUPPLY MASS	18290

MAIN ENG. ISP = 485

AUX. PROP. ISP = 220

EVENT	DELTA V(ft/s)	PROP USAGE (lb)	LOSSES (lb)	MASS (lb)
STARTBURN	---	---	---	115530
SEPARATE	10	163	6	115361
PHASE	0	0	5	115356
PHASE INJECT	4494	28866	92	86398
COAST	0	0	5	86393
TRANS. INJECT	5530	25779	37	60577
COAST	50	220	139	60218
6XGEO ORB CIR	3317	11531	37	48649
TRIM	30	106	40	48503
REND. & DOCK	70	477	157	29579
PHASE	0	0	16	29562
TRANS. INJECT	3333	5686	37	23840
COAST	65	112	139	23588
AEROMANEUVER	0	0	311	23277
COAST	0	0	695	22582
RAISE PERIGEE	145	209	37	22336
COAST	0	0	1	22335
LEO CIRC.	407	575	37	21723
REND. & DOCK	60	183	10	21529
RESERVES	450	612	0	20835
UNLOAD P/L	---	---	11000	9835

		lb
NOMINAL MAIN PROPELLANT	=	73084
RESERVE MAIN PROPELLANT	=	612
NOMINAL AUX. PROPELLANT	=	824
RESERVE AUX. PROPELLANT	=	82
TOTAL LOSSES	=	1109

Figure 4-5 Performance Code Output

numbers on the trajectory illustrated in figure 4-6 correspond to important events in the timeline and velocity change data listed in figure 4-7.

The lunar base mission requires three types of transportation vehicles: (1) a shuttle orbiter to raise payload from the Earth to a low Earth orbit operations center, (2) an orbital transfer vehicle that takes payloads from LEO to lunar orbit and back, and (3) a lunar transfer vehicle (fig. 4-8) 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 orbital transfer vehicle (OTV). The OTV then propels the payload, the resupply module, into lunar orbit. After circularizing in low lunar orbit, the manned OTV module has a rendezvous with a lunar transfer vehicle (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 low earth orbit aerobrake maneuver. The phasing orbit operation and shuttle rendezvous proceed as stated in section 4.3.

The shuttle payload to LEO has previously been given as 65,000 lb (29,480 kg), and the OTV payload capacity is recalculated (lunar orbit trajectory is different from 6 X GEO) at 23,210 lb (10,530 kg). The LTV has been parametrically sized and costed in a previous study (ref. 84). The maximum LTV payload is calculated to be 40,668 lbs (18,450 kg). Because this lunar base is a mining facility, it is assumed that the OTV will bring only liquid hydrogen propellant for the LTV. Liquid oxygen is produced from lunar soil.

4.5 Asteroid Base

The 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 (refs. 86 and 91).

a. Payload and propellant are launched from the Earth's surface to a low Earth orbit (LEO) staging base (operations center) by a heavy lift launch vehicle (fig. 4-9). This vehicle has the capacity to lift 490,000 lb (222,222 kg) to LEO.

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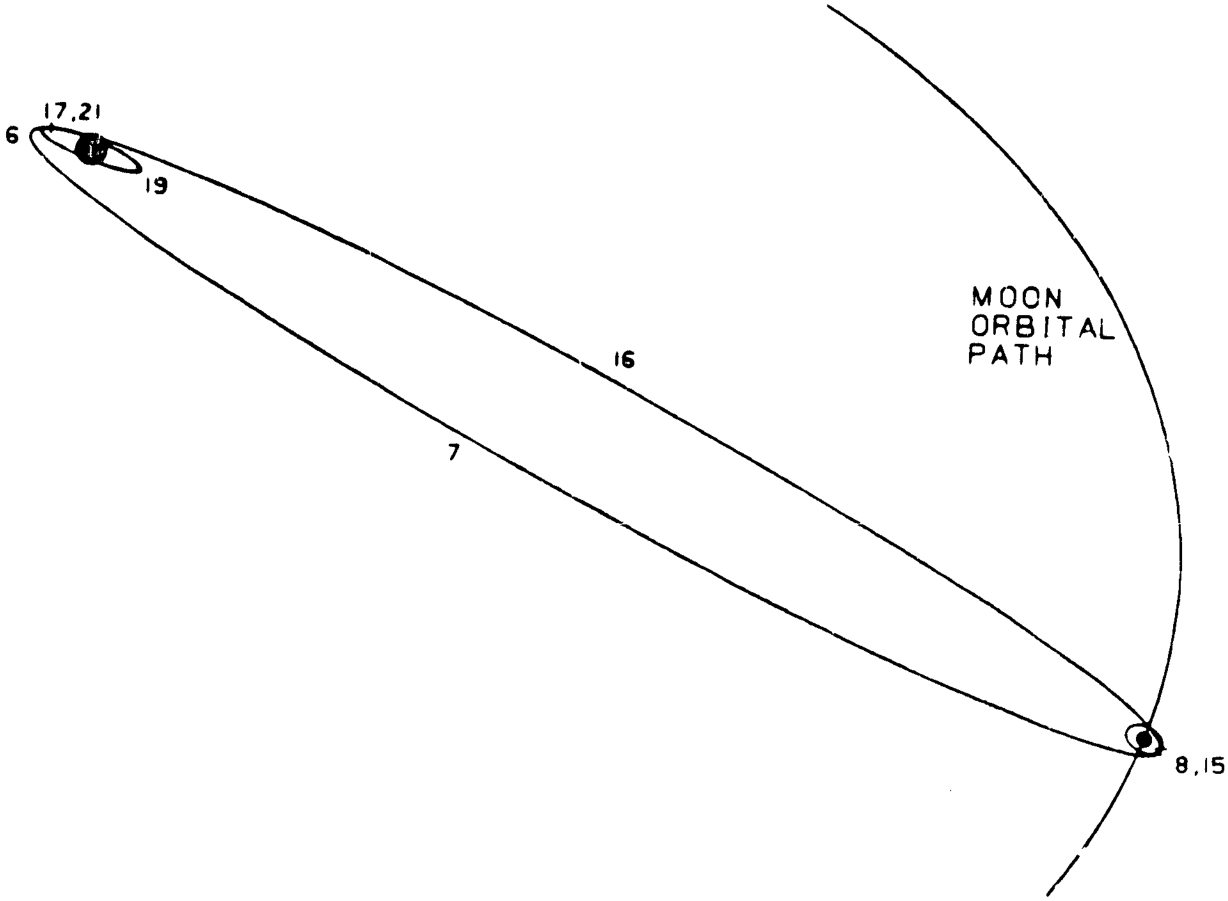

NOTE: POSITION NUMBERS REFER TO IMPORTANT EVENTS DETAILED IN FIGURE 4-7

Figure 4-6 Lunar Base Trajectory

LUNAR SURFACE EXPLORATION

DESTINATION: Lunar Surface

TRANSFER ORBIT PARAMETERS: V TLI = 3.113 km/sec

Circularize V LOI = .903 km/sec

Trans orbit 1/2 period: 90 hrs.

No.	Activity	Event Duration Hrs.	E.T. @ End of Event Hrs.	V km/sec
1.	STS ascent & circularize @ 160 nm.	3.06	3.06	
2.	Crew transfer: Erect & checkout manned OTV	4.00	7.06	
3.	Release OTV: Phase in 160 nm. orbit	11.00	18.06	
4.	Phasing burn	.17	18.23	.400
5.	Coast in phasing orbit	3.00	21.23	
6.	Translunar insertion burn	.11	21.34	2.713
7.	Coast to Lunar orbit intercept, midcourse correction	45.00	66.34	
8.	Lunar orbit insertion & plane change	45.00	101.34	.903
9.	LTV ascent	1.00	102.34	1.846
10.	Rendezvous with, LTV transfer operations	18.06	120.40	.165
11.	LTV landing	1.20	121.60	2.094
12.	Coast in orbit; plane change burn	15.00	136.60	.037
13.	Trans Earth insertion burn	.06	136.66	.820
14.	Coast to aerobrake maneuver; midcourse correction	45.00	181.66	
15.	Aerobraking maneuver	45.00	226.66	
16.	Coast to apogee	.79	227.45	
17.	Jettison ballute; raise perigee to 160 nm.	.06	227.51	
18.	Coast 1/2 REV to 160 nm. perigee	.79	228.30	
19.	Burn to circularize at 160 nm. for rendezvous	.06	228.36	.124
20.	Orbit trim & gravity gradient stabilize	2.00	230.36	
21.	OTV recovery; crew transfer	4.42	234.78	
22.	STS/OTV E deorbit & landing			

Figure 4-7 Timeline and Velocity Change Data Sheet

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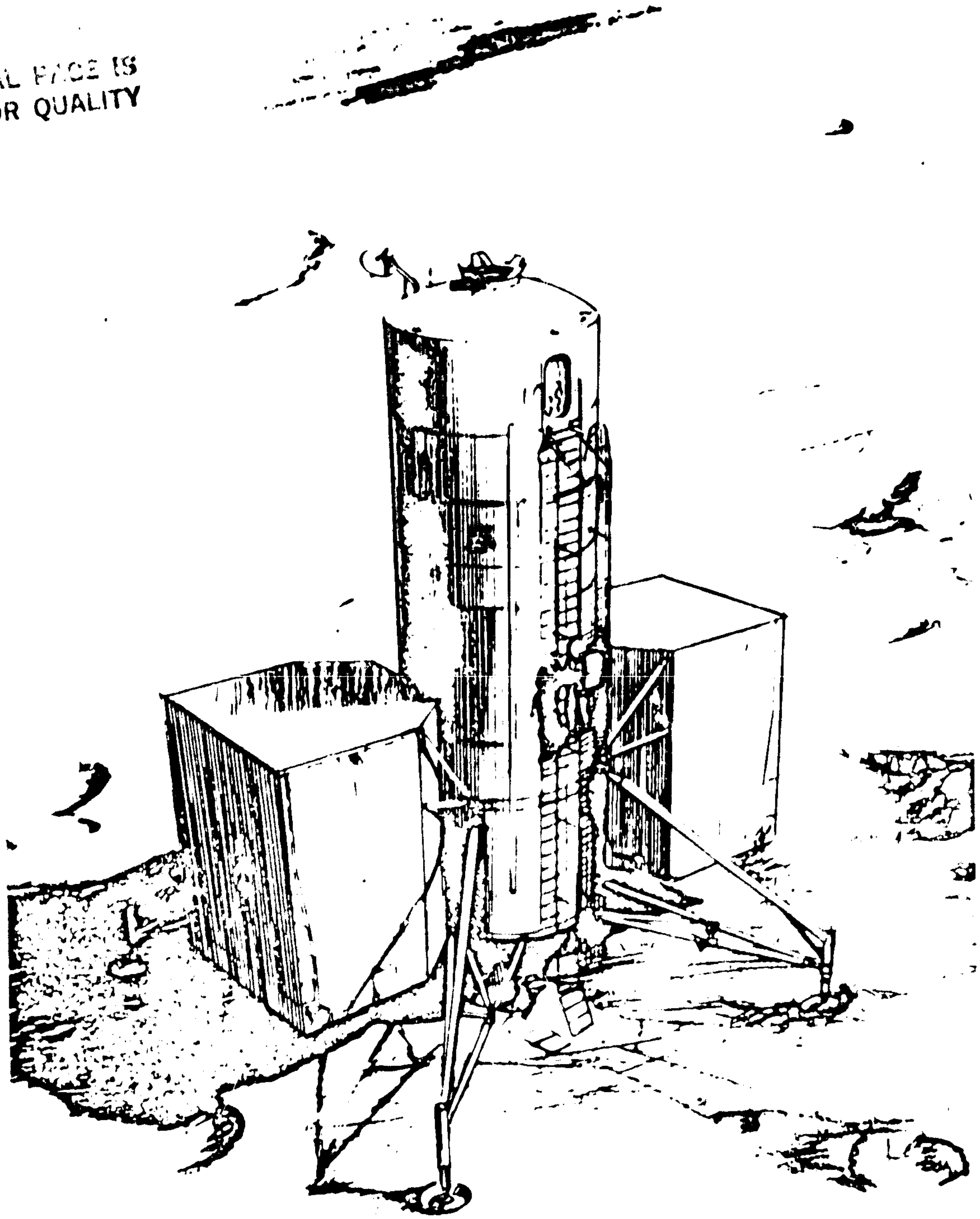

Figure 4-8 Lunar Transfer Vehicle

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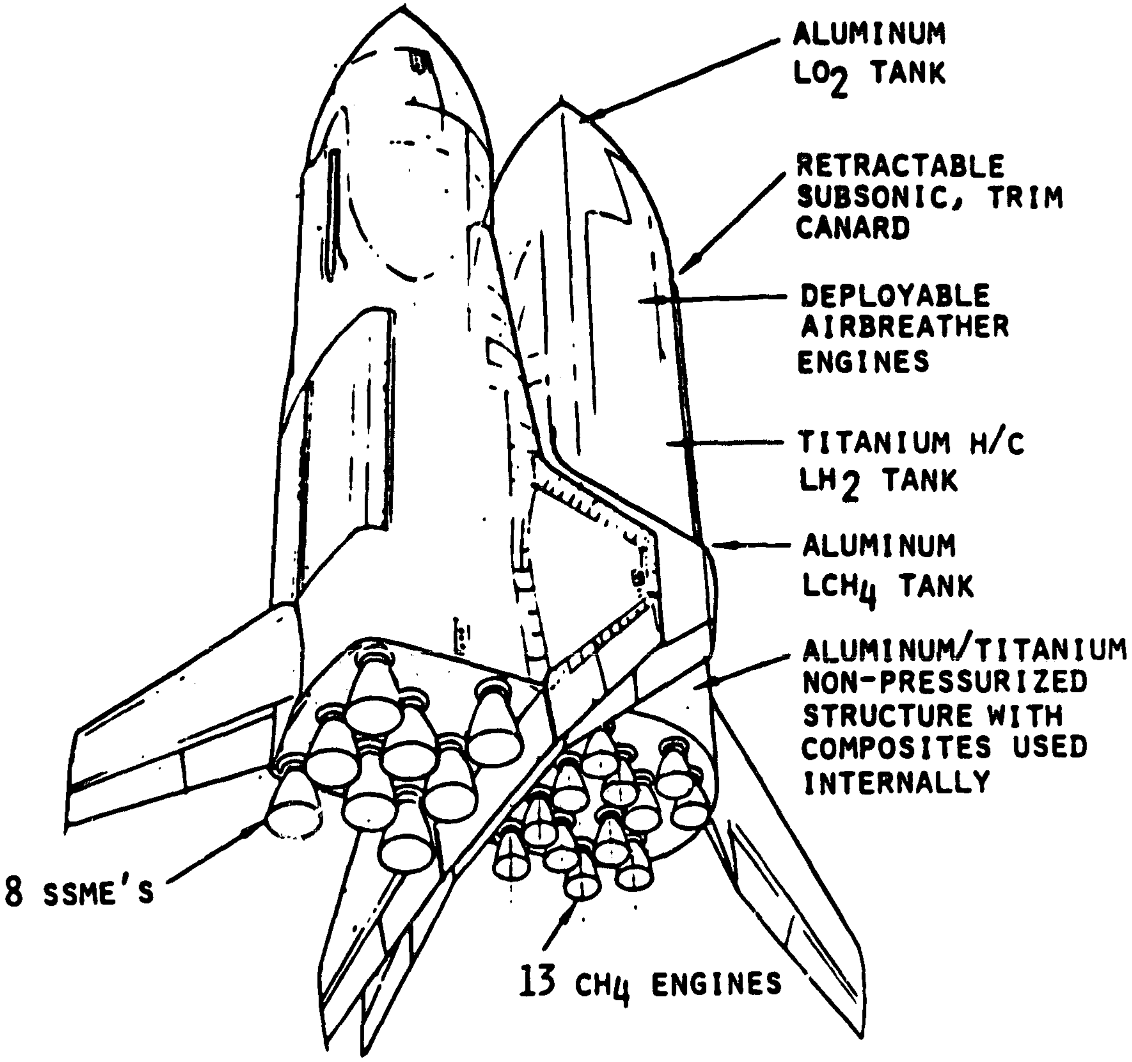

Figure 4-9 Heavy Lift Launch Vehicle

b. 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 (fig. 4-10) for the 174-hr trip through the Van Allen belts to the GEO. This vehicle can lift a payload of 500,000 lb (226,757 kg) to geosynchronous orbit. The personnel and any priority cargo are transported on an enlarged version of the previously described aerobraked OTV for faster trip (6 hr) to the GEO assembly base.

c. The GEO base serves as the final assembly area for the large fusion rocket system used to propel payloads out to the asteroids. Cargo and propellant are unloaded from electric-powered transfer vehicles sent up from the LEO base. The enlarged OTV used to transfer personnel and priority cargo is designed to transport 441,000 lb (200,000 kg) from LEO to GEO. The complex fusion propulsion system is assembled at the base with the fusion power core, propellant tanks, large thermal radiators, and the personnnel and priority cargo modules. The resulting vehicle, shown in figure 4-11, can transport 1250 passengers and 150 metric tons of priority cargo to the asteroids.

The gross start mass for the resupply mission would be 10,000 metric tons, of which power plant comprises 2000 tons; hydrogen propellant, 4000 tons; and payload, 4000 tons (1250-person habitat plus consumables and priority cargo). The power plant consists of two 6 GW fusion reactors utilizing the deuterium-deuterium fusion reaction. The total power plant provides 4.8 GW of thrust power while radiating almost 2.8 GW of waste heat and 4.4 GW of high energy neutrons.

d. There are two methods the fusion rocket will use to propel vehicles to the asteroid base: fast transfer for personnel and priority cargo, and slow transfer for nonpriority cargo. The manned resupply mission is a fast hyperbolic transfer orbit consisting of an 11-day thrust period to achieve hyperbolic velocity, followed by a 226-day coasting, and a 13-day deceleration to match velocity with the asteroid base. The return mission leaves the asteroid approximately 113 days later for a reverse of the ascent mission.

The second method is used to accelerate unmanned cargo pods on a slow elliptical (Hohmann) transfer orbit out to the asteroid base. Figure 4-12 illustrates the

