NASA TECHNICAL MEMORANDUM TM-1 09927

Life Support Systems Analysis and Technology Trades for a Lunar Outpost

J.F. Ferrall, G.B. Ganapathi, N.K. Rohatgi, and P.K. Seshan

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA

December 1994

DRAFT

NASA

TABLE OF CONTENTS

LIST OF FIGURES

' LIST OF FIGURES
(continued)

APPENDIX :

LIST OF TABLES

NOMENCLATURE

2BMS	Two bed molecular sieve
4BMS	Four bed molecular sieve
ACRS	Advanced carbon reactor system
AIRE	Air evaporator
APC	Air polarized concentrator
AR	Air revitalization
ASCII	American standard code for information interchange
ASPEN PLUS	State-of-the-art chemical process simulation software program from AspenTech, Inc.
BL	Baseline
CLLS	Closed loop life support
COMB	Combustion
C02EL	CO_2 electrolysis
co2EL/BD	CO_2 electrolysis/Boudouard reactor
CPGM	Concentrated polluted gas mix
EBSS	Emergency backup storage specification
EBSSA	Emergency backup storage specification-air
EDC	Electrochemical depolarized concentrator
ELDI	Electrochemical deionization
ELIOH	Emergency lithium hydroxide
ESF	Exhaust storage factor
FD	Freeze drying
GM FS	Generic modular flow schematic
GTVO	Gaseous trash venting option
HABVOL	Habitation volume
HW	Hygiene water
ICES	International Conference on Environmental Systems
JSC	Johnson Space Center
JPL	Jet Propulsion Laboratory
LiOH	Lithium hydroxide
LiSSA	Life support systems analysis
LiSSA-ST	Life support systems analysis-simulation tool
LiSSA-TT	Life support systems analysis-trade tool
LSS	Life support system
LTVO	Liquid trash venting option
MCL	Mission crew loading
MCS	Maximum crew size
MF	Multifiltration
MFHW	Multifiltration hygiene water
MFPW	Multifiltration potable water
MSFC	Marshall Space Flight Center
OACT	Office of Advanced Concepts and Technology
OD	One-way duration
P/c	Physical chemical
PCES	Property constant estimation system

PC/LSS	Physical chemical life support system
Pw	Potable water
RLS	Regenerative life support
RO	Reverse osmosis
ROHW	Reverse osmosis hygiene water
ROPW	Reverse osmosis potable water
RSL	Resupply launches
RTOP	Research and technology objectives and plans
SAE	Society of Automotive Engineers
SAB	Sabatier
SAWD	Solid amine water desorption
Scwo	Supercritical water oxidation
S FE	Subsystem functional element
S FWE	Static feed water electrolysis
SPE	Solid polymer electrolyte
SPELF	Solid polymer electrolyte-liquid feed
Ss	Subsystem
SSF	Space Station Freedom
STDO	Solids trash dumping option
SWT	Solid waste treatment
TD	Thermal drying
TMD	Total mission duration
TCS	Total crew size
TCC	Trace contaminant control
T & HC	Temperature and humidity control
TIMES	Thermoelectric integrated membrane evaporation system
VCD	Vapor compression distillation
VPCAR	Vapor phase catalytic ammonia removal
WM	Water management
Wox	Wet oxidation
WP	Water processing
WR	Water recovery
W. R.T.	With respect to
WVE	Water vapor electrolysis

This page left intentionally blank

EXECUTIVE SUMMARY

The Office of Advanced Concepts and Technology funded the development of a rigorous systems analysis software tool for physical-chemical life support. As part of this development, a technology trade study was conducted to illustrate the use of the tool . This document presents the results of this study. Such studies can help break down the mindset that repeatedly commits enormous resources into a variety of technology hardware-even upto to flight qualification-before performing rigorous systems analysis. By conducting system and technology trade studies at every branch of the technology development decision tree, great savings in resources can be realized.