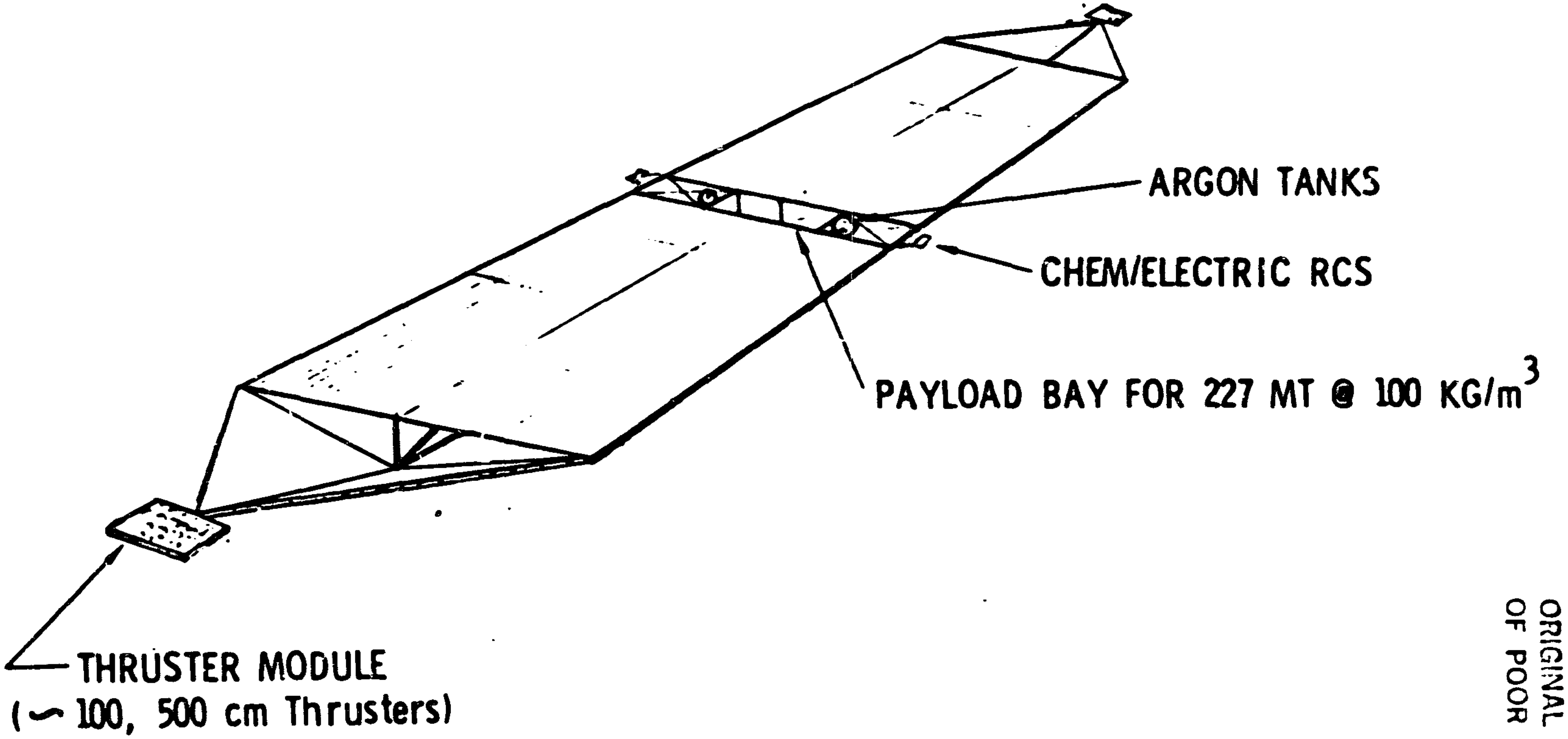

Figure 4-10 Solar Electric LEO to GEO Vehicle

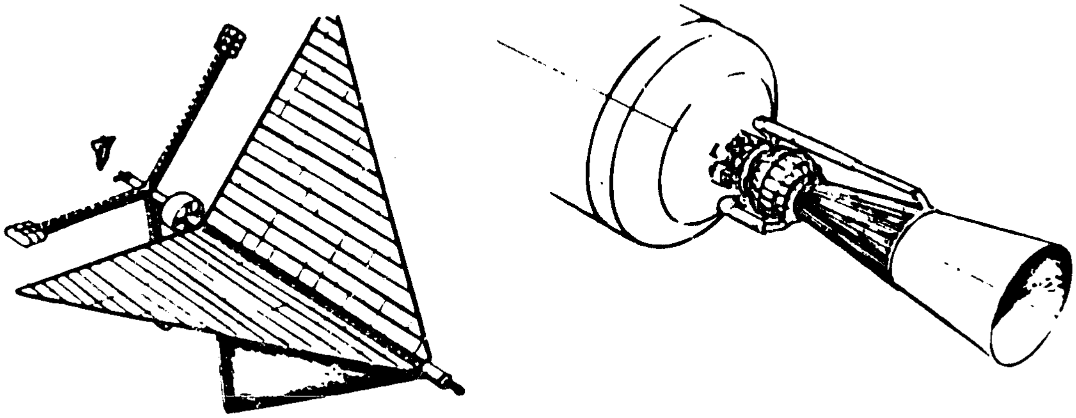

Figure 4-11 Fusion Propulsion System

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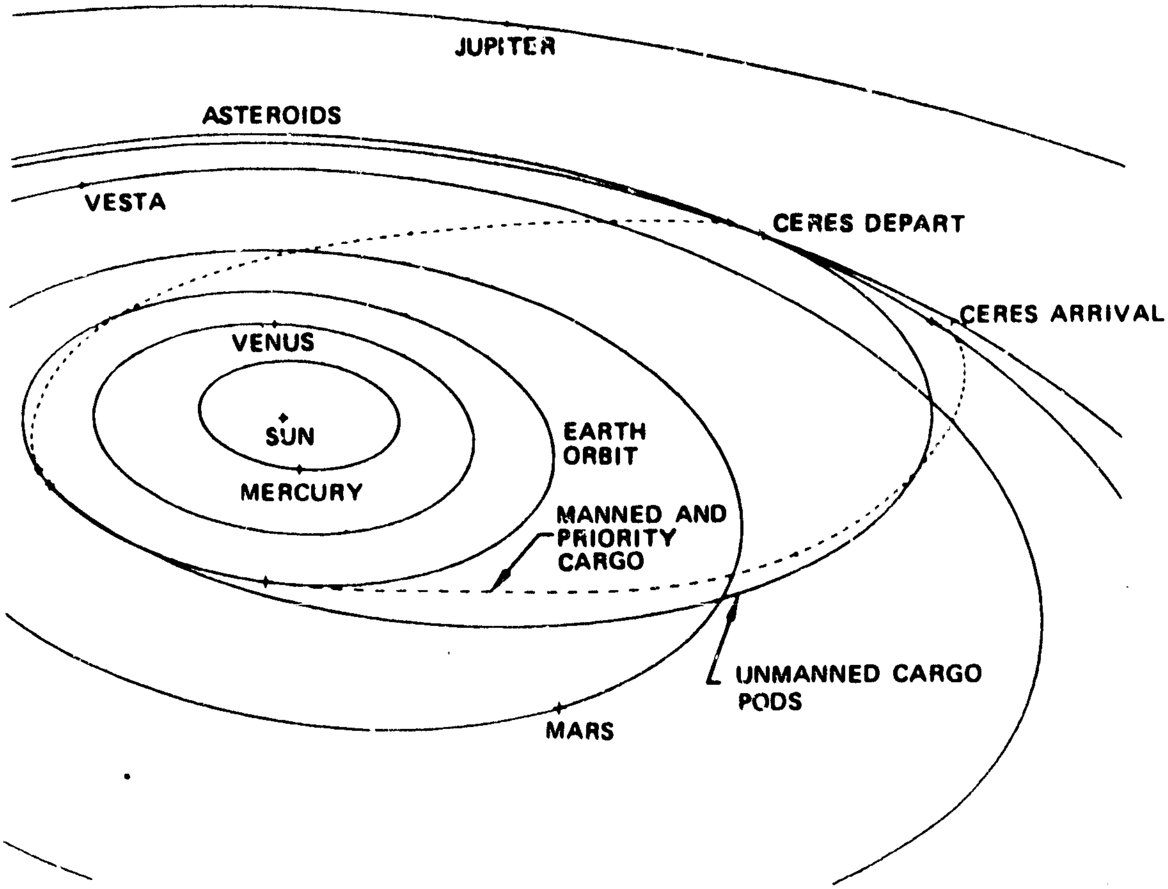

Figure 4-12 Asteroid Mission Trajectories

different trajectories. The slower trip takes 130 days longer but costs less than half of what the fast, hyperbolic trip costs. All nonpriority cargo is brought to the asteroid facility in this manner. Empty cargo pods are not returned to Earth, they may be discarded or used in a variety of ways as storage modules or CELSS modules.

e. A fleet of two fusion rockets is envisioned. They each make one round trip per asteroid orbit (synodic cycle) to the asteroid mining facility and leave a few days apart. Because of the synodic cycle, the fusion rocket vehicles are delayed at the asteroid base for approximately 113 days, at the GEO location they are delayed approximately 288 days. During these delays the fusion rockets are used to decelerate unmanned cargo pods at the asteroid base and to accelerate the pods at GEO. Cargo pod launches are timed to arrive at the asteroid base shortly after the manned resupply vehicles so that the fusion rockets can decelerate the cargo pods. The rendezvous opportunity (synodic cycle) repeats itself every 928 days. This transportation system allows half of the total crew to be rotated each cycle.

4.6 Mars Surface Exploration

The Mars mission spacecraft illustrated in figure 4-13 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 nose cone and correct lift-drag) in order to dump excess velocity. The returning Earth-intercept module must also carry an aerobraking ballute.

The Mars mission sequence is shown in figure 4-14 and proceeds as follows:

a. The unassembled mission spacecraft modules are brought from Earth to a LEO operations base using the shuttle orbiter. After the vehicle is assembled, fueled, and supplied, the crew enters the spacecraft and begins their 950-day mission.

b. From LEO a single long burn propels the spacecraft into a heliocentric transfer trajectory to Mars intercept. The trip from LEO to Mars takes approximately 205 days.

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Figure 4-13 Manned Mars Space Vehicle

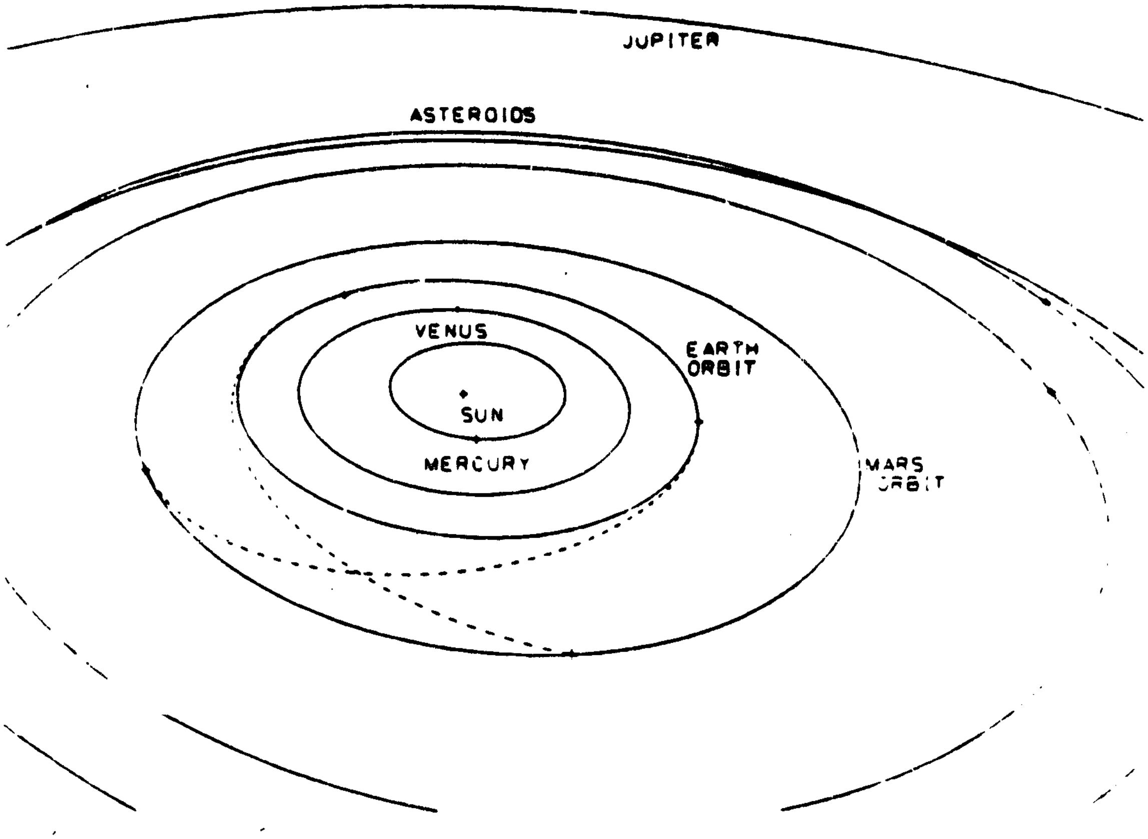

Figure 4-14 Mars Mission Trajectory

c. At Mars, the velocity change is accomplished by using an aerobraking maneuver into the Mars atmosphere. The spacecraft is then established in an elliptical parking orbit around Mars. After several days in orbit, the Mars surface landing module separates from the propulsion stages and the transfer habitat module and lands on the Martian surface. Planetary exploration is accomplished over the next year and a half.

d. After the exploration period has been completed, the personnel and necessary cargo fly in the ascent module up to the orbiting spacecraft. All nonessential equipment and material must be left on the Martian surface because of the severe cost of lifting materials into orbit. After the spacecraft rendezvous, and after personnel and materials are transferred, the spacecraft initiates an engine burn to move into a transfer trajectory to Earth.

e. The trip back to Earth will take approximately 200 days. An aerobraking pass through the Earth's atmosphere accomplishes most of the velocity change necessary to establish the spacecraft in a low Earth orbit. Once this orbit is established, the spacecraft and crew are recovered and returned to Earth by the space shuttle.

5.0 LIFE SUPPORT SYSTEMS CHARACTERIZAION

The life support systems considered for this study are water, air revitalization (oxygen and carbon dioxide), waste management, and food. There are three basic methods of supplying these materials to the spacecraft crew: (1) the materials can be stored aboard at time of launch for the entire mission with provision of storing waste products, (2) supplies can be brought to the crew via a transportation vehicle that also returns the waste to Earth or (3) they can be supplied by recycling the waste products into reusable materials. The first two methods are commonly called resupply or open systems and the last method is known as regenerative, recycle, or a closed system. It is possible to have several open and closed system combinations using the four life support areas; for example, a recycling water system combined with resupply of air and food, and corresponding waste products returned to Earth. Various combinations of open and closed systems are referred to as closure scenarios and are further defined and discussed in section 5.5.

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: required materials such as water, O_2, food; appropriate storage containers; recycling equipment; pressure vessel to house the elements, based on a weight penalty of the volume occupied by the system elements; and the resupply module, based on the volume of material to be resupplied. Power requirements were also determined for each system type. Figure 5-1 shows the logic flow used to derive the weight, volume, and power estimates. The development of these estimates are discussed in sections 5.1 through 5.4 for the water, oxygen, carbon dioxide, waste, and food systems.

A four-man crew segment was used as a basic module size for estimating EC/LS weight, volume, and power requirements. The rationale for this baseline selection was as follows:

a. A four-man module 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.

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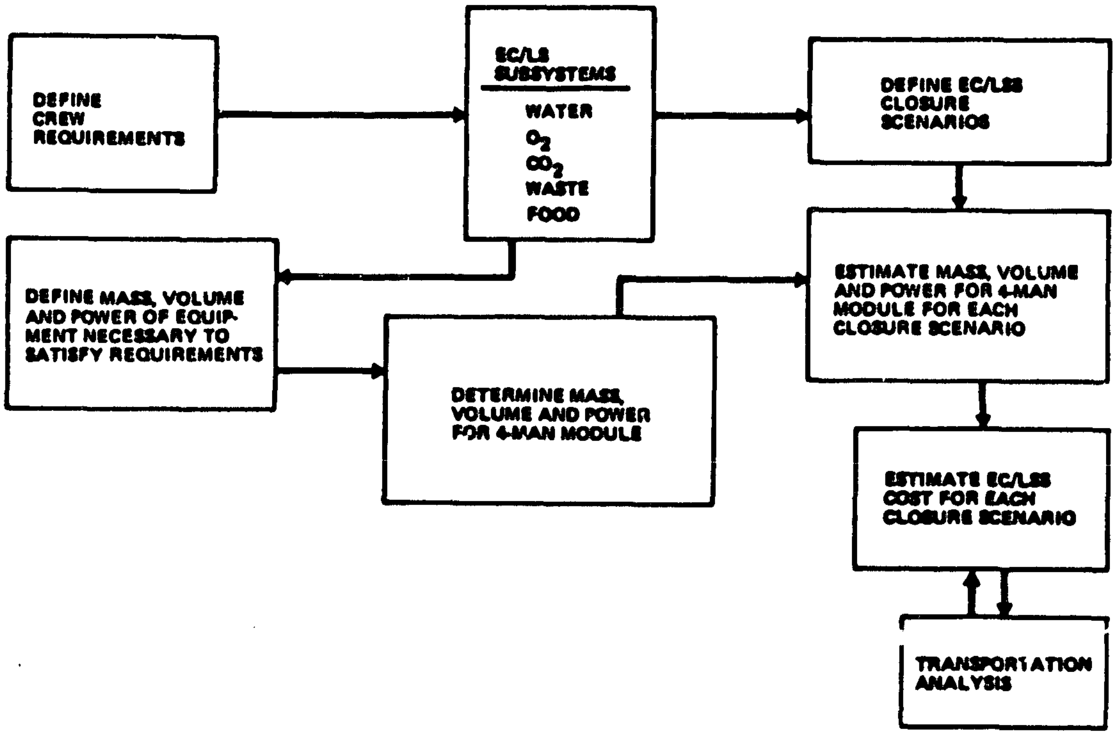

Figure 5-1 Approach to Life Support Systems Characterization

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. The most current data base for the physiochemical systems is based on a four-man module (Space Operations Center).

5.1 Water System

The development of the weight, volume, and power requirements for supplying water to a four-man crew in space is discussed in this section. Water loads given in table 5-1 show the average human input and output. Domestic water used in the spacecraft environment is estimated and is considered to be adequate for providing crew members with a reasonable cleanliness level.

Table 5-2 lists the equipment that could be used to supply the water requirements. Shuttle-type water storage tanks were used for the baseline. Vapor compression distillation volume and power estimate was an example used for water purification equipment to obtain weight, volume, and power estimates.

The operating data shown in table 5-3 is representative of minimum water loads during degradation or failure of equipment. Man's ingested water requirements do not decrease. This results in a requirement for making the ingested water supply system redundant. However, if an emergency arises, domestic water can be reduced or eliminated to relieve the system.

Tables 5-4 and 5-5 show the items used to develop weight, volume, and power estimates for an open water system and a recycling system. These estimates are derived for a 4-man module with a 90-day resupply cycle. The number of units on these tables refer to the number of equipment items, described in table 5-2, necessary to provide the requirements and redundancy for a 4-man module. A comparison of the two water systems presented in table 5-6, shows the advantages of the closed water system in weight and volume saved for both initial materials and resupply. The initial weight of the open system (12,446 kg) is an order of magnitude greater than the recycle system (1,320 kg), and the resupply weight of 10,892 kg is 2 orders of magnitude greater than the recycle resupply of 94 kg. The result of this trade is certainly not surprising–the closing of this

Table 5-1 Typical Water Loads (Ref. 62 and 79)

SOURCE	kg (lb)/ MAN-DAY		
INGESTED H_2O			
DRINKING	1.85	(4.09)	
FOOD PREPARATION	0.72	(1.58)	
METABOLIC	0.39	(0.86)	
WATER IN FOOD	0.45	(1.00)	
TOTAL	3.41	(7.53)	
OUTPUT H_2O			
URINE	1.50	(3.31)	
PERSPIRATION AND RESPIRATION	1.82	(4.02)	
FECES WATER	0.09	(0.20)	(NORMALLY NOT RECOVERED)
TOTAL	3.41	(7.53)	
DOMESTIC H_2O			
URINAL FLUSH	0.50	(1.09)	
HAND WASH	1.81	(4.00)	
SHOWER	3.63	(8.00)	
CLOTHES WASH	12.48	(27.50)	
DISHWASHER	1.81	(4.00)	
TOTAL	20.23	(44.59)	

Table 5-2 Water Equipment Design Data (Ref. 63)

(UNIT DEFINITIONS)

EQUIPMENT	DESIGN DATA	
WATER STORAGE TANK (SHUTTLE TYPE)	CAPACITY/TANK DRY WEIGHT/TANK STORAGE VOLUME/TANK POWER CONSUMPTION/TANK	73.5 KG (162 LB) 22.9 KG (50.5 LB) 0.19 M^3 (6.75 FT^3) 3.3 WATTS
EVAPORATION WATER PURIFICATION UNIT VAPOR COMPRESSION DISTILLATION (VCD)	WATER FLOW RATE DRY WEIGHT VOLUME POWER CONSUMPTION	1.86 KG (4.1 LB)/HR 188.2 KG (415 LB) 1.0 M^3 (37 FT^3) 360 WATTS
WATER QUALITY MONITOR	DRY WEIGHT VOLUME POWER CONSUMPTION	27.2 KG (60 LB) 0.11 M^3 (3.8 FT^3) 40 WATTS

Table 5-3 Water Operating Level Data (4-Man Module, 90-Day Resupply) (Ref. 63)

OPERATING LEVEL	kg (LB)/4-MAN – DAY		
	INGESTED H_2O	WASH H_2O	TOTAL
OPERATIONAL	10.3 (22.7)	80.8 (178;	93.2 (201)
90-DAY DEGRADED	10.3 (22.7)	40.5 (89)	50.7 (112)
21-DAY EMERGENCY	10.3 (22.7)	0	10.3 (22.7)

Table 5-4 Open Water System/Equipment Data Summary (4-Man Module, 90-Day Resupply)

ITEM	NUMBER OF UNITS		TOTAL CAPACITY	TOTAL WEIGHT kg	TOTAL STORAGE VOLUME m^3	NOMINAL POWER CONSUMPTION WATTS
	REQ.	REDUND.				
POTABLE WATER STORAGE TANKS	13	13	1911 kg	595.4	4.94	10
DOMESTIC WATER STORAGE TANKS	100		7350 kg	2290	19	10
EMERGENCY WATER STORAGE TANKS	3		221 kg	68.7	0.57	10
PLUMBING, ETC. (15% OF 3)				10.3	0.09	—
SUBTOTAL				2964.4	24.6	30
INITIAL CHARGE						
POTABLE H_2O (26 TANKS)				1911	—	—
DOMESTIC H_2O (100 TANKS)				7350	—	—
EMERGENCY H_2O (4 TANKS)				221	—	—
TOTAL				12446	24.6	30
90 DAY RESUPPLY				10694	21.5	—

Table 5-5 Recycle Water System/Equipment Data Summary (4-Man Module, 90-Day Resupply)

ITEM	NUMBER OF UNITS		TOTAL CAPACITY	TOTAL WEIGHT kg	TOTAL STORAGE VOLUME m^3	NOMINAL POWER CONSUMPTION WATTS
	REQ.	REDUND.				
PRETREAT CHEM. TANK	1		73.5 kg	22.9	0.19	3.3
DIRTY H_2O STORAGE TANK	2	1	220.5 kg	68.7	0.57	10
EVAPORATION PURIFICATION UNIT	1	1	3.72 kg/hr	376.4	2.0	720
WATER QUALITY MONITOR	1			27.2	0.11	40
POTABLE H_2O STORAGE TANK	2	1	220.5 kg	68.7	0.57	10
EMERGENCY H_2O STORAGE TANK (21 DAYS)	3		221 kg	68.7	0.57	13.2
PLUMBING, ETC. (15%)				98.3	0.63	—
SUBTOTAL				730.9	4.64	796.5
INITIAL H_2O CHARGE, 8 TANKS				516	—	—
INITIAL SPARES & CONSUMABLES				74.2	0.22	—
TOTAL				1320	4.86	796.5
90 DAY RESUPPLY				93.6	0.20	—

Table 5-6 Water System Summary (4-Man Module, 90-Day Resupply)

SYSTEM TYPE	MASS KG	VOLUME M^3	NOMINAL POWER WATTS
OPEN SYSTEM	12,446	25	30
90-DAY RESUPPLY	10,892	22	—
RECYCLE SYSTEM	1,320	5	797
90-DAY RESUPPLY	94	0.2	--

system has been highlighted for some time in the advancement of water recycling equipment.

5.2 Air Revitalization System

The air revitalization system includes oxygen generation, carbon dioxide removal, humidity control, air contaminate removal, and odor control. Man's input and output loads for oxygen and carbon dioxide are given in table 5-7.

Oxygen is continuously required for metabolic processes within the body, therefore it must be continuously replenished in the air. It can be supplied from stored oxygen in tanks, from recycling using water electrolysis, or from photosynthesis. Carbon dioxide, as a toxic waste product of metabolism, must be maintained below a maximum safe level by removing and storing it, by processing and recycling it back into the system as water, which can be fed into the water electrolysis unit or by photosynthesis. The other elements of air revitalization are associated with removing various other contaminants, and are required for both the open and closed systems. Table 5-8 defines the various equipment units used for air revitalization and lists the applicable design data.

Degraded and emergency operating levels are given in table 5-9. The levels shown are based on a nominal habitat pressure of 1 atmosphere, which this study used as the baseline.

Weight, volume and power estimates for a four-man air revitalization module are shown for the open system in table 5-10 and the recycle system in table 5-11. In the open system, oxygen is stored in tanks and carbon dioxide is removed and stored in lithium hydroxide canisters. In the recycling case, the two systems work together. Carbon dioxide is removed using a solid amine bed that concentrates the CO_2 to be later released into a reduction process (Sabatier) that produces water. The water is then electrolyzed to produce oxygen.

A summary of the open and recycle systems is presented in table 5-12. The advantage of one system over the other is not nearly as pronounced as for the water system, although recycling has advantages in initial weight, resupply weight, and volume. Depending on mission analysis, the power requirement is higher for recycling, though it still remains advantageous to use recycling equipment.

*Table 5-7 Oxygen/Carbon Dioxide Typical Loads * (Ref. 63 and 79)*

SOURCE	kg (LB)/MAN-DAY
INPUT	
OXYGEN	0.835 (1.84)
OUTPUT	
CARBON DIOXIDE	1 (2.20)

*ASSUMES METABOLIC RATE = 2800 kcal.

Table 5-8 Air Revitalization Equipment Design Data (Ref. 63, 72 and 80)

(UNIT DEFINITIONS)

EQUIPMENT	DESIGN DATA	
OXYGEN STORAGE TANK	SPHERICAL TANK	0.64 m (2.1 FT) DIA
	GAS VOLUME	0.137 m^3 (4.86 FT^3)
	STORAGE VOLUME	0.26 m^3 (9.26 FT^3
	TANK DRY WEIGHT	18.8 kg (41.4 LB)
	CHANGE PRESSURE	3300 PSIA
	OXYGEN/TANK	43.9 kg (96.8 LB)
	POWER CONSUMPTION	2 WATTS
OXYGEN GENERATOR (WATER ELECTROLYSIS)	O_2 PRODUCTION	0.49 KG (1.08 LB)/HR.
	FLIGHT WEIGHT	170 KG (375 LB)
	FLIGHT VOLUME	0.74 m^3 (26 FT^3)
	POWER CONSUMPTION	3530 WATTS
CARBON DIOXIDE REMOVAL (LiOH, 2 CARTRIDGE UNIT)	CO_2 REMOVAL RATE/UNIT	0.16 kg (0.36 LB)/HR
	FLIGHT WEIGHT	90.7 kg (200 LB)
	FLIGHT VOLUME	0.42 m^3 (15 FT^3)
	POWER CONSUMPTION	60 WATTS
	CARTRIDGE USAGE	2/4-MAN-DAY
	WEIGHT/2 CARTRIDGES	5.8 kg (12.8 LB)
	VOLUME/2 CARTRIDGES	0.01 m^3 (0.46 FT^3)
ODOR CONTROL UNIT (CHARCOAL)	CAPACITY/UNIT	4-MAN-DAY
	FLIGHT WEIGHT	9.1 kg (20 LB)
	FLIGHT VOLUME	0.03 m^3 (1 FT^3)
	CHARCOAL USAGE	0.06 kg (0.13 LB)/MAN DAY
DEHUMIDIFIER	CAPACITY/UNIT	4-MAN-DAY
	FLIGHT WEIGHT	39.2 kg (86.5 LB)
	FLIGHT VOLUME	0.14 m^3 (5 FT^3)
	POWER CONSUMPTION	102.5 WATTS
CARBON DIOXIDE REMOVAL (SOLID AMINE)	CAPACITY/UNIT	4-MAN-DAY
	FLIGHT WEIGHT	53.5 kg (118 LB)
	FLIGHT VOLUME	0.18 m^3 (6.3 FT^3)
	POWER CONSUMPTION	349 WATTS
AIR CONTAMINANT REMOVAL (CATALYTIC OXIDIZER)	CAPACITY/UNIT	4-MAN-DAY
	FLIGHT WEIGHT	24.5 kg (54 LB)
	FLIGHT VOLUME	0.18 m^3 (6.26 FT^3)
	POWER CONSUMPTION	190.5 WATTS
CARBON DIOXIDE REDUCTION (SABATIER)	CAPACITY/UNIT	8-MAN-DAY
	FLIGHT WEIGHT	48.5 kg (107 LB)
	FLIGHT VOLUME	0.36 m^3 (12.6 FT^3)
	POWER CONSUMPTION	96 WATTS
ATMOSPHERIC MONITOR (PERKIN-ELMER-CAMS UNIT)	CAPACITY/UNIT	4-MAN-DAY
	FLIGHT WEIGHT	22.7 kg (50 LB)
	FLIGHT VOLUME	0.07 m^3 (2.5 FT^3)
	POWER CONSUMPTION	100 WATTS

Table 5-9 Oxygen/Carbon Dioxide Operating Level Data (4-Man Module, 90-Day Resupply) (Ref. 63)

OPERATING LEVEL	mm Hg (psia)		mm Hg
	TOTAL PRESSURE	O_2 PARTIAL PRESSURE	CO_2 PARTIAL PRESSURE
OPERATIONAL	760 (14.7)	160 (3.1)	3.8 MAX.
90-DAY DEGRADED	517-760 (10.0-14.7)	124-197 (2.4-3.8)	7.6 MAX
21-DAY EMERGENCY	517-760 (10.0-14.7)	119-202 (2.3-3.9)	12.0 MAX

Table 5-10 Open Air Revitalization System/Equipment Data Summary (4-Man Module, 90-Day Resupply)

ITEM	NUMBER OF UNITS		TOTAL CAPACITY	TOTAL WEIGHT, kg	TOTAL STORAGE VOLUME, m^3	NOMINAL POWER CONSUMPTION, WATTS
	REQ	REDUND.				
OXYGEN STORAGE TANKS	7	7	615 kg	263.2	3.64	14
OXYGEN EMERGENCY TANKS	2		88 kg	37.6	0.52	–
PLUMBING, etc. (15% OF 3 TANKS)				2.8	0.12	–
LiOH CO_2 REMOVAL SYSTEM						
2 CARTRIDGE UNIT	1		0.16 kg/hr	90.7	0.42	50
DEHUMIDIFIER	1	1		78.4	0.28	205
CATALYTIC BURNER	1	1		49	0.35	381
ATMOSPHERE MONITOR	1			22.7	0.07	100
ODOR CONTROL	1	1		18.2	0.06	–
PLUMBING, ETC. (15% EQUIP)				38.9	0.18	–
SUB TOTAL				601.5	5.64	750
INITIAL SPARES AND CONSUMABLES				1679	1.78	–
TOTAL				2280.5	7.4	750
90 DAY RESUPPLY				998	2.84	–

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Table 5-11 *Recycle Air Revitalization System/Equipment Data Summary (4-Man Module, 90-Day Resupply)*

ITEM	NUMBER OF UNITS		TOTAL CAPACITY	TOTAL WEIGHT, kg	TOTAL STORAGE VOLUME m^3	NOMINAL POWER CONSUMPTION, WATTS
	REQ.	REDUND.				
OXYGEN GENERATOR	½	½	0.40 kg/hr	170	0.74	3530
STORED EMERGENCY OXYGEN	2		88 kg	37.6	0.52	—
CO_2 REMOVAL-SOLID AMINE	1	1		107	0.36	698
CO_2 REDUCTION-SABATIER	½	½		48.5	0.35	95
DEHUMIDIFIER	1	1		78.4	0.28	206
CATALYTIC BURNER	1	1		49	0.35	381
ATMOSPHERE MONITOR	1			22.7	0.07	100
ODOR CONTROL	1	1		18.2	0.06	—
PLUMBING, ETC. (15% EQUIP.)				79.7	0.41	—
SUBTOTAL				611.1	3.14	5009
INITIAL SPARES & CONSUMABLES				185	0.29	—
TOTAL				796.1	3.43	5009
90 DAY RESUPPLY				46	0.16	—

Table 5-12 *Air Revitalization System Summary (4-Man Module, 90-Day Resupply)*

SYSTEM TYPE	MASS kg	VOLUME m^3	NOMINAL POWER WATTS
OPEN SYSTEM	2,281	7.4	750
90-DAY RESUPPLY	998	2.8	----
RECYCLE SYSTEM	796	3.4	5,009
90-DAY RESUPPLY	46	0.2	----

5.3 Waste System

The waste system consists of the human fecal material and trash that includes such items as uneaten food, packaging material, wet wipes, and tissues. The typical weight of waste loads is shown in table 5-13.

Waste products can be collected, compacted, and stored; or they can be processed into usable materials. The equipment involved in waste management is given in table 5-14. To estimate weight, volume, and power requirements, a wet oxidation unit was assumed for the waste recycling equipment. The development of estimates for the open and closed systems is shown in tables 5-15 and 5-16.

Examination of the waste system summary data, table 5-17, indicates very little difference between the open and closed systems. Closing the waste system alone, in this content, is not cost-effective when considering oxidation equipment development costs. However, when the food system is closed, waste recycling becomes very important in that minerals contained in waste products must be reclaimed and processed into usable materials. Discarding the waste would be counterproductive to achieving a high level of closure with minimum resupply requirements.

5.4 Food System

The nominal weight of dry food required to sustain life is 1.6 lb/man/day. Associated with preparation of this food is residual water and packaging, which brings the total food load to 3.6 lb/man/day (see table 5-18). This number is used for calculating the basic weight of food used in the storage and resupply sections of of this study.

The alternative to packaged food is to grow food onboard the spacecraft. Growing food to sustain man in space involves a number of variables such as food type—plants, animals, single-cell protein type organisms, and so forth; food quantity—how much of what type of food is required to provide a nutritionally balanced diet; growth techniques—what food types require different culture techniques and food type and culture techniques that are compatible with the spacecraft environment. Since it was not possible to investigate all possible variables during this study, the following guidelines were adopted:

Table 5-13 Waste Typical Loads (Ref. 63 and 79)

SOURCE	kg (LB)/MAN-DAY
<u>HUMAN SOLIDS OUTPUT</u>	
FECES SOLIDS	0.11 (0.24)
FECES WATER	0.09 (0.20)
TOTAL	0.20 (0.44)
<u>TRASH</u>	0.82 (1.80)

Table 5-14 Waste Management Equipment Design Data (Ref. 63 and 64)

(UNIT DEFINITIONS)

EQUIPMENT	DESIGN DATA	
WASTE COLLECTOR (COMMODE)	CAPACITY/UNIT	210 MANDAYS
	FLIGHT WEIGHT	40.8 kg (90 LB)
	FLIGHT VOLUME	0.35 m^3 (12.2 FT^3)
	POWER CONSUMPTION	120 WATTS
EMERGENCY WASTE COLLECTION (BAGS)	CAPACITY/UNIT	360 MAN DAYS
	FLIGHT WEIGHT	6.8 kg (15 LB)
	FLIGHT VOLUME	0.028 m^3 (1 FT^3)
	POWER CONSUMPTION	0
TRASH COMPACTOR	CAPACITY/UNIT	360 MANDAYS
	COMPACTED VOLUME	0.02 m^3 (0.7 FT^3)/BAG
	FLIGHT WEIGHT	18.1 kg (40 LB)
	FLIGHT VOLUME	0.2 m^3 (7 FT^3)
	POWER CONSUMPTION	120 WATTS
WET OXIDATION UNIT (INCLUDES GRINDING, SLURRYING, REACTION CHAMBER, VCD, ETC.)	CAPACITY/UNIT	27.9 kg (61.4 LB)/DAY
	FLIGHT WEIGHT	93.3 kg (205.6 LB)
	FLIGHT VOLUME	0.49 m^3 (17.3 FT^3)
	POWER CONSUMPTION	285 WATTS

Table 5-15 Open Waste Management System/Equipment Data Summary (4-Man Module, 90-Day Resupply

ITEM	NUMBER OF UNITS		TOTAL CAPACITY	TOTAL WEIGHT, kg	TOTAL STORAGE VOLUME, m^3	NOMINAL POWER CONSUMPTION, WATTS
	REQ	REDUND				
WASTE COLLECTOR	2		420 MAN DAYS	81.6	0.70	240
EMERGENCY WASTE COLLECTION	1			6.8	0.028	0
TRASH COMPACTOR	1		0.02 m^3/bag	18.1	0.2	120
SUBTOTAL				106.5	0.93	360
INITIAL SPARES & CONSUMABLES				85.3	0.76	—
TOTAL				191.8	1.69	360
90-DAY RESUPPLY				82.7	0.75	—

Table 5-16 Recycle Waste Management System/Equipment Data Summary (4-Man Module, 90-Day Resupply)

ITEM	NUMBER OF OF UNITS		TOTAL CAPACITY	TOTAL WEIGHT, kg	TOTAL STORAGE VOLUME, m^3	NOMINAL POWER CONSUMPTION, WATTS
	REQ	REDUND.				
WASTE COLLECTOR	2		420 MANDAYS	81.6	0.70	240
EMERGENCY WASTE COLLECTION	1			6.8	0.028	0
WET OXIDATION UNIT				16	0.45	52
PLUMBING, ETC. (15% OF WET OXIDATION UNIT)				2.4	0.07	—
SUBTOTAL				106.8	1.25	292
INITIAL SPARES AND CONSUMABLES				26.7	0.3	—
TOTAL				133.5	1.6	292
90 DAY RESUPPLY				16.1	0.2	—

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Table 5-17 Waste System Summary (4-Man Module, 90-Day Resupply)

SYSTEM TYPE	MASS kg	VOLUME m^3	NOMINAL POWER WATTS
OPEN SYSTEM	191.8	1.69	360
90-DAY RESUPPLY	82.7	0.75	---
RECYCLE SYSTEM	133.5	1.6	292
90-DAY RESUPPLY	16	0.2	---

Table 5-18 Food Requirement and Packaging Loads (Ref. 8, 79 and 63)

SOURCE	KG (LB)/MAN-DAY
FOOD, DRY	0.73 (1.6)
WATER, CONTAINED IN FOOD	0.45 (1.0)
PACKAGING	0.45 (1.0)
TOTAL	1.63 (3.6)

a. Only common, edible plants with available design data were considered. The plants considered are not necessarily the optimum choices for the mission, but are representative for a generic analysis.

b. Three diets were considered for analysis:

1. Salad vegetables grown to supplement a standard packaged food diet, considered as 3% salad and 97% packaged food.

2. Plant growth to contribute 50% of the diet; the other 50% supplied as packaged food.

3. Plant growth to contribute 97% of the diet, a vegetarian diet; the remaining 3% supplied as vitamins, such as B-12, seasonings, and other miscellaneous condiments.

The individual plants included in the three diets are listed in tables 5-19, 5-20, and 5-21. Growth data available in the literature are shown in the tables with the associated references. These data were used to estimate growing areas, harvest rates, biomass holdup, and plant wastes, which are required to establish plant growth equipment requirements as shown in table 5-22. In addition, table 5-22 presents the derivation and references of other equipment design data necessary to calculate weight, volume, and power requirements associated with plant growth. In some cases, the data base was insufficient to obtain design numbers, so engineering estimates were used. For example, the sixth item in table 5-22 refers to the quantity of water required to supply plants with nutrients and for transpiration. In one reference the quantity of transpiration water recommended was an amount that, when applied on a per-growth-area basis, amounted to a reservoir depth of 5.5 in. For aeroponically grown plants, this quantity of water was considered excessive. A water depth of 2 in was assumed to be adequate and was used for this study. The quantity of water required for transpiration is still an open question that has considerable impact on system weight.

Using the basic data from table 5-22, equipment estimates were calculated for each of the three diets selected for study. These data are presented in tables 5-23, 5-24, and 5-25. The equipment is sized for four-man modules to make it comparable with the physiochemical systems that were analyzed.

Table 5-19 Plant Growth Data for Salad Plants – 3% Diet

PLANT SPECIES	A * YIELD, EDIBLE DRY MATERIAL $g \cdot m^{-2} \cdot DAY^{-1}$ (REF. 43)	B CONSUMPTION RATE, EDIBLE DRY MATERIAL $g \cdot PERSON^{-1} \cdot DAY^{-1}$ (REF. 43)	C GROWING AREA REQUIRED $m^2 \cdot PERSON^{-1}$ $B \div A$ * *	D CONSUMPTION RATE, EDIBLE FRESH MATERIAL $g \cdot PERSON^{-1} \cdot DAY^{-1}$ (REF. 43)	E EDIBLE FRESH FRACTION OF PLANT (REF. 43)	F TOTAL FRESH BIOMASS HARVEST RATE $g \cdot PERSON^{-1} \cdot DAY^{-1}$ $D \div E$	G TOTAL TIME TO HARVEST, DAYS (REF. 43)	H TOTAL FOOD PRODUCING BIOMASS HOLDUP $KG \cdot PERSON^{-1}$ $1/2(F \times G)\frac{1}{1000}$	I NON-EDIBLE FRESH BIOMASS (PLANT WASTE) $g \cdot PERSON^{-1} \cdot DAY^{-1}$ $F - D$
LETTUCE	8.5	1.07	0.12	20.1	0.730	27.5	28	0.39	7.4
TOMATO	6.2	8.17	1.32	116.7	0.84	138.9	215	14.93	22.2
CARROT	21.3	1.61	0.08	11.7	0.489	23.9	80	0.96	12.2
TOTALS		10.85	1.52	148.5		190.3		16.28	41.8

* COLUMN IDENTIFIERS

* * DATA IN COLUMN B DIVIDED BY DATA IN COLUMN A

Table 5-20 Plant Growth Data for 50% Plant Diet

PLANT SPECIES	A * YIELD, EDIBLE DRY MATERIAL g . m^{-2} . DAY^{-1} (REF. 43)	B CONSUMPTION RATE, EDIBLE DRY MATERIAL g . PERSON^{-1} . DAY^{-1} (REF. 43)	C GROWING AREA REQUIRED m^{2} . PERSON^{-1} B ÷ A * *	D CONSUMPTION RATE, EDIBLE FRESH MATERIAL g . PERSON^{-1} . DAY^{-1} (REF. 43)	E EDIBLE FRESH FRACTION OF PLANT (REF. 43)	F TOTAL FRESH BIOMASS HARVEST RATE g . PERSON^{-1} . DAY^{-1} D ÷ E	G TOTAL TIME TO HARVEST, DAYS (REF. 43)	H TOTAL FOOD PRODUCING BIOMASS HOLDUP KG . PERSON^{-1} 1/2(F X G) $\frac{1}{1000}$	I NON-EDIBLE FRESH BIOMASS (PLANT WASTE) g . PERSON^{-1} . DAY^{-1} F - D
DRY BEANS	21.1	14.08	0.67	16.2	0.119	136.1	47	3.20	119.9
PEANUTS	8.2	10.75	1.31	12.3	0.026	473.1	110	26.02	460.8
CABBAGE	9.9	1.50	0.15	25.9	0.952	27.2	30	0.41	1.3
CARROT	21.3	1.61	0.08	11.7	0.489	23.9	80	0.96	12.2
TOMATO	6.2	8.17	1.32	116.7	0.84	138.9	215	14.93	22.2
POTATO	13.7	18.34	1.34	131.0	0.727	180.2	120	10.81	49.2
GREEN BEANS	26.3	3.86	0.15	44.8	0.332	134.3	60	4.06	90.1
LETTUCE	8.6	1.07	0.12	20.1	0.730	27.5	28	0.39	7.4
MELONS	19.9	16.95	0.85	253.0	0.754	335.5	107	17.95	82.5
PEAS	0.6	1.57	2.62	9.7	0.037	262.2	50	6.56	252.5
WHEAT	58.5	306.77	5.24	352.2	0.133	2,648.1	100 (REF 73)	132.41	2,295.9
TOTALS		384.6	13.85	993.6		4,387.6		217.69	3,394.0

* COLUMN IDENTIFIERS

* * DATA IN COLUMN B DIVIDED BY DATA IN COLUMN A

Table 5-21 Plant Growth Data for 97% Plant Diet (Modest Vegetarian)

PLANT SPECIES	A * YIELD, EDIBLE DRY MATERIAL g . m^{-2} . DAY^{-1} (REF. 28)	B CONSUMPTION RATE, EDIBLE DRY MATERIAL g . $PERSON^{-1}$. DAY^{-1} (REF. 28)	C GROWING AREA REQUIRED m^2 . $PERSON^{-1}$ B ÷ A * *	D CONSUMPTION RATE, EDIBLE FRESH MATERIAL g . $PERSON^{-1}$. DAY^{-1} (REF. 28)	E EDIBLE FRESH FRACTION OF PLANT (REF.)	F TOTAL FRESH BIOMASS HARVEST RATE g . $PERSON^{-1}$. DAY^{-1} D ÷ E	G TOTAL TIME TO HARVEST, DAYS (REF.)	H TOTAL FOOD PRODUCING BIOMASS HOLDUP KG . $PERSON^{-1}$ 1/2(F X G) $\frac{1}{1000}$	I NON-EDIBLE FRESH BIOMASS (PLANT WASTE) g . $PERSON^{-1}$. DAY^{-1} F - D
SOYBEAN	25	62	2.3	216	0.44 (54)	491	114 (54)	27.99	275
POTATO	30	76	2.5	360	0.727 (43)	495	120 (43)	29.70	135
MUSTARD GREENS	40	1.2	0.03	10.8	0.80 (EST)	14	60 (15)	0.42	3.2
PEANUTS	15	32	2.1	32.4	0.026 (43)	1,246	110 (43)	68.53	1,213.6
RICE	25	70	2.8	234	0.13 (EST)	1,800	110 (73)	99.00	1,566
PEA POD	30	5.4	0.18	30	0.33 (EST)	91	50 (15)	2.28	61
SPLIT PEA	25	72	2.9	240	0.037 (43)	6,486	50 (43)	162.15	6,246
CORN	25	41	1.6	135.6	0.04 (EST)	3,390	90 (34)	152.55	3,254.4
KALE	40	1.8	0.05	10.8	0.80 (EST)	14	60 (15)	0.42	3.2
DRY BEANS	25	71	2.8	228	0.119 (43)	1,916	47 (43)	45.03	1,688
WHEAT	25	72	2.9	136.2	0.133 (43)	1,024	100 (73)	51.20	887.8
TURNIP GREENS	40	1.2	0.03	10.8	0.80 (EST)	14	60 (15)	0.42	3.2
CHICKPEA	25	75	3.0	228	0.33 (EST)	691	50 (EST)	17.28	463
OATS	25	41	1.6	216	0.13 (EST)	1,662	100 (EST)	83.10	1,446
BROCCOLI	30	4.8	0.16	45	0.20 (EST)	225	60 (15)	6.75	180
TOTALS		626.4	25.00	2,133.6		19,559		746.82	17,425.4

* COLUMN IDENTIFIERS

* * DATA IN COLUMN B DIVIDED BY DATA IN COLUMN A

Table 5-22 Food System Equipment Design Data

EQUIPMENT/ELEMENT	DERIVATION	DESIGN DATA	REFERENCE
PLANT AREA FOR 50% PLANT DIET	INCLUDES 11 PLANTS PRODUCING 385 G DRY EDIBLE MATERIAL/PERSON/DAY	14 m^2/PERSON	43
PLANT AREA FOR 97% PLANT DIET	INCLUDES 15 PLANTS PRODUCING 626 G DRY EDIBLE MATERIAL/PERSON/DAY	25 m^2/PERSON	26
PLANT AREA FOR SALAD PLANTS	BASED ON LETTUCE, TOMATOES, AND CARROTS PRODUCING 10.85 G OF DRY EDIBLE MATERIAL/PERSON/DAY	1.52 m^2/PERSON	43
HEIGHT ALLOWED FOR GROWTH	INCLUDES ROOT GROWTH, ILLUMINATED PORTION AND LIGHTS	1.5 m HEIGHT	ESTIMATE
ADDITIONAL VOLUME	FOR ANCILLARY EQUIPMENT AND CREW MOVEMENT	25% OF PLANT GROWTH VOL.	ESTIMATE
TRANSPIRATION AND NUTRIENT WATER	USED 2 INCHES OF WATER DEPTH PER THE GROWING AREA	0.0508 m DEEP X AREA	ESTIMATE
PLANT CELLULAR WATER	70-90% OF PLANT'S FRESH WEIGHT IS WATER. USED 80% AS AN AVERAGE	80% OF FRESH WEIGHT	17
INITIAL CELLULAR WATER CHARGE	WATER CONTAINED IN BIOMASS HOLDUP MUST BE INITIALLY SUPPLIED	80% OF FRESH BIOMASS HOLDUP	17 AND 43
WATER CONTAINMENT STRUCTURE	USE SHUTTLE TANKS. CAPACITY 73.5 KG/TANK	MASS - 22.9 KG/TANK	63
PLANT ILLUMINATION	WILL USE INDIRECT SOURCE OF LIGHTING	150 WATTS/m^2	17 AND 19
PLANT SUPPORT STRUCTURE	CALCULATED AVERAGE WEIGHT FOR 22 PLANT SPECIES	7.2 KG/m^2	20
LIGHTS AND SUPPORT STRUCTURE	REFERENCE SAYS 150 LB/0.98 m^2 COULD BE REDUCED; THEREFORE USED 75 LB	34 KG/m^2	43
CONTROL CONSOLE AND CO_2 ANALYZER	25 LB AND 10 LB, BOTH FIXED WEIGHTS	16 KG	43
HUMIDIFICATION/DEHUMIDIFICATION EQUIPMENT	REFERENCE GIVES 233 LB/0.98 m^2 WITH A 0.6 SCALING FACTOR	(107.8 KG)/(m^2) 0.6	43
MISCELLANEOUS COMPONENTS: WIRE, PIPING, VALVES, ETC.	REFERENCE GIVES 30 LB/0.98 m^2 WITH A 0.6 SCALING FACTOR	(13.9 KG)/(m^2) 0.6	43
FOOD HARVESTING EQUIPMENT	REFERENCE TO 1 GRAIN HARVESTER – NOT APPLICABLE FOR SMALL AREAS	800 KG/HARVESTER	43
FOOD PROCESSING EQUIPMENT	BASED ON K (NP)^X, WHERE K = 302.7 AND X = 0.415 ARE DETERMINED BY FITTING A CURVE TO THE DATA FOR POPULATIONS OF 10 AND 100 PERSONS; NP = PERSONS	(302.7) (NO. OF PEOPLE)$^{0.415}$	43 AND 38
FOOD WASTE	ASSUME DIFFERENCE OF TOTAL HARVEST RATE AND CONSUMPTION RATE AS NON-EDIBLE	DIET DEPENDENT	ESTIMATE
WET OXIDATION WASTE UNIT	UNIT INCLUDES GRINDING, SLURRYING AND VCD. CAPACITY 27.9 KG/DAY/UNIT (USE 80% SCALE UP FACTOR FOR MULTIPLE UNITS)	MASS = 93.3 KG/UNIT	64
PLANT O_2 GENERATED	AVERAGE FOR PLANTS IN 50% AND 100% DIETS ≅ 25 $\ell\, O_2/m^2$/DAY	35.7 G O_2/m^2/DAY	20
PLANT CO_2 ASSIMILATED	USE 0.95 ASSIMILATION QUOTIENT PER M. M. AVERNER, NASA AMES	33.9 G CO_2/m^2/DAY	
WATER PROCESSED	AVERAGE FOR PLANTS IN 50% AND 100% DIETS ≅ 3 $\ell\, H_2O/m^2$ /DAY	3000 G/m^2/DAY	20
EQUIPMENT POWER (PER FULL HABITAT MODULE)	SUM: HUMID./DEHUMID. (2500 W) + CONTROL AND CO_2 ANALYZER (200 W) + VENTILATION (2600 W) + HEAT TRANSPORT AND REJECTION (3400 W)	8700 WATTS/FULL MODULE	63

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Table 5-23 *Food System Equipment Estimates for 4-Man Module*
Diet: (Supplemental Salad Plants) 3% Plant Growth – 97% Resupply

EQUIPMENT/ELEMENT	DERIVATION	DESIGN DATA
PLANT GROWTH AREA	(1.52 m^2/PERSON (4 PEOPLE)	6 m^2
PLANT GROWTH VOLUME	(6 m^2) (1.5 m)	9 m^3
ADDITIONAL MODULE VOLUME	(9 m^3) (0.25)	2.25 m^3
TRANSPIRATION AND NUTRIENT WATER	(6 m^2) (0.0508 m) = 0.3048 m^3 of WATER	305 KG H_2O
PLANT CELLULAR WATER (INITIAL CHARGE)	(16.28 KG/PERSON BIOMASS HOLDUP) (0.80 WATER FACTOR) (4 PEOPLE)	52 KG H_2O
STRUCTURE FOR WATER TRANSPORT	(305 KG + 52 KG) ÷ (73.5 KG TANK CAPACITY) (22.9 KG TANK DRY WEIGHT)	114 KG TANKAGE
PLANT SUPPORT STRUCTURE	(7.2 KG/m^2) (6 m^2)	43 KG
LIGHTS AND SUPPORT STRUCTURE	(34 KG/m^2) (6 m^2)	204 KG
CONTROL CONSOLE AND CO_2 ANALYZER	FIXED WEIGHT	16 KG
HUMIDIFICATION/DEHUMIDIFICATION EQUIPMENT	(107.8 KG) (6 m^2)$^{(0.6)}$	315 KG
MISCELLANEOUS COMPONENTS: WIRE, PIPING, VALVES, ETC.	(13.9 KG) (6 m^2)$^{(0.6)}$	41 KG
FOOD HARVESTING EQUIPMENT	NOT APPLICABLE FOR SMALL AREA – ASSUME HAND HARVEST	NA
FOOD PROCESSING EQUIPMENT	NOT APPLICABLE FOR SALAD PLANTS SCENARIO	NA
FOOD WASTE	(41.8 G/PERSON/DAY) (4 PEOPLE)	0.167 KG
WASTE PROCESSING EQUIPMENT (FOOD, HUMAN, TRASH)	NOT APPLICABLE FOR SALAD PLANTS SCENARIO	NA
EQUIPMENT POWER	(8700 WATTS HAB. MOD.) (11.25 m^3 TOTAL VOLUME) ÷ (140.5 m^3 HAB. MOV. VOLUME)	696 WATTS
ILLUMINATION POWER	(150 WATTS/m^2) (6 m^2)	900 WATTS

*Table 5-24 Food System Equipment Estimates for 4-Man Module
Diet: 50% Plant Growth – 50% Food Resupply*

EQUIPMENT/ELEMENT	DERIVATION	DESIGN DATA
PLANT GROWTH AREA	(14 m^2/PERSON) (4 PEOPLE)	56 m^2
PLANT GROWTH VOLUME	(56 m^2) (1.5 m)	84 m^3
ADDITIONAL MODULE VOLUME	(84 m^3) (0.25)	21 m^3
TRANSPIRATION AND NUTRIENT WATER	(56 m^2) (0.0508 m) = 2.845 m^3 OF WATER	2845 KG H_2O
PLANT CELLULAR WATER (INITIAL CHARGE)	(217.69 KG/PERSON BIOMASS HOLDUP) (0.80)(4 PEOPLE)	696.6 KG H_2O
STRUCTURE FOR WATER TRANSPORT	(2845 KG + 696.6 KG) ÷ (73.5 KG TANK CAPACITY) (22.9 KG TANK DRY WEIGHT)	1099 KG TANKAGE
PLANT SUPPORT STRUCTURE	(7.2 KG/m^2) (56 m^2)	403.2 KG
LIGHTS AND SUPPORT STRUCTURE	(34 KG/m^2) (56 m^2)	1904 KG
CONTROL CONSOLE AND CO_2 ANALYZER	FIXED WEIGHT	16 KG
HUMIDIFICATION/DEHUMIDIFICATION EQUIPMENT	(107.8 KG) $(56\ m^2)^{(0.6)}$	1206.5 KG
MISCELLANEOUS COMPONENTS: WIRE, PIPING, VALVES, ETC.	(13.9 KG) $(56\ m^2)^{(0.6)}$	155.6 KG
FOOD HARVESTING EQUIPMENT	NOT APPLICABLE FOR SMALL AREA. ASSUME HAND HARVEST.	NA
FOOD PROCESSING EQUIPMENT	[(302.7) $(4\text{ PEOPLE})^{(0.415)}$ KG] [0.50 FOR 50% DIET]	269 KG
FOOD WASTE	(3394.0 G/PERSON/DAY) (4 PEOPLE)	13.58 KG/DAY
WASTE PROCESSING EQUIPMENT (FOOD, HUMAN, TRASH)	(13.58 KG FOOD WASTE/DAY) + (1.0 KG) (4) ÷ (27.9 KG/DAY/UNIT) = < 1 UNIT	93.3 KG
EQUIPMENT POWER	(8700 WATTS HAB. MOD.) (105 m^3 TOTAL VOL.) ÷ (140.5 m^3 HAB. MOD. VOL.)	6502 WATTS
ILLUMINATION POWER	(150 WATTS/m^2) (56 m^2)	8400 WATTS

Table 5-25 Food System Equipment Estimates for 4-Man Module
Diet: (Vegetarian) 97% Plant Growth – 3% Food Resupply

EQUIPMENT/ELEMENT	DERIVATION	DESIGN DATA
PLANT GROWTH AREA	($25\ m^2$/PERSON) (4 PEOPLE)	$100\ m^2$
PLANT GROWTH VOLUME	($100\ m^2$) (1.5 m)	$150\ m^3$
ADDITIONAL MODULE VOLUME	($150\ m^3$) (0.25)	$37.5\ m^3$
TRANSPIRATION AND NUTRIENT WATER	($100\ m^2$) (0.0508 m) = $5.08\ m^3$ OF WATER	5080 KG H_2O
PLANT CELLULAR WATER (INITIAL CHARGE)	(746.82 KG/PERSON BIOMASS HOLDUP) (0.80) (4 PEOPLE)	2389.8 KG H_2O
STRUCTURE FOR WATER TRANSPORT	(5080 KG + 2389.8 KG) ÷ (73.5 KG/TANK CAPACITY) (22.9 KG/TANK DRY WEIGHT)	2336 KG TANKAGE
PLANT SUPPORT STRUCTURE	(7.2 KG/m^2) ($100\ m^2$)	720 KG
LIGHTS AND SUPPORT STRUCTURE	(34 KG/m^2) ($100\ m^2$)	3400 KG
CONTROL CONSOLE AND CO_2 ANALYZER	FIXED WEIGHT	16 KG
HUMIDIFICATION/DEHUMIDIFICATION EQUIPMENT	(107.8 KG) ($100\ m^2$) $^{(0.6)}$	1708.5 KG
MISCELLANEOUS COMPONENTS: WIRE, PIPING, VALVES, ETC.	(13.9 KG) ($100\ m^2$) $^{(0.6)}$	220.3 KG
FOOD HARVESTING EQUIPMENT	NOT APPLICABLE FOR SMALL AREA. ASSUME HAND HARVEST.	NA
FOOD PROCESSING EQUIPMENT	[(302.7) (4 PEOPLE) $^{(0.415)}$ KG] [1.0 FOR 97% DIET]	538.1 KG
FOOD WASTE	(17425.4 G/PERSON/DAY) (4 PEOPLE)	69.7 KG
WASTE PROCESSING EQUIPMENT (FOOD, HUMAN, TRASH)	[(68.7 KG FOOD WASTE/DAY) + (1.0 KG) (4)] ÷ (27.9 KG/DAY/UNIT) = < 3 UNITS (3 UNITS) (93.3 KG/UNIT) (80% SCALE UP FACTOR)	223.9 KG
EQUIPMENT POWER	(8700 WATTS HAB. MOD.) ($187.5\ m^3$ TOTAL VOL.) ÷ ($140.5\ m^3$ HAB. MOD. VOL.)	11610 WATTS
ILLUMINATION POWER	(150 WATTS/m^2) ($100\ m^2$)	15000 WATTS

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In keeping with the logic flow (fig. 5-1), the food system equipment estimates (tables 5-23 to 5-25) were combined with the food system operating level data (table 5-26) to describe the open food system (table 5-27), and the food growing system for each of the three diets (tables 5-28, 5-29, and 5-30). In table 5-28, the waste processing equipment is stated as being included in with the EC/LS equipment. This is because the quantity of additional waste generated by the 3% plant growth diet is a relatively insignificant quantity, approximately 0.2 kg/day, as shown in table 5-23. The quantity of waste generated by 50% and 97% vegetable diets is more significant, 14 kg and 70 kg respectively. The waste processing equipment estimates to handle these increased food system wastes in addition to the human waste and trash are shown in tables 5-29 and 5-30.

The food system summary data in table 5-31 show the comparison of the open system and the three plant diet systems with respect to mass, volume, and power. In analyzing these data, one can see that the system weight, volume, and power parameters increase as you go from the open system to increasingly more plant growth. Conversely, the resupply mass and volume decrease with more plant growth. At first it would seem that growing plants to close the food system would not be advantageous; however, because the resupply requirements would decrease with increasing plant growth, eventually a point would be reached when the resupply mass of the open system would surpass the large recycling equipment mass and power requirements of the plant growth systems. This subject is discussed in more detail in section 6.0 where the various EC/LS systems are compared in terms of mission analysis and transportation costs.

5.5 Closure Scenarios with Associated Mass Estimates

Seven closure scenarios were selected to enable the comparison of an entirely open system with various physiochemical system closures, and the comparison of a closed physiochemical system with three food-growing scenarios. Table 5-32 defines these seven closure scenarios. Scenario codes A through G were assigned to the cases, and will be used as identifiers in this report.

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

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Table 5-26 Food System Operating Level Data (4-Man Module, 90-Day Resupply (Ref. 63)

OPERATING LEVEL	kg (LB)/4-MAN-DAY		
	FOOD + WATER	PACKAGING	TOTAL
OPERATIONAL	4.7 (10.4)	1.8 (4.0)	6.5 (14.4)
DEGRADED	2.7 (5.9)	1.03 (2.28)	3.72 (8.2)

Table 5-27 Open Food System/Data Summary (4-Man Module, 90-Day Resupply)

ITEM	NUMBER OF UNITS		TOTAL CAPACITY	TOTAL WEIGHT KG	TOTAL STORAGE VOLUME M^3	NOMINAL POWER CONSUMPTION WATTS
	REQ.	REDUND.				
FOOD + PACKAGING	1		360 MAN DAYS	587.9	1.7	------
CONTINGENCY FOOD + PACKAGING		1	360 MAN DAYS	334.8	0.97	------
STORAGE CONTAINER (25% OF FOOD WT.)				231		------
STORAGE VOLUME (60% OF FOOD VOL.)					1.6	------
TOTAL				1154	4.3	------
90-DAY RESUPPLY				736	2.7	------

Table 5-28 Food Growing System/Equipment Data Summary
Diet: 3% Plant Growth - 97% Food Resupply (4-Man Module, 90-Day Resupply)

ITEM	TOTAL WEIGHT, kg	TOTAL STORAGE VOLUME, m^3	NOMINAL POWER CONSUMPTION, WATTS
WATER RESERVOIR	357		
WATER TANKS	114		
PLANT GROWTH STRUCTURE	43		
PLANT GROWTH EQUIPMENT (INCLUDES LIGHTS, ANALYZER, HUMIDITY CONTROL, ETC.)	576		
HARVESTING AND PROCESSING EQUIPMENT	0		
WASTE PROCESSING EQUIPMENT (INCLUDES FOOD AND HUMAN WASTES AND TRASH)	(INCLUDED WITH EC/LS EQUIPMENT)		
TOTAL PLANT GROWTH VOLUME		11.25	
POWER CONSUMPTION			1,596
SUBTOTAL	1,090	11.25	1,596
INITIAL FOOD SUPPLY – COMPLETE FOR 90 DAYS (PLUS CONTINGENCY)	1,154	4.3	——
INITIAL SPARES (10% OF EQUIPMENT)	58	0.1	——
TOTAL	2,302	15.65	1,596
90-DAY RESUPPLY (97% OF DIET AND SPARES AT 3% OF EQUIPMENT)	730	2	——

Table 5-29 Food Growing System/Equipment Data Summary
Diet: 50% Plant Growth - 50% Food Resupply (4-Man Module, 90-Day Resupply)

ITEM	TOTAL WEIGHT, kg	TOTAL STORAGE VOLUME, m^3	NOMINAL POWER CONSUMPTION, WATTS
WATER RESERVOIR	3,542		
WATER TANKS	1,099		
PLANT GROWTH STRUCTURE	403		
PLANT GROWTH EQUIPMENT (INCLUDES LIGHTS, ANALYZER, HUMIDITY CONTROL, ETC.)	3,282		
HARVESTING AND PROCESSING EQUIPMENT	269		
WASTE PROCESSING EQUIPMENT (INCLUDES FOOD AND HUMAN WASTES AND TRASH)	93		
TOTAL PLANT GROWTH VOLUME		105.0	
POWER CONSUMPTION			14,900
SUBTOTAL	8,688	105.0	14,900
INITIAL FOOD SUPPLY FOR 90 DAYS	735	2.7	----
INITIAL SPARES (10% OF EQUIPMENT)	364	0.8	----
TOTAL	9,787	108.5	14,900
90-DAY RESUPPLY (50% OF FOOD AND SPARES AT 3% OF EQUIPMENT)	477	1.6	----

Table 5-30 Food Growing System/Equipment Data Summary
Diet: 97% Plant Growth - 3% Food Resupply (4-Man Module, 90-Day Resupply)

ITEM	TOTAL WEIGHT, kg	TOTAL STORAGE VOLUME, m^3	NOMINAL POWER CONSUMPTION, WATTS
WATER RESERVOIR	7,470		
WATER TANKS	2,336		
PLANT GROWTH STRUCTURE	720		
PLANT GROWTH EQUIPMENT (INCLUDES LIGHTS, ANALYZER, HUMIDITY CONTROL, ETC.)	5,345		
HARVESTING AND PROCESSING EQUIPMENT	536		
WASTE PROCESSING EQUIPMENT (INCLUDES FOOD AND HUMAN WASTES AND TRASH)	224		
TOTAL PLANT GROWTH VOLUME		187.5	
POWER CONSUMPTION			26,600
SUBTOTAL	16,633	187.5	26,600
INITIAL FOOD SUPPLY FOR 90 DAYS	736	2.7	
INITIAL SPARES (10% OF EQUIPMENT)	611	1.5	
TOTAL	17,979	191.7	26,600
90-DAY RESUPPLY (3% OF DIET AND SPARES AT 3% OF EQUIPMENT)	205	1.0	----

Table 5-31 Food System Summary (4-Man Module, 90-Day Resupply)

SYSTEM TYPE	MASS, kg	VOLUME, m^3	NOMINAL POWER, WATTS
OPEN SYSTEM	1,164	4.3	----
90-DAY RESUPPLY	736	2.7	----
3% PLANT GROWTH - 97% RESUPPLY	2,302	16.7	1,596
90-DAY RESUPPLY	730	2.7	----
50% PLANT GROWTH - 50% RESUPPLY	9,787	108.6	14,900
90-DAY RESUPPLY	477	1.6	----
97% PLANT GROWTH - 3% RESUPPLY	17,979	191.7	26,600
90-DAY RESUPPLY	206	1.0	----

Table 5-32 EC/LSS Closure Scenarios

SCENARIO CODE	EC/LSS				
	WATER	O_2/CO_2	WASTE	FOOD	
A	0	0	0	0	
B	X	0	0	0	
C	0	X	0	0	
D	X	X	0	0	
E	X	X	0	X	(3% OF DIET SALAD VEGETABLES)
F	X	X	X	X	(50% OF DIET ALL PLANT MATERIAL)
G	X	X	X	X	(97% OF DIET VEGETARIAN)

0 DENOTES RESUPPLY AND/OR STORAGE

X DENOTES RECYCLE OR ON-BOARD GENERATION further assumed that waste removed from the water by the plants during transpiration is removed from the inedible plant material during waste processing. The other important advantage offered 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 oxygen generated. These relationships and the percentages of crew requirements satisfied by the three plant-growth scenarios are presented in table 5-33.

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 for water purification or air revitalization from plant growth. 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%. The equipment data summary utilizing these credits is shown in table 5-34. Credits given for the 97% food growth scenario were assumed to be 100% for all three materials, even though the CO_2 removal is shown to be only 85% of the new 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. The credits given for the 97% food growth example, are presented in table 5-35.

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 of these modules were derived from Space Operations Center data (reference 63). The habitat module was used as a baseline to estimate the housing module for CELSS equipment. The basic elements and associated weights are shown in table 5-36. The derived weight-to-volume factor of 44.0 kg/m^3 is used as a volume penalty in later calculations. The derivation of the volume penalty applied for the resupply module (27.8 kg/m^3) is given in table 5-37.

Total system mass and power requirements were determined for each of the closure scenarios. The development of these data are presented in tables 5-38 through 5-44 for closure scenarios A through G. The equipment and supplies data for initial total mass and

Table 5-33 Water Purification and Air Revitalization Credits from Plant Growth (4-Man Module, 90-Day Resupply)

ITEM	DERIVATION	AMOUNT, kg/DAY	% OF CREW REQUIREMENT
NOMINAL REQUIREMENTS/4-MAN CREW			
WATER		93.2	---
OXYGEN		3.3	---
CARBON DIOXIDE		4.0	---
3% PLANT GROWTH – 97% FOOD RESUPPLY			
WATER	(3,000g H_2O) (6 m^2)	18	19%
OXYGEN	(35.7g O_2) (6 m^2)	0.21	6%
CARBON DIOXIDE	(33.9g CO_2) (6 m^2)	0.20	5%
50% PLANT GROWTH – 50% FOOD RESUPPLY			
WATER	(3,000g H_2O) (56 m^2)	168	180%
OXYGEN	(35.7g O_2) (56 m^2)	2.0	61%
CARBON DIOXIDE	(33.9g CO_2) (56 m^2)	1.9	48%
97% PLANT GROWTH – 3% FOOD RESUPPLY			
WATER	(3,000g H_2O) (100 m^2)	300	322%
OXYGEN	(35.7g O_2) (100 m^2)	3.6	109%
CARBON DIOXIDE	(33.9g CO_2) (100 m^2)	3.4	85%

Table 5-34 Water, O_2 / CO_2 and Waste System Equipment Data Summary Utilizing Capabilities of the 50% Plant Growth Scenario (4-Man Module, 90-Day Resupply)

ITEM	NUMBER OF UNITS		TOTAL CAPACITY	TOTAL WEIGHT, kg	TOTAL STORAGE VOLUME, m^3	NOMINAL POWER CONSUMPTION, WATTS
	REQ	REDUND				
WATER (ASSUME 100% WATER PURIFICATION BY PLANTS)						
EMERGENCY WATER STORAGE	3		221 kg H_2O	289	0.57	---
WATER QUALITY MONITOR	1			27	0.11	40
SUBTOTAL				316	0.68	40
O_2/CO_2 (ASSUME 50% AIR REVITALIZATION BY PLANTS)						
RECYCLING SYSTEM	1/2			398	1.72	2,506
SUBTOTAL				398	1.72	2,506
WASTE (INCLUDED WITH PLANT GROWTH EQUIPMENT)				---	---	---
TOTAL				714	2.4	2,546
90-DAY RESUPPLY				24.6	0.09	---

Table 5-35 Water, O_2 / CO_2 and Waste System Equipment Data Summary Utilizing Capabilities of the 97% Plant Growth Scenario (4-Man Module, 90-Day Resupply)

ITEM	NUMBER OF UNITS		TOTAL CAPACITY	TOTAL WEIGHT, kg	TOTAL STORAGE VOLUME, m^3	NOMINAL POWER CONSUMPTION, WATTS
	REQ	REDUND				
WATER (ASSUME 100% WATER PURIFICATION BY PLANTS)						
EMERGENCY WATER STORAGE	3		221 kg H_2O	289	0.57	---
WATER QUALITY MONITOR	1			27	0.11	40
SUBTOTAL				316	0.68	40
O_2/CO_2 (ASSUME 100% AIR REVITALIZATION BY PLANTS)						
EMERGENCY O_2 STORAGE	2		88 kg O_2	125.6	0.52	---
EMERGENCY CO_2 REMOVAL	1			54.0	0.18	---
ATMOSPHERE MONITOR	1			22.7	0.07	100
SUBTOTAL				202.3	0.77	100
WASTE (INCLUDED WITH PLANT GROWTH EQUIPMENT)				---	---	---
TOTAL				518.3	1.45	140
90-DAY RESUPPLY				4.4	0.01	---

Table 5-36 Mass Estimate for CELSS Module (Based on Space Operations Center Habitat Module, Ref. 63)

ELEMENT	DESCRIPTION	MASS, kg
Habitat Module Size and Volume	4.267 m dia x 9.82 m ℓ = 140.5 m^3	
Module Mass Estimates		
• Structure	Includes 2.2 mm aluminum pressure skin; ring frames, dome ring frames, main support rings, support longerons, trunnions, etc.	2712
• Mechanisms	Berthing Port	68
• Thermal Control	Includes radiator skin, tubes and pedestals, freon coolant, multilayer insulation, cold plates, etc.	2792
• Misc. Electrical Equipment	Includes bussing, harnesses, boxes, connectors, switches, interior lighting, etc.	615
Total Mass Estimate		6187
Weight to Volume Ratio	6187 kg/140.5 m^3	44.0 kg/m^3

Table 5-37 Mass Estimate for Resupply Module (Based on Space Operations Center Logistics Module, Ref. 63)

ELEMENT	DESCRIPTION	MASS kg
Logistics Module Size and Volume	4.47 m dia x 6.60 m ℓ = 103.6 m^3	
Module Mass Estimates		
• Structure	Includes 2.2 mm aluminum skin; support rings, longerons and trunnions, storage support structure; entry hatch, etc.	2001
• Mechanisms	Berthing Port	68
• Thermal Control	Radiator panel, multilayer insulation and miscellaneous components	85
• Misc. Electrical Equipment	Harnesses, interior lighting, miscellaneous equipment	145
• Storage Cabinets, Freezer, etc.		581
Total Mass Estimate		2880
Weight to Volume Ratio	2880 kg/103.6 m^3	27.8 kg/m^3

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Table 5-38 Mass and Power Estimates for Closure Scenario A (4-Man Module, 90-Day Resupply)

EC/LS SYSTEM	INITIAL TOTAL MASS, kg	INITIAL TOTAL VOLUME, m^3	90-DAY RESUPPLY MASS, kg	90-DAY RESUPPLY VOLUME, m^3	NOMINAL POWER, WATTS
EQUIPMENT AND SUPPLIES					
WATER (OPEN WITH RESUPPLY)	12,446	24.6	10,894	21.5	30
O_2/CO_2 (OPEN WITH RESUPPLY/STORAGE)	2,281	7.4	998	2.8	750
WASTE (OPEN WITH STORAGE)	192	1.7	83	0.8	360
ADD 10% PACKAGING VOL. FOR ABOVE		3.4		2.5	
FOOD (OPEN WITH RESUPPLY)	1,154	4.3	735	2.7	----
SUBTOTAL	16,073	41.4	12,710	30.3	1,140
PRESSURE MODULE ESTIMATES					
CELSS MODULE (44.0 kg/m^3)	1,822				
RESUPPLY MODULE (27.8 kg/m^3)			842		
TOTAL MASS AND POWER ESTIMATE FOR CLOSURE SCENARIO	17,895		13,552		1,140

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Table 5-39 Mass and Power Estimates for Closure Scenario B (4-Man Module, 90-Day Resupply)

EC/LS SYSTEM	INITIAL TOTAL MASS, kg	INITIAL TOTAL VOLUME, m^3	90-DAY RESUPPLY MASS, kg	90-DAY RESUPPLY VOLUME, m^3	NOMINAL POWER, WATTS
<u>EQUIPMENT AND SUPPLIES</u>					
WATER (RECYCLE)	1,320	4.9	94	0.2	797
O_2/CO_2 (OPEN WITH RESUPPLY/STORAGE)	2,281	7.4	998	2.8	750
WASTE (OPEN WITH STORAGE)	192	1.7	83	0.8	360
ADD 10% PACKAGING VOL. FOR ABOVE		1.4		0.4	
FOOD (OPEN WITH RESUPPLY)	1,154	4.3	735	2.7	——
SUBTOTAL	4,947	19.7	1,910	6.9	1,907
<u>PRESSURE MODULE ESTIMATES</u>					
CELSS MODULE (44.0 kg/m^3)	867				
RESUPPLY MODULE (27.8 kg/m^3)			192		
TOTAL MASS AND POWER ESTIMATE FOR CLOSURE SCENARIO	5,814		2,102		1,907

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Table 5-40 Mass and Power Estimates for Closure Scenario C (4-Man Module, 90-Day Resupply)

EC/LS SYSTEM	INITIAL TOTAL MASS, kg	INITIAL TOTAL VOLUME, m^3	90-DAY RESUPPLY MASS, kg	90-DAY RESUPPLY VOLUME, m^3	NOMINAL POWER, WATTS
EQUIPMENT AND SUPPLIES					
WATER (OPEN WITH RESUPPLY)	12,446	24.6	10,894	21.5	30
O_2/CO_2 (RECYCLE)	786	3.4	46	0.2	5,009
WASTE (OPEN WITH STORAGE)	192	1.7	83	0.8	360
ADD 10% PACKAGING VOL. FOR ABOVE		3.0		2.3	
FOOD (OPEN WITH RESUPPLY)	1,164	4.3	736	2.7	———
SUBTOTAL	14,588	37.0	11,758	27.5	5,399
PRESSURE MODULE ESTIMATES					
CELSS MODULE (44.0 kg/m^3)	1,628				
RESUPPLY MODULE (27.8 kg/m^3)			765		
TOTAL MASS AND POWER ESTIMATE FOR CLOSURE SCENARIO	16,216		12,523		5,399

Table 5-41 Mass and Power Estimates for Closure Scenario D (4-Man Module, 90-Day Resupply)

EC/LS SYSTEM	INITIAL TOTAL MASS, kg	INITIAL TOTAL VOLUME, m^3	90-DAY RESUPPLY MASS, kg	90-DAY RESUPPLY VOLUME, m^3	NOMINAL POWER, WATTS
EQUIPMENT AND SUPPLIES					
WATER (RECYCLE)	1,320	4.9	94	0.2	797
O_2/CO_2 (RECYCLE)	796	3.4	46	0.2	5,009
WASTE (OPEN WITH STORAGE	192	1.7	83	0.8	360
ADD 10% PACKAGING VOL. FOR ABOVE		1.0		0.1	
FOOD (OPEN WITH RESUPPLY)	1,154	4.3	735	2.7	—
SUBTOTAL	3,462	15.3	958	4.0	6,166
PRESSURE MODULE ESTIMATES					
CELSS MODULE (44.0 kg/m^3)	673				
RESUPPLY MODULE (27.8 kg/m^3)			111		
TOTAL MASS AND POWER ESTIMATE FOR CLOSURE SCENARIO	4,135		1,069		6,166

Table 5-42 Mass and Power Estimates for Closure Scenario E (4-Man Module, 90-Day Resupply)

EC/LS SYSTEM	INITIAL TOTAL MASS, kg	INITIAL TOTAL VOLUME, m^3	90-DAY RESUPPLY MASS, kg	90-DAY RESUPPLY VOLUME, m^3	NOMINAL POWER, WATTS
EQUIPMENT AND SUPPLIES					
WATER (RECYCLE WITH NO CREDIT FOR PLANT GROWTH)	1,320	4.9	94	0.2	797
O_2/CO_2 (RECYCLE WITH NO CREDIT FOR PLANT GROWTH)	796	3.4	46	0.2	5,009
WASTE (OPEN WITH STORAGE)	192	1.7	83	0.8	360
ADD 10% PACKAGING VOL. FOR ABOVE		1.0		0.1	
FOOD (3% PLANT GROWTH-97% RESUPPLY)	2,302	15.7	730	2.7	1,596
SUBTOTAL	4,610	26.7	953	4.0	7,762
PRESSURE MODULE ESTIMATES					
CELSS MODULE (44.0 kg/m^3)	1,175				
RESUPPLY MODULE (27.8 kg/m^3)			111		
TOTAL MASS AND POWER ESTIMATE FOR CLOSURE SCENARIO	5,785		1,064		7,762

Table 5-43 Mass and Power Estimates for Closure Scenario F (4-Man Module, 90-Day Resupply)

EC/LS SYSTEM	INITIAL TOTAL MASS, kg	INITIAL TOTAL VOLUME, m^3	90-DAY RESUPPLY MASS, kg	90-DAY RESUPPLY VOLUME, m^3	NOMINAL POWER, WATTS
EQUIPMENT AND SUPPLIES					
WATER (RECYCLE WITH CREDIT FOR PLANT GROWTH)	316	0.68	24.6	0.09	40
O_2/CO_2 (RECYCLE WITH CREDIT FOR PLANT GROWTH)	398	1.72			2,506
WASTE (RECYCLE - INCLUDED IN PLANT GROWTH EQUIPMENT)	——	——	——	——	——
ADD 10% PACKAGING VOL. FOR ABOVE		0.2		0.009	
FOOD (50% PLANT GROWTH - 50% RESUPPLY)	9,787	108.5	477	1.6	14,900
SUBTOTAL	10,501	111.1	502	1.7	17,446
PRESSURE MODULE ESTIMATES					
CELSS MODULE (44.0 kg/m^3)	4,888				
RESUPPLY MODULE (27.8 kg/m^3)			47		
TOTAL MASS AND POWER ESTIMATE FOR CLOSURE SCENARIO	15,389		549		17,446

Table 5-44 Mass and Power Estimates for Closure Scenario G (4-Man Module, 90-Day Resupply)

EC/LS SYSTEM	INITIAL TOTAL MASS, kg	INITIAL TOTAL VOLUME, m^3	90-DAY RESUPPLY MASS, kg	90 DAY RESUPPLY VOLUME, m^3	NOMINAL POWER, WATTS
EQUIPMENT AND SUPPLIES					
WATER (RECYCLE WITH CREDIT FOR PLANT GROWTH)	316	0.68	4.4	0.01	40
O_2/CO_2 (RECYCLE WITH CREDIT FOR PLANT GROWTH)	202	0.77			100
WASTE (RECYCLE INCLUDED IN PLANT GROWTH EQUIPMENT)	----	----	----	----	----
ADD 10% PACKAGING VOL. FOR ABOVE		0.15		0.001	
FOOD (97% PLANT GROWTH 3% RESUPPLY)	17,979	181.7	205	1.0	26,600
SUBTOTAL	18,497	183.3	209	1.01	26,740
PRESSURE MODULE ESTIMATES					
CELSS MODULE (44.0 kg/m^3)	8,505				
RESUPPLY MODULE (27.8 kg/m^3)			28		
TOTAL MASS AND POWER ESTIMATE FOR CLOSURE SCENARIO	27,002		237		26,740

volume, 90-day resupply mass and volume, and power requirements were taken from the summary tables 5-6, 5-12, 5-17, and 5-31. The pressure module mass estimates were derived by multiplying the initial total volume times the CELSS module factor of 44.0 kg/m^3, and the 90-day resupply volume by the resupply module factor of 27.8 kg/m^3.

6.0 STUDY RESULTS

The total mass and power estimates developed for each of the closure scenarios, shown previously in tables 5-38 through 5-44, are used to generate two sets of comparisons. The first set compares the mass data from the open system, closure scenario A, with each of the physiochemical system closures, scenarios B, C, and D. See table 5-32 for these scenario codes. The second set compares the closed physiochemical system, D, with each of the food closure scenarios, E, F, and G. These two sets of comparisons, discussed in section 6.1, are based strictly on the mass and power estimates that were developed in section 5 for each of the closure scenarios and do not include any transportation considerations. The transportation analysis, section 4, is used in combination with the closure mass estimates to derive potential cost savings that may be available by closing the food system. These cost data are discussed in section 6.2. Section 6.3 presents the conclusions and recommendations based on these study results.

6.1 Mass Comparisons

The mass comparisons for each closure scenario must be worked separately for each mission, since the factors for converting power to mass and the radiation shielding factors are different for each mission. These power conversion and radiation shielding factors were discussed previously in section 3 and listed in table 3-1. The comparisons for each mission are discussed in the paragraphs below.

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 the plants, see table 5-33, the physiochemical 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.

6.1.1 LEO–Low Inclination Mission

Mass estimate data used for comparing the open EC/LS system versus the physiochemical system closures are summarized in table 6-1 for the LEO low inclination mission. Mission-dependent mass penalties for power and radiation shielding are added onto initial launch mass numbers. For this mission the power penalty factor is 113 kg/kW

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Table 6-1 Physiochemical Mass Estimate Comparisons Mission: LEO – Low Inclination (4 Men)

CLOSURE SCENARIO CODE	EC/LSS INITIAL LAUNCH MASS, KG	POWER PENALTY, KG AT 113 KG/KW	RADIATION SHIELDING, KG AT 0 g/CM^2	TOTAL INITAIL LAUNCH MASS, KG	90-DAY RESUPPLY MASS, KG	1-YEAR RESUPPLY MASS, KG
A	17,895	129	NOT REQD	18,024	13,552	54,208
B	5,814	215	NOT REQD	6,029	2,102	8,408
C	16,216	610	NOT REQD	16,826	12,523	50,092
D	4,135	697	NOT REQD	4,832	1,069	4,276

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, since 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 6-1, from the data in table 6-1, show the weight advantages of closing the physiochemical systems. All closures show an immediate advantage over the open system, although the combined water and air systems closure provide the greatest weight savings. The physiochemical system closure comparisons follow this pattern for other missions as well. Also, 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 physiochemical systems have not been included in this report.

Mass estimate data used for comparing food system closures, scenarios F and G, with the closed physiochemical system, scenario D, are shown in table 6-2. The mass penalties for power and radiation shielding are the same as discussed previously for this mission.

These data were used to draw the lines in figure 6-2. Breakeven times for the LEO–Low Inclination mission are shown at the intersecting points of the curves for scenarios F and G and 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.

6.1.2 LEO–High Inclination Mission

Mass estimate data for the LEO–High Inclination mission given in table 6-2, show a relatively low power penalty factor of 32 kg/kW with no shielding required. The power factor is low because the solar arrays are exposed to the sun during the entire orbit, which reduces the heavy battery requirement. The curves for this mission are shown in figure 6-3. In response to the low power penalty, breakeven times occur slightly earlier than for the low inclination mission, at 5.6 and 7.1 years for food closures F and G respectively.

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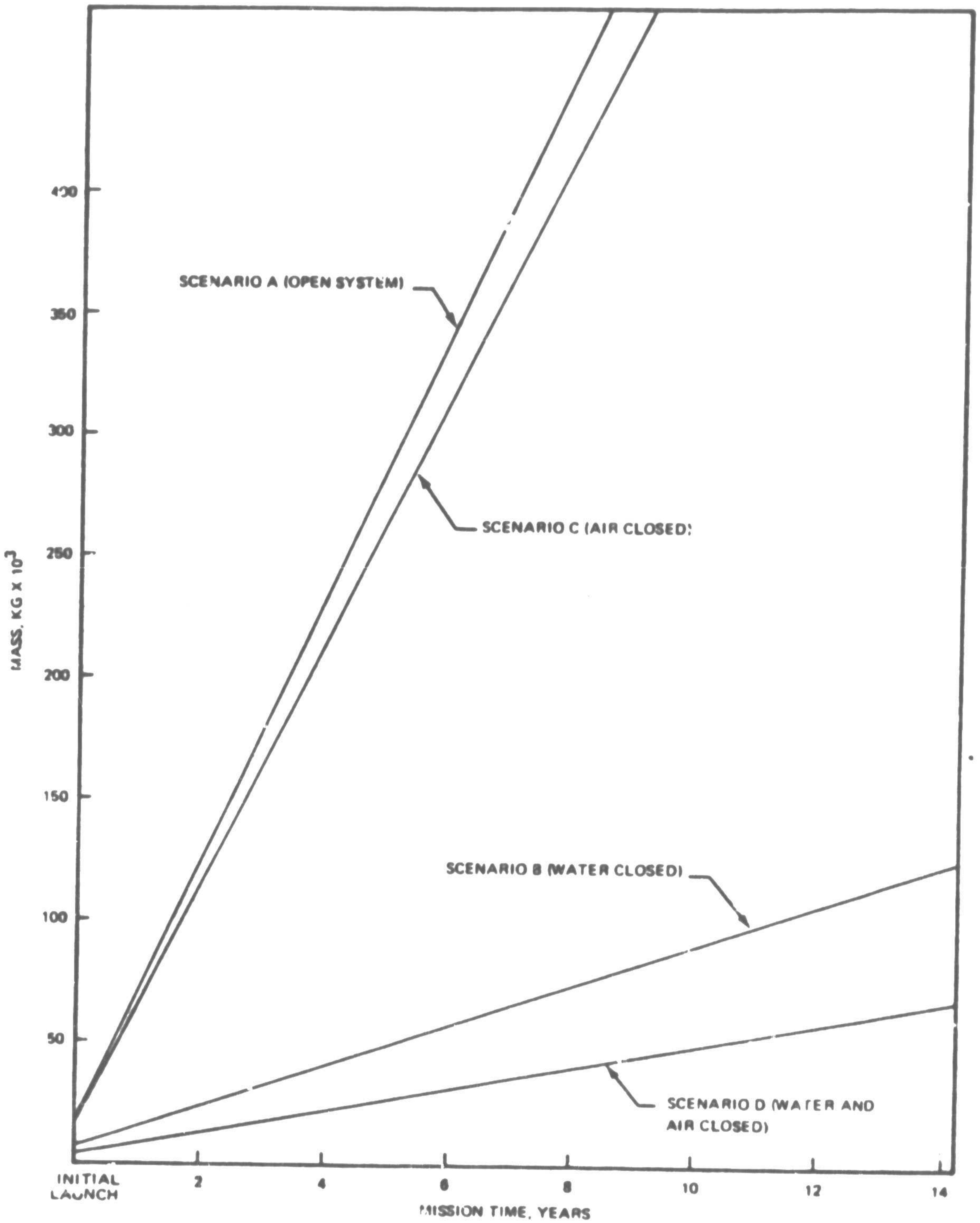

Figure 6-1 Mass Comparison of Physiochemical Systems Mission: LEO - Low Inclination (4 Men)

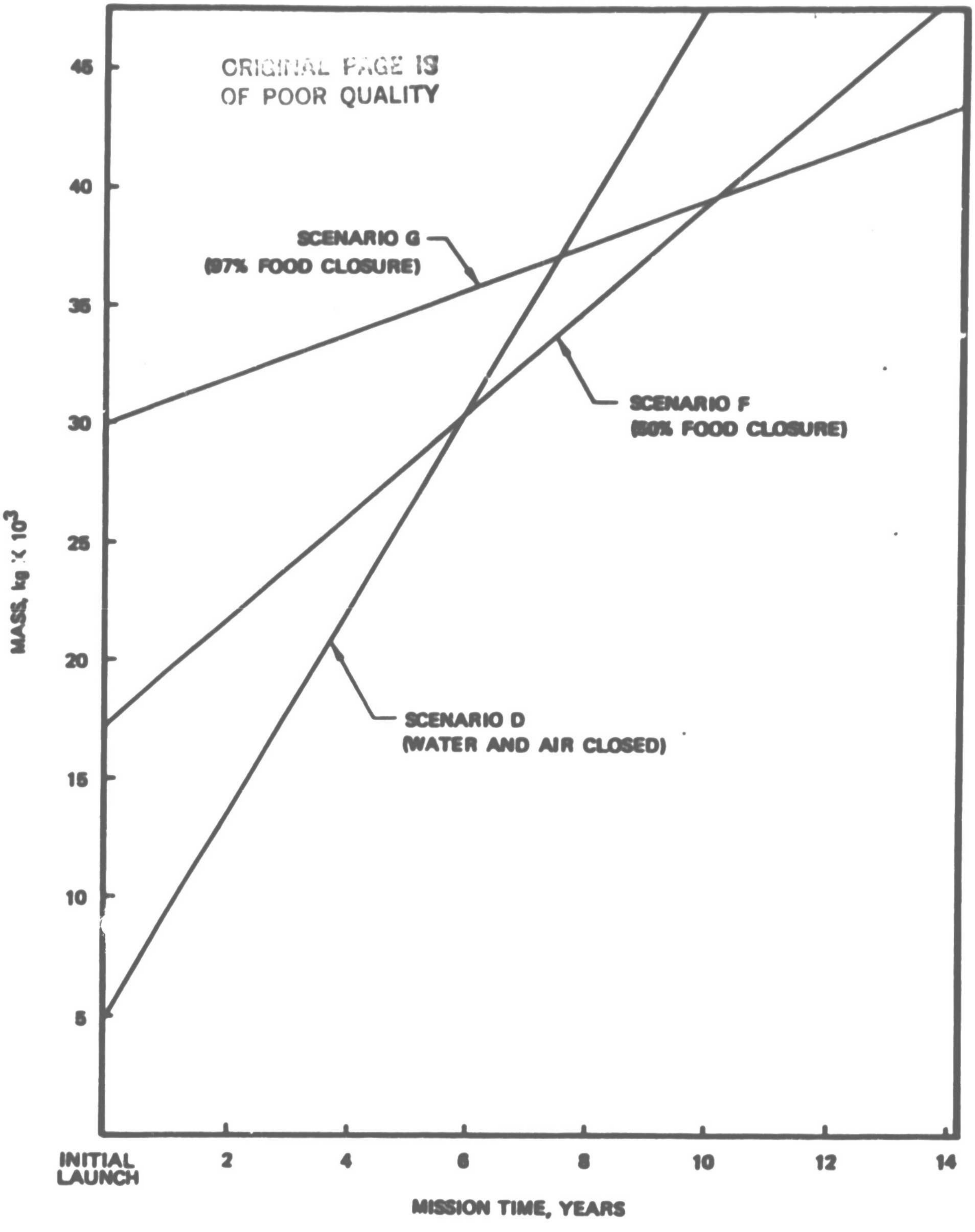

Figure 6-2 Estimated Breakeven Time. Mission: LEO – Low Inclination (4 Men)

Table 6-2 Mass Estimate Comparisons Mission: LEO - Low Inclination (4 Men)

CLOSURE SCENARIO CODE	SC/LSS INITIAL LAUNCH MASS, KG	POWER PENALTY, KG AT 113 KG/KW	RADIATION SHIELDING, KG AT 0 g/CM^2	TOTAL INITIAL LAUNCH MASS, KG	90-DAY RESUPPLY MASS, KG	1-YEAR RESUPPLY MASS, KG
D	4,135	697	NOT REQ'D	4,832	1,069	4,276
F	15,389	1,971	NOT REQ'D	17,360	549	2,186
G	27,062	3,822	NOT REQ'D	30,884	237	948

Table 6-3 Mass Estimate Comparisons Mission: LEO - High Inclination (4 Men)

CLOSURE SCENARIO CODE	SC/LSS INITIAL LAUNCH MASS, KG	POWER PENALTY, KG AT 32 KG/KW	RADIATION SHIELDING, KG AT 0 g/CM^2	TOTAL INITIAL LAUNCH MASS, KG	90-DAY RESUPPLY MASS, KG	1-YEAR RESUPPLY MASS, KG
D	4,135	197	PROBABLY NOT REQ'D	4,332	1,069	4,276
F	15,389	558	PROBABLY NOT REQ'D	15,947	549	2,186
G	27,062	596	PROBABLY NOT REQ'D	27,658	237	948

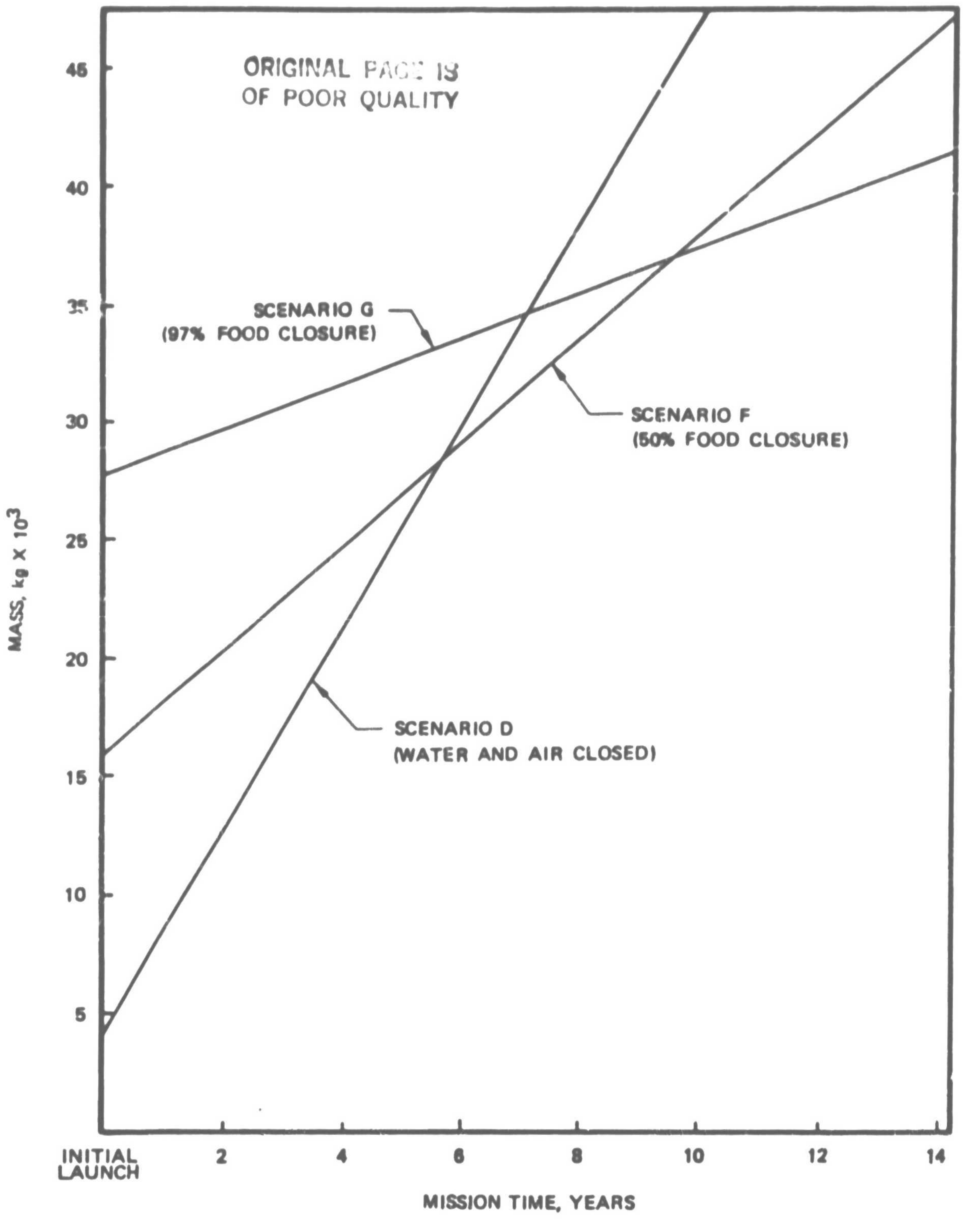

Figure 6-3 Estimated Breakeven Time, Mission: LEO - High Inclination (4 Men)

6.1.3 6 x GEO Mission

Table 6-4 summarizes the closure scenario data for the 6 x GEO mission. This mission has a relatively low power penalty because of the orbit. However, the radiation shielding becomes a significant weight factor at 10 g/cm^2 because the orbit is above the Van Allen radiation belt. The increased burden for radiation shielding is evident in the breakeven time (shown by the curves plotted in figure 6-4) of 10.5 years for closure scenario F, and 12.9 years for scenario G.

6.1.4 Lunar Base Mission

The Lunar Base Mission mass estimates are shown in table 6-5. This mission was selected as a 12-man permanent base on the lunar surface. The increased crew size increases the overall mass estimates. Nuclear power was selected for this mission because of the long day-to-night cycle that requires artificial light during the night cycle to aid plant photosynthesis. Lunar soil can be used to shield the nuclear power generator and to protect the base from solar radiation. The curves in figure 6-5 show the breakeven times of 5.7 years and 7.2 years for scenarios F and G respectively. This mission could have a long mission life, making closure of the food cycle very desirable.

6.1.5 Asteroid Mission

Since the Asteroid mission was defined for 5,000 people, the mass estimates used in the previous scenarios had to be adjusted. Figure 6-6 shows the adjustments made for equipment, resupply, and power requirements. The mass estimates were reduced by 25% to allow for economic and technological advancement, since the mission is programmed for the 2050 era.

A second consideration for this mission was to use the unmanned cargo pods, defined in the transportation analysis, as CELSS modules. Since these cargo pods are not reused for transportation, they are available and adequate for use as CELSS modules. Each module would be approximately 3000m^3, and 43 modules would be required each supply period (928 days) to transfer cargo. The first 43 would supply enough space to house the CELSS equipment associated with scenario F, and in 928 days the second 43 modules would add sufficient space for scenario G.

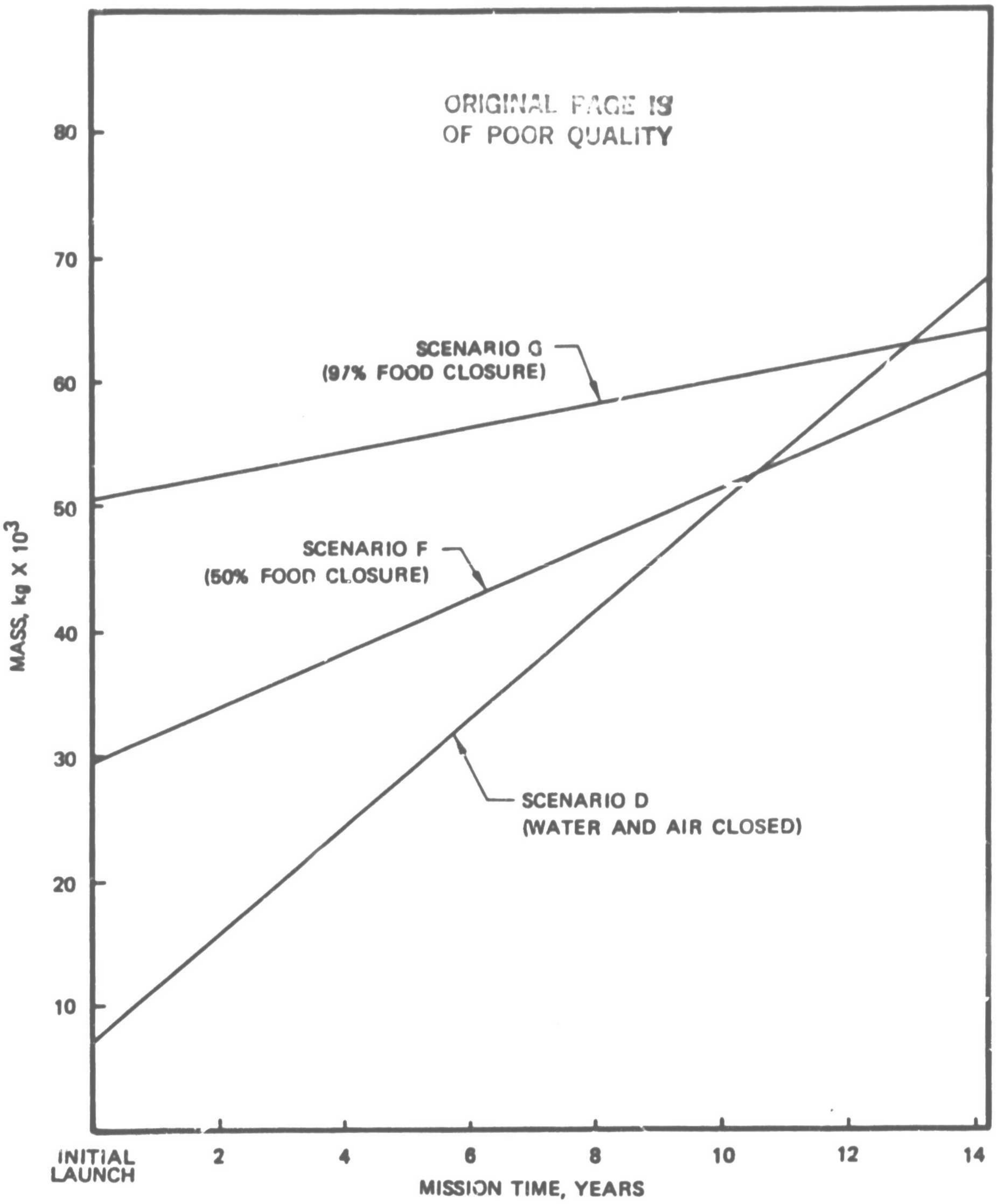

Figure 6-4 Estimated Breakeven Time. Mission: 6X GEO (4 Men)

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Table 6-4 Mass Estimate Comparisons Mission: 6X GEO (4 Men)

CLOSURE SCENARIO CODE	EC/LSS INITIAL LAUNCH MASS, KG	POWER PENALTY, KG AT 36 KG/KW	RADIATION SHIELDING, KG AT 10 g/CM^2	TOTAL INITIAL LAUNCH MASS, KG	180-DAY RESUPPLY MASS, KG	1-YEAR RESUPPLY MASS, KG
D	5,204	222	1,769	7,196	2,138	4,276
F	15,938	628	12,843	29,409	1,098	2,196
G	27,239	983	22,346	50,547	474	948

Table 6-5 Mass Estimate Comparisons Mission: Lunar Base (12 Men)

CLOSURE SCENARIO CODE	EC/LSS INITIAL LAUNCH MASS, KG	POWER PENALTY, KG AT 45.3KG/KW	RADIATION SHIELDING, KG AT 0 g/CM^2	TOTAL INITIAL LAUNCH MASS, KG	90-DAY RESUPPLY MASS, KG	1-YEAR RESUPPLY MASS, KG
D	12,405	838	NOT REQ'D (USE LUNAR SOIL)	13,243	3,707	12,828
F	46,167	2,371	NOT REQ'D (USE LUNAR SOIL)	48,538	1,647	6,588
G	81,006	3,634	NOT REQ'D (USE LUNAR SOIL)	84,640	711	2,844

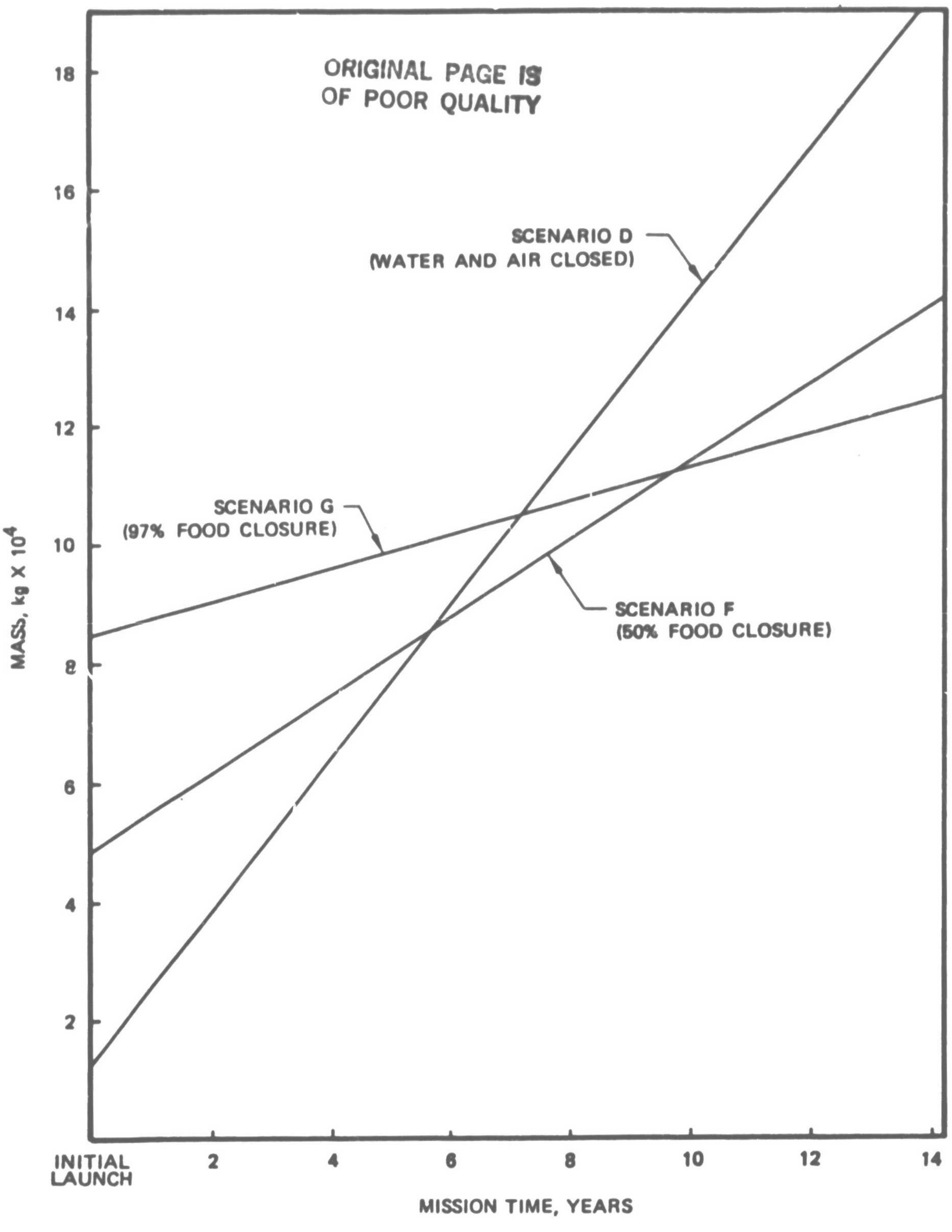

Figure 6-5 Estimated Breakeven Time. Mission: Lunar Base (12 Men)

SCENARIO D

RECYCLE EQUIPMENT

577 KG/PERSON X 0.75 = 433 KG/PERSON

FOOD GROWTH EQUIPMENT

NONE = 0

EQUIPMENT RESUPPLY

0.62 KG/PERSON/DAY X 0.75 = 0.46 KG/PERSON/DAY

FOOD RESUPPLY

2.04 KG/PERSON/DAY = 2.04 KG/PERSON/DAY

POWER REQUIREMENT

1541.5 WATTS/PERSON X 0.75 X 94.3 X 10^{-3} = 109 KG/PERSON

TOTAL EQUIPMENT AND POWER = 542 KG/PERSON

TOTAL RESUPPLY = 2.5 KG/PERSON/DAY

SCENARIO F

RECYCLE EQUIPMENT

178.5 KG/PERSON X 0.75 = 133.9 KG/PERSON

FOOD GROWTH EQUIPMENT

2172 KG/PERSON X 0.75 = 1629 KG/PERSON

EQUIPMENT RESUPPLY

0.37 KG/PERSON/DAY X 0.75 = 0.28 KG/PERSON/DAY

FOOD RESUPPLY

1.02 KG/PERSON/DAY = 1.02 KG/PERSON/DAY

POWER REQUIREMENT

4361.25 WATTS/PERSON X 0.75 X 94.3 X 10^{-3} = 308 KG/PERSON

TOTAL EQUIPMENT AND POWER = 2071 KG/PERSON

TOTAL RESUPPLY = 1.3 KG/PERSON/DAY

SCENARIO G

RECYCLE EQUIPMENT

129.5 KG/PERSON X 0.75 = 97 KG/PERSON

FOOD GROWTH EQUIPMENT

4158.25 KG/PERSON X 0.75 = 3119 KG/PERSON

EQUIPMENT RESUPPLY

0.52 KG/PERSON/DAY X 0.75 = 0.39 KG/PERSON/DAY

FOOD RESUPPLY

0.06 KG/PERSON/DAY = 0.06 KG/PERSON/DAY

POWER REQUIREMENT

6685 WATTS/PERSON X 0.75 X 94.3 X 10^{-3} = 473 KG/PERSON

TOTAL EQUIPMENT AND POWER = 3689 KG/PERSON

TOTAL RESUPPLY = 0.45 KG/PERSON/DAY

Figure 6-6 Mass Adjustments for Asteroid Mission

The mass estimate data given in table 6-6 includes only the modules and equipment used at the asteroid base for each closure scenario. The modules and EC/LS equipment, scenario D, used to transfer the crew and the priority cargo between the low Earth orbit staging area and the asteroid base are not included in the mass estimate data for this mission. (See section 4.5 for a discussion of the transportation analysis for this mission.) The data are not included because the mass would remain the same for this portion of the mission regardless of the closure scenario being considered at the base, and therefore these data would have no direct effect on the mission mass comparisons.

The closure scenario mass data are plotted in figure 6-7. The breakeven times for closing the food system occur very early in this mission, approximately 1 year for closure scenario F, and 1.8 years for scenario G. With these early breakeven points it would be cost effective to close the food system at the beginning of the mission, or to build up to full closure as the necessary cargo pods arrive at the base.

6.1.6 Mars Surface Exploration Mission

The Mars mission considered for this study is a sortie type requiring equipment and supplies to be loaded onboard initially, as no resupply is available during the mission. A summary of the mission, taken from section 4.6, follows:

a. Modules of a vehicle are transported and assembled in LEO and with a crew aboard travels to Mars and is established into a Mars orbit (trip requires approximately 205 days.

b. The crew and required equipment are transferred to a landing module that lands on Mars.

c. The crew remains on the surface to conduct scientific exploration (200- and 543-day staytimes were considered for this study).

d. The crew returns to the orbiting vehicle.

e. The crew then returns to Earth, requiring approximately 200 days for travel.

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Table 6-6 Mass Estimate Comparisons Mission: Asteroid Base (5,000 Men - 928-Day Resupply Cycle)

CLOSURE SCENARIO	EQUIPMENT AND POWER MASS, MT	1 RESUPPLY CYCLE MASS, MT	INITIAL EQUIPMENT, POWER, 1 RESUPPLY CYCLE MASS, MT	EQUIPMENT, POWER AND RESUPPLY FOR 10 YEARS (10 YEARS = 3.94 CYCLES) MASS, MT
D	2,710	11,600	14,310	60,014
F	10,355	6,032	16,387	40,153
G	18,445	2,088	20,533	28,760

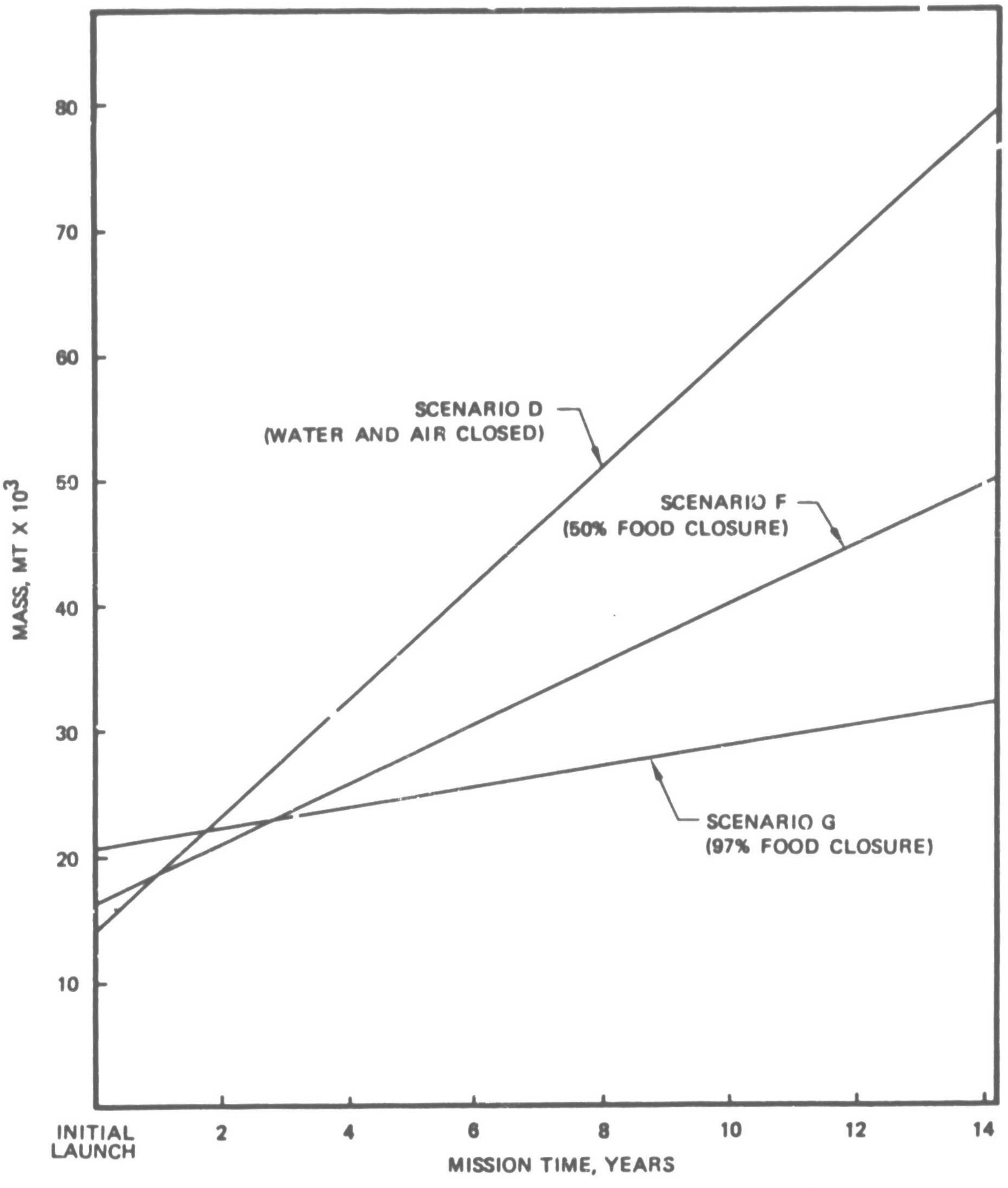

Figure 6-7 Estimated Breakeven Time. Mission: Asteroid Base (5,000 Men)

A unique feature of this mission is that any modules, power sources, or equipment that are not required to return the crew to Mars orbit, would be left on Mars. The propellant penalty for lifting noncritical material off the surface of Mars is prohibitive.

Table 6-7 shows the mass data and closure scenarios used for this study. The resupply equivalent data given in column 3 of this table were used only to calculate the additional mass of equipment and supplies required in excess of the initial mass for the total mission.

For this mission, three closure scenarios and two surface exploration periods (200 and 543 days) were analyzed. As shown in figure 6-8, the breakeven times do not occur within the time frame of this mission. Based on these data, it does not appear that CELSS would benefit this mission.

6.2 Cost Estimates

Each mission incorporates a different transportation scenario, and therefore each mission is assessed a different transportation cost. The costs presented in table 6-8 are specific costs for vehicles to be used in near term, Earth-Moon missions. Table 6-9 presents the total transportation costs for all six selected missions. The transportation costs for the Mars and Asteroid missions reflect additional space operations work such as in-space vehicle assembly tasks.

These tables present both real (shuttle) and projected operating costs. The numbers are felt to be conservative projections of future costs, for example; the present difference in shuttle launch costs between Kennedy Space Center and Vandenburg Air Force Base may no longer exist in 1995 for the LEO monitoring base; however, the conservative projections used in this study maintain that differential. Projections for the asteroid mission (70 years into the future) necessarily include significant technical advancement and the corresponding cost decrease.

The transportation costs for each mission were applied to the mass summaries (sec. 6.1) for the various scenarios from which cumulative cost curves were constructed. Figure 6-9 illustrates the cost comparison of the physiochemical system closures for the low inclination LEO base. From the figure it is evident that scenario D is the optimum system for the physiochemical considerations. As stated in the previous section, the

Table 6-7 *Mass Estimate Comparisons. Mission: Mars Surface Exploration (8 Men)*

MISSION SCENARIO	INITIAL EQUIPMENT MASS, KG	RESUPPLY EQUIVALENT MASS, KG	TOTAL EQUIPMENT MASS, KG	POWER PENALTY SOLAR ARRAY AT 37 KG/KW, KG	POWER PENALTY NUCLEAR AT 48.5 KG/KW, KG	TOTAL EQUIPMENT AND POWER MASS, KG	TOTAL MISSION MASS, KG
CLOSURE SCENARIO D TRIP TO MARS ORBIT AND RETURN 401 DAYS	8,270	7,483	15,753	456		16,209	
CLOSURE SCENARIO D STAY ON MARS SURFACE 200 DAYS 543 DAYS	8,270 8,270	2,566 10,690	10,836 18,960		598 598	11,434 19,558	27,843 35,787
CLOSURE SCENARIO F STAY ON MARS SURFACE 200 DAYS 543 DAYS	30,778 30,778	1,318 6,490	32,096 33,268		1,692 1,692	33,788 37,960	49,897 64,189
CLOSURE SCENARIO G STAY ON MARS SURFACE 200 DAYS 543 DAYS	54,004 54,004	569 2,370	54,573 56,374		2,594 2,594	57,167 58,968	73,378 76,177

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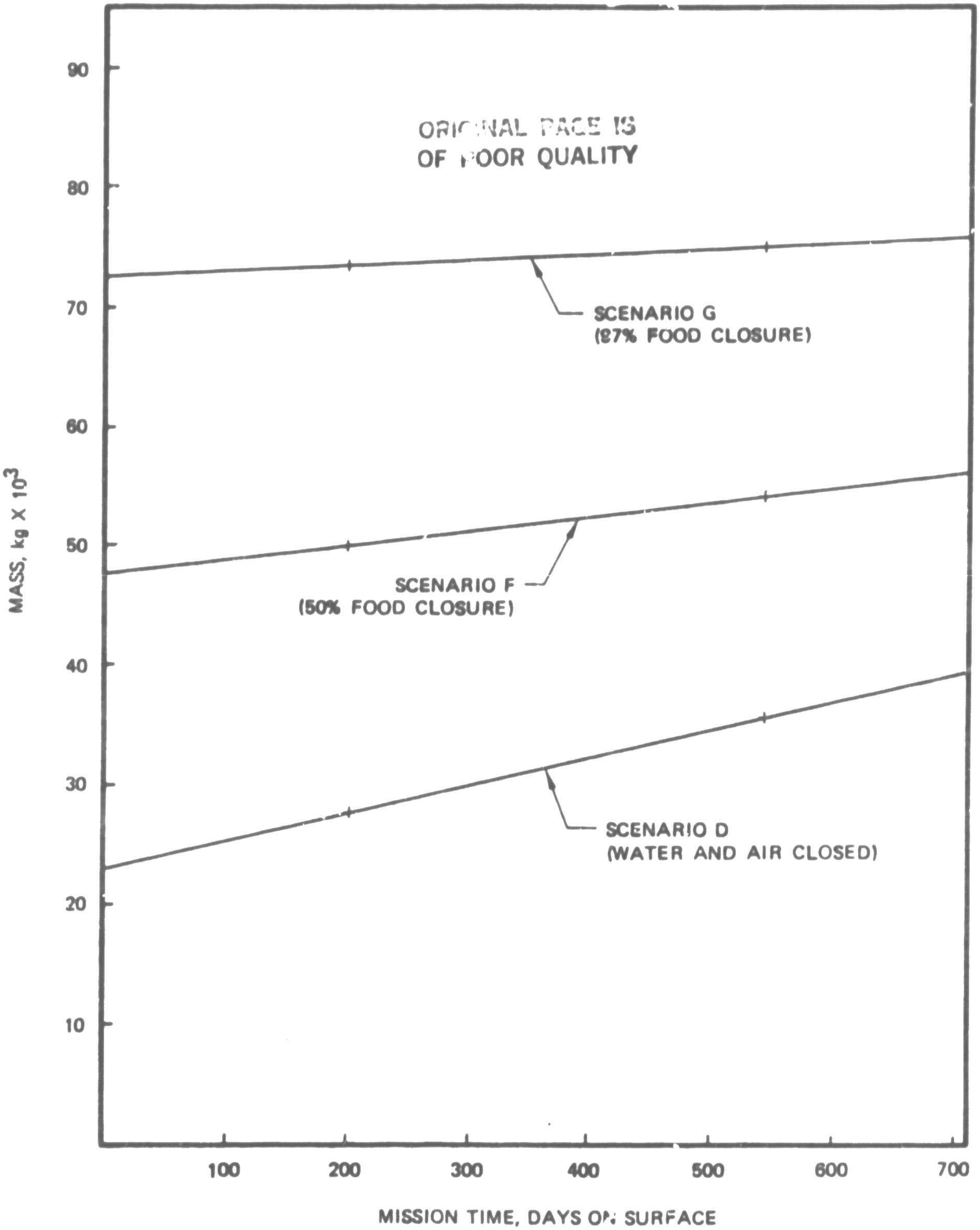

Figure 6-8 Estimated Breakeven Time. Mission: Mars Surface Exploration (8 Men)

Table 6-8 Vehicle Transportation Costs

	SHUTTLE ORBITER (1982 ERA)		MANNED OTV (1995 ERA)		LTV (2010 ERA)
	KSC	VAFB	6X GEO	LUNAR ORBIT	LUNAR SURFACE
COST:	$80 MIL/FLIGHT	$115 MIL/FLIGHT	$26 MIL/FLIGHT	$26 MIL/FLIGHT	$9.8 MIL/FLIGHT
PAYLOAD:	65,000 LBS	25,000 LBS	18,290 LBS	23,210 LBS	40,670 LBS
SPECIFIC COST:	1231 $/LB (2713 $/KG)	4600 $/LB 10,141 $/KG)	1422 $/LB (3134 $/KG)	1120 $/LB (2470 $/KG)	241 $/LB (532 $/KG)

Table 6-9 Mission Transportation Costs

	LEO LOW	LEO HIGH	6X GEO	LUNAR	ASTEROID	MARS
SPECIFIC COST ($/KG):	2,713	10,141	5,847	5,714	462	3,179
TIME FRAME	1990	1995	1995	2010	2050	2010

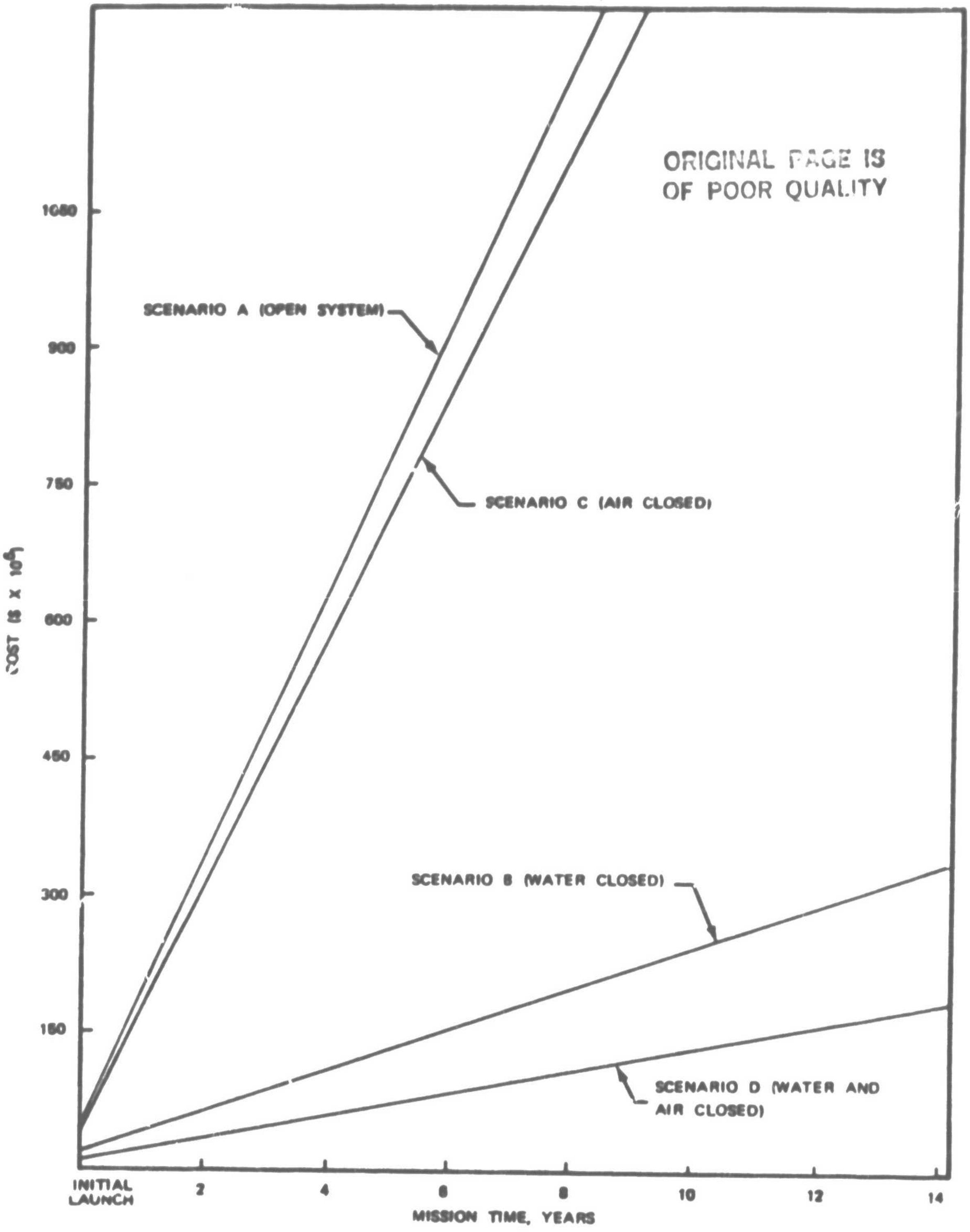

Figure 6-9 Cost Comparison of Physiochemical Systems
Mission: LEO - Low Inclination (4 Men)

comparison for the LEO—low inclination mission is representative of the other missions; therefore no other physiochemical cost comparisons are presented.

Figure 6-10 projects the cumulative cost data for comparing food system closures for a four-person, LEO operations base in a low inclination orbit. For the first 6 years of operation, physiochemical scenario D is the least expensive system. If station life is expected to be between 6 and 10 years, scenario F, the 50% food closure, is the minimum cost system. For 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 physiochemical system—or almost one-half of the cumulative transportation cost of the system.

All of the missions within the Earth-Moon system show similar results (see figures 6-9 and 6-11) except for the Military Command Post in 6 X GEO; figure 6-12. In this mission CELSS must pay a large mass penalty for shielding the plant-growing module from the severe radiation environment. Even with this penalty, the 50% CELSS closure is cost effective around year 10, and the 97% CELSS closure is cost effective at year 17. At 15 years the potential cost savings for 50% CELSS closure amounts to 30 million dollars. For the LEO high inclination base, figure 6-11 gives the optimum system breakeven points at 5½ years for 50% CELSS closure, and 11 years for 97% CELSS closure. The lunar base times shown in figure 6-13 are 5½ years for 50% CELSS closure and 9½ years for 97% CELSS closure.

The available use of discarded cargo modules, and the advancement of technology enabled CELSS to show an economic breakeven on the Asteroid mission at the time of the first resupply and rotation cycle. Figure 6-14 shows this 2½ year cost optimization point and also demonstrates that the potential savings of a 97% CELSS closure mission is greater than the initial cost of the system.

The Mars exploration mission cumulative transportation costs, diagrammed in figure 6-15, clearly demonstrate that this mission is not suitable for CELSS. The optimization point for a 50% CELSS closure is calculated to be for a surface stay of 1948 days (5 years), and for 97% CELSS closure the surface stay would be 3357 days (9 years). These extended surface stays are outside the scope of a sortie mission.

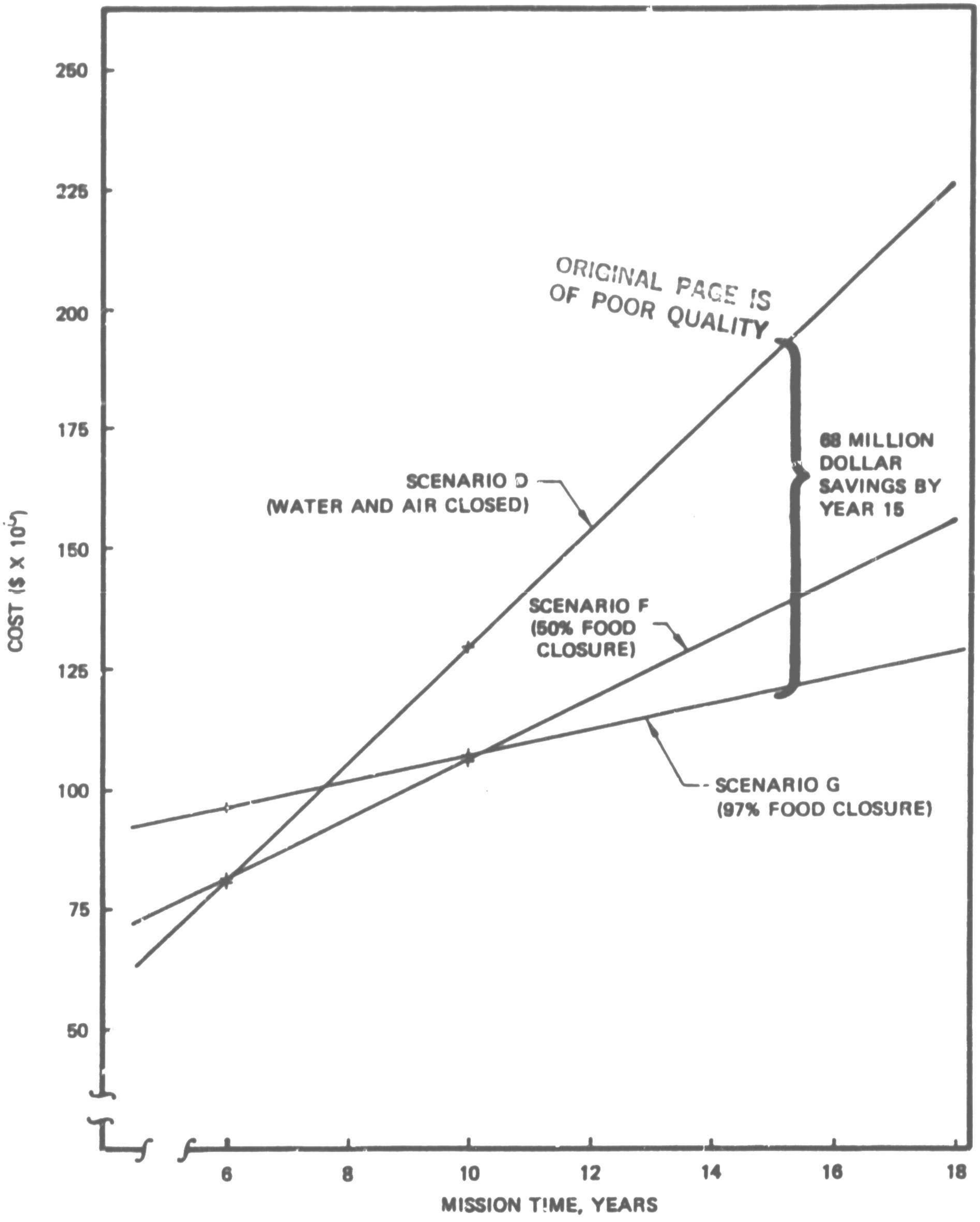

Figure 6-10 Cumulative Cost Savings with CELSS Mission: LEO – Low Inclination

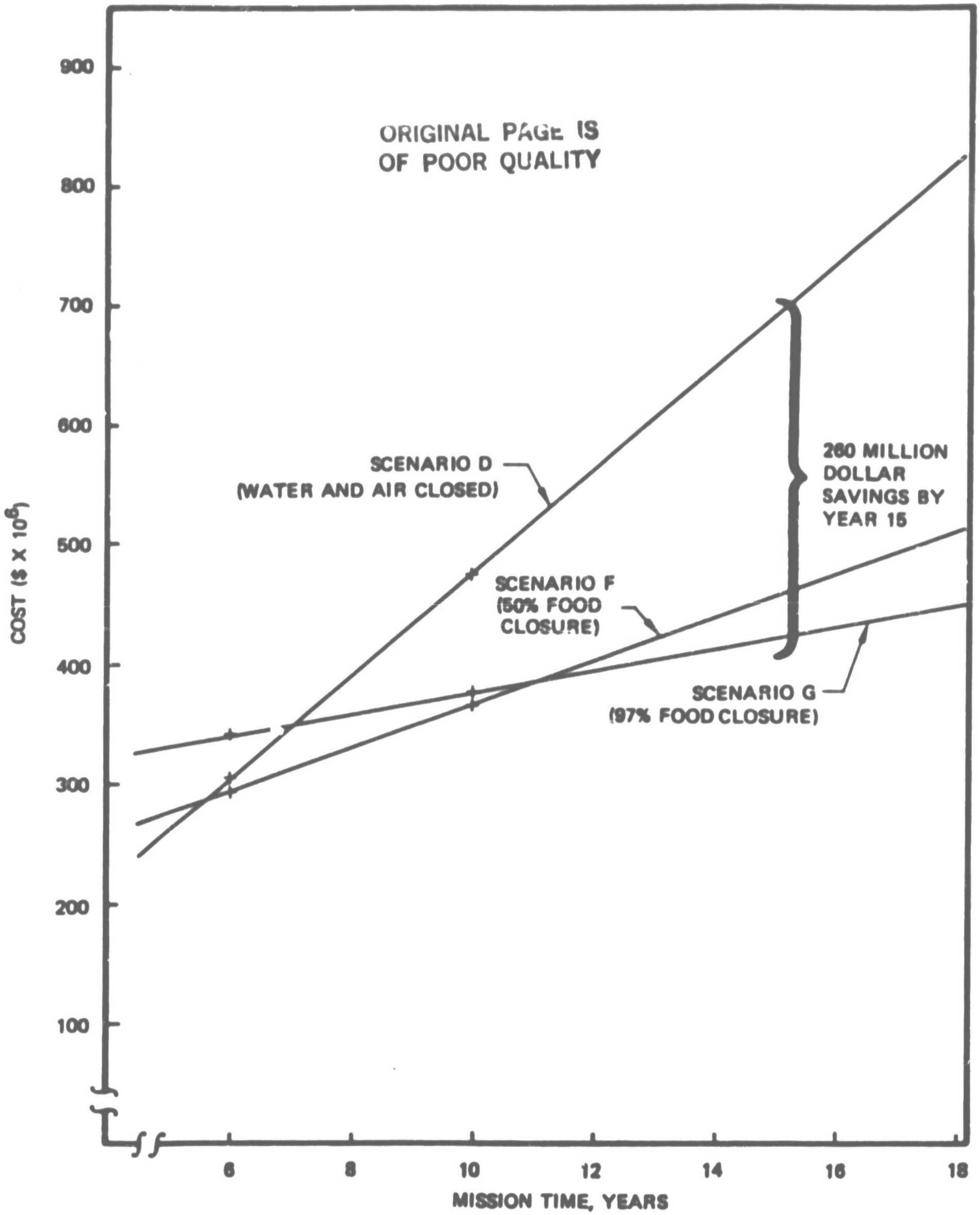

Figure 6-11 Cumulative Cost Savings with CELSS Mission: LEO – High Inclination

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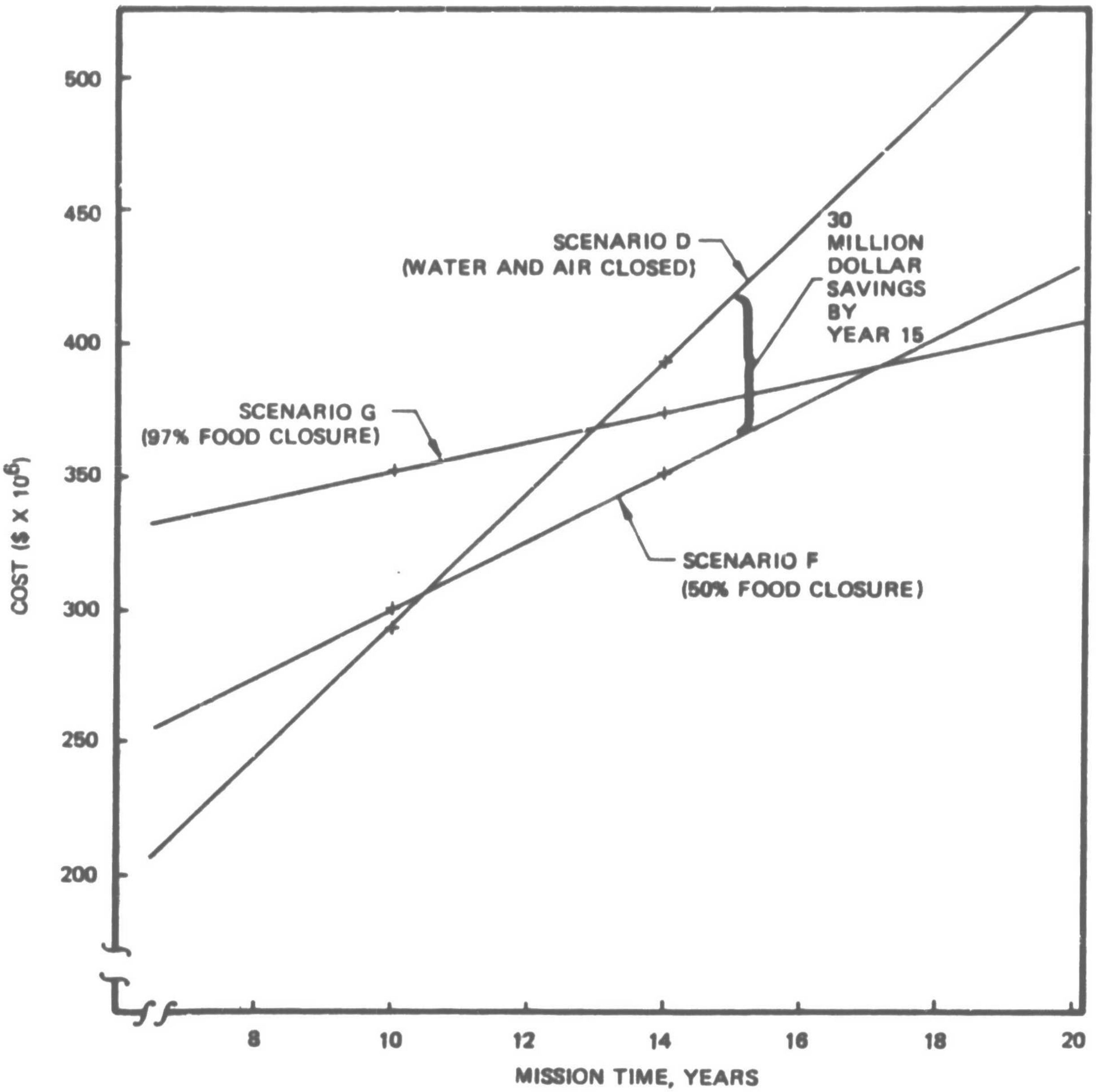

Figure 6-12 Cumulative Cost Savings with CELSS Mission: 6 X GEO

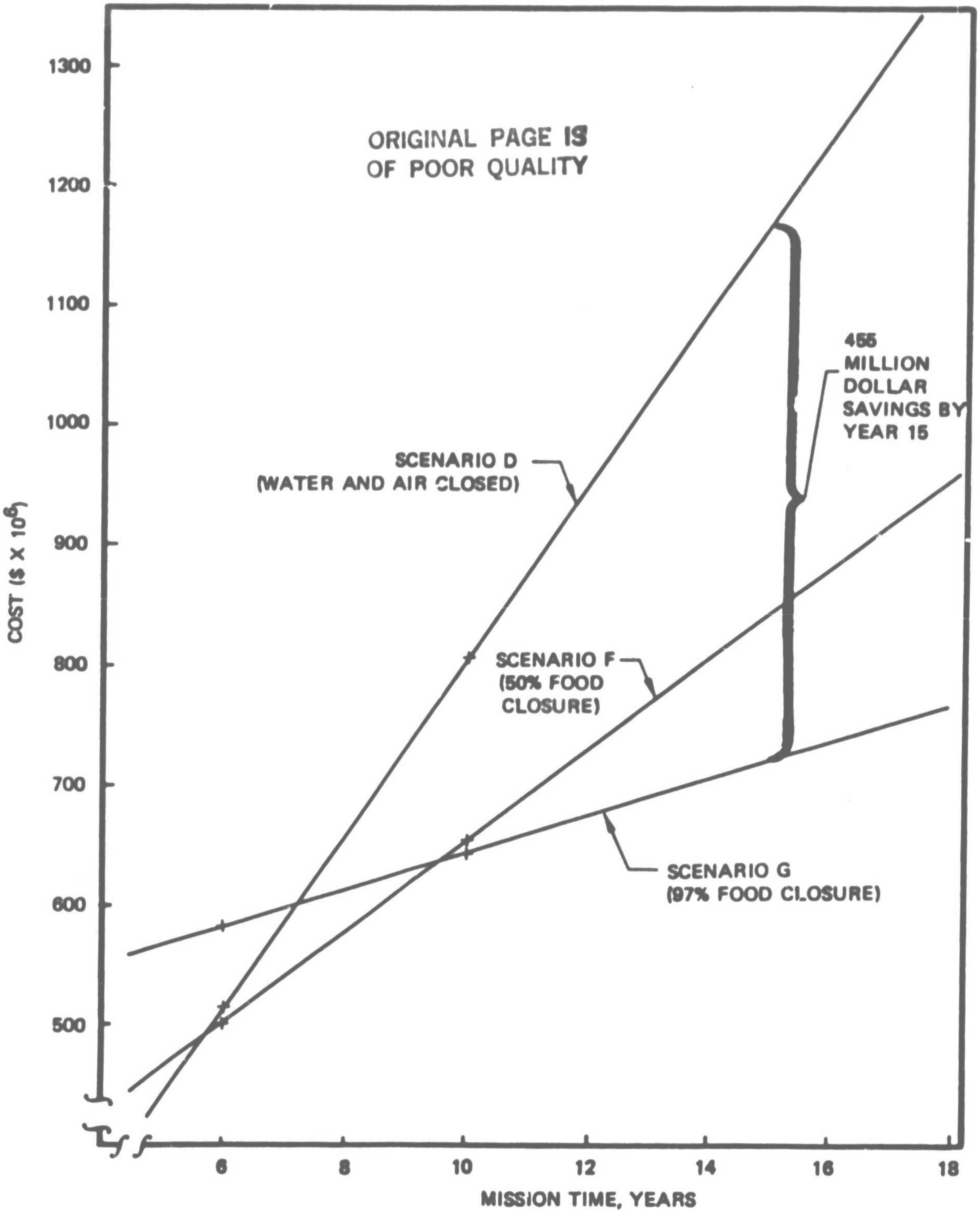

Figure 6-13 Cumulative Cost Savings with CELSS Mission: Lunar Base (12 Men)

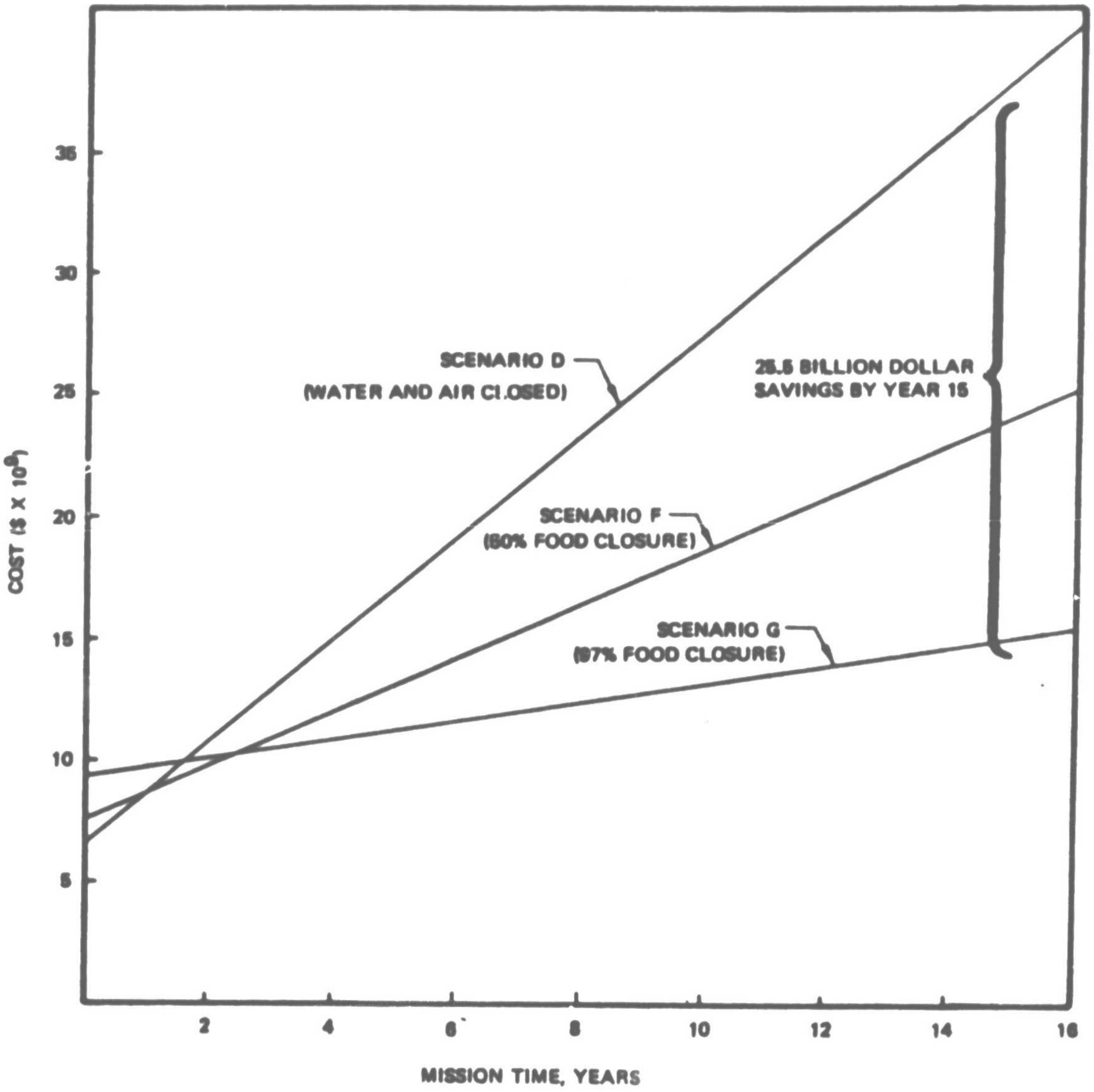

Figure 6-14 Cumulative Cost Savings with CELSS Mission: Asteroid Base

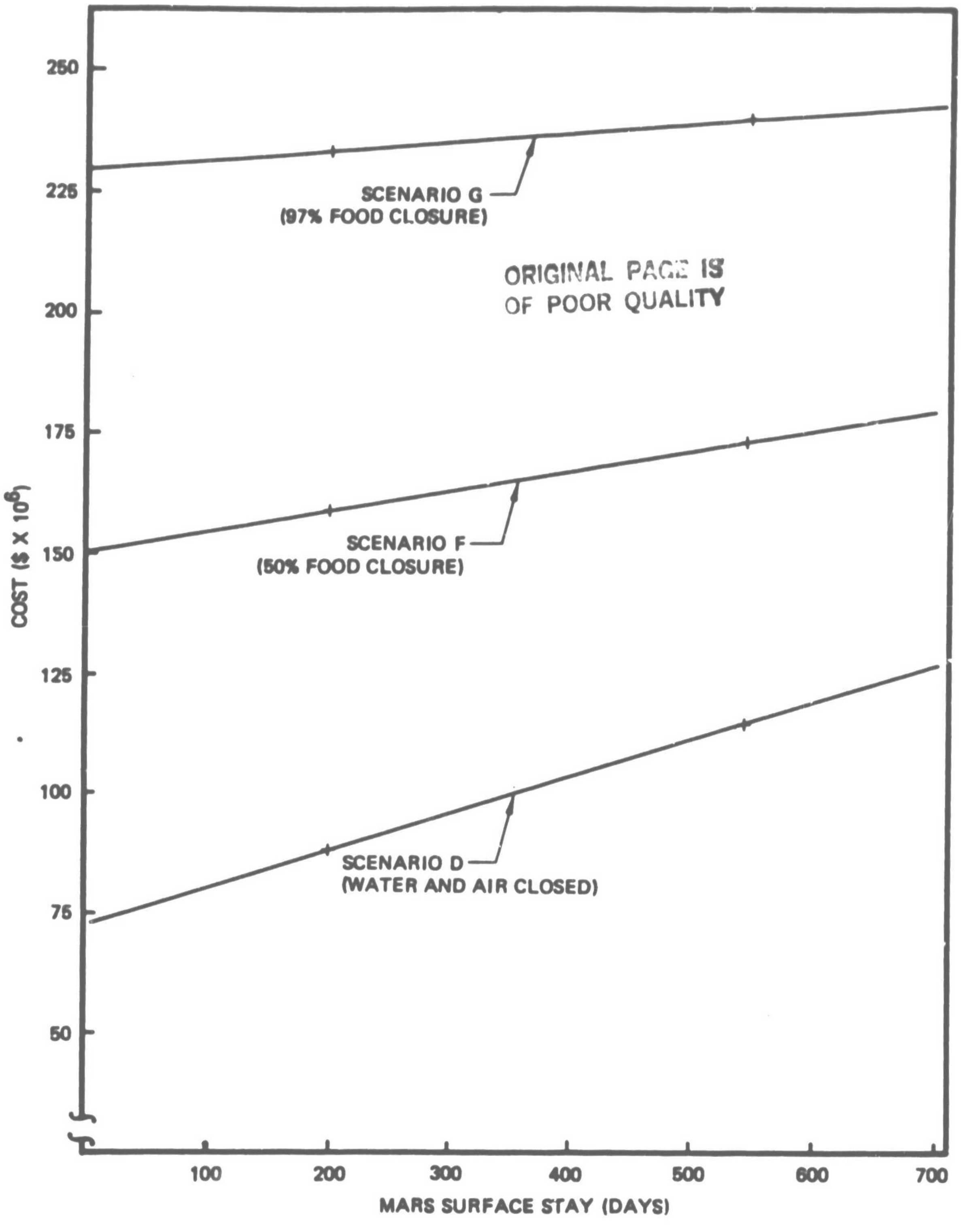

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Figure 6-15 Cumulative Cost of CELSS Mission: Mars Surface Exploration

6.3 Conclusions and Recommendations

The conclusions from this study are summarized below.

1. Small, manned space stations orbiting within the Earth-Moon system could benefit from CELSS.

2. Large, manned bases beyond the Earth-Moon system will probably require CELSS.

3. Short duration, nonpermanent type missions, such as the Mars "sortie" mission analyzed in this study, will probably not benefit from CELSS.

4. CELSS component weight and volume data that were available in the literature or estimated for this study are considered to be conservative. Therefore, as additional data become available and the existing data are further refined, support for CELSS could become even more favorable than shown by this study.

The following recommendations are submitted for consideration.

1. A need exists for CELSS concept configuration analysis. One approach to this analysis is to use preliminary design methods to configure various layouts and to perform weight and volume trades. This technique will facilitate system characterization.

2. Sensitivity analyses need to be conducted on the various elements of CELSS, e.g., diet, nutrition, plant yield, plant 0_2 production, water volume requirements, etc. These analyses are in order to determine which elements have the greatest effect on the total system. These elements then become the highest priority items for study.

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