Life support system and technology trades were performed for a hypothetical lunar outpost using the NASA/JPL Life Support Systems Analysis (LiSSA) software tool. Steady-state material and energy balance calculations were made using a chemical-process simulation program called ASPEN PLUS on a one-person, daily basis. Inputs to the life support simulation model included metabolic balance load data, hygiene load data, technology selection, and various assumptions for process operations.

METABOLIC BALANCE AND HYGIENE LOAD BASIS

A metabolic balance was generated based on literature data and equivalent estimates of chemical formulas for metabolic waste species. The elemental compositions of the food and waste solids were specified since models of chemical processing and transformation require the use of stoichiometric coefficients. Representative chemical formulas used for food and waste streams are as follows:

Food protein	C_4H_5ON
Food carbohydrate	$C_6H_{12}O_6$
Food fat	$C_{16}H_{32}O_2$
Urine solids	$C_2H_6O_2N_2$
Feces solids	$C_{42}H_{69}O_{13}N_5$
Sweat solids	$C_{13}H_{28}O_{13}N_2$
Wash solids	$C_{13}H_{28}O_{13}N_2$.

TECHNOLOGY SELECTION

A baseline set of technologies has been used against which comparisons have been made. The baseline set was configured into a system only for the purpose of trade analysis. Twenty-two cases were run with technology choices substituted for the baseline technology in Case 1 as shown in Table ES-1. The baseline

Table ES-1. Case Runs and Technology Choices

CASE NO.	AR SS			WM SS			SWT SS	
	CO_2 REMOVAL	CO_2 REDUCTION	O_2 GENERATION	POTABLE H_2O PROCESSING	HYGIENE H_2O PROCESSING	URINE PROCESSING	DRYING	OXIDATION
1 (BL)	4BMS	BOSCH	SFWE	MF	RO	TIMES	NONE	NONE
2	2BMS	"	"	"	"	"	"	"
3	EDC	"	"	"	"	"	·	"
4	APC	"	"	·	·	"	·	·
5	SAWD	"	"	"	·	"	"	"
6	LIOH	NONE	·	"	"	"	"	·
7	4BMS	SABATIER	"	"	"	"	"	"
8	"	ACRS	"	"	"	"	"	"
9	"	CO2EL/BD	"	"	"	"	"	"
10	"	BOSCH	WVE	·	·	"	"	"
11	"	"	SPELF	·	"	"	"	"
12	·	·	SFW_E	RO	"	"	"	·
13	·	"	"	ELDI	"	"	"	"
14	"	"	·	MF	MF	"	"	"
15	·	·	·	·	RO	VCD	·	"
16	"	·	·	"		VPCAR	·	"
17	"	·	·	·	·	AIRE	·	"
18	"	"	·	·	·	TIMES	FD	·
19	·	"	·	·	·	·	TD	"
20	"	"	"	·	·	"	NONE	COMB
21	"	·	"	·	·	"	"	WOX
22	"	"	"	·	·	·	"	SCWO

technologies are:

Air Revitalization (AR) Subsystem:

CO_2 Removal:	Four-bed molecular sieve
CO_2 Reduction:	Bosch
O_2 Generation:	Static--feed water electrolysis

Water Management (WM) Subsystem:

Potable Water Processing:	Multifiltration
Hygiene Water Processing:	Reverse osmosis
Urine Processing:	Thermoelectric integrated membrane evaporation system

Solid Waste Treatment (SWT) Subsystem:

Drying:	None
Oxidation:	None.

SYSTEM MODELING AND MISSION PARAMETER ASSUMPTIONS

Some of the assumptions used to model the life support system are as follows:

Air Revitalization and Cabin Air:
- Cabin pressure = 1 atmosphere.
- Cabin air maximum temperature = 27° C.
- Cabin air minimum temperature = 16° C.
- Maximum CO_2 partial pressure = 2.7 mm Hg.
- The cabin air leakage rate is assumed to be very small (< 0.001v%/day of the habitable volume).

Water Management and Purity:
- Water processed in potable water processing is assumed to meet potable water requirements similar to those established for Space Station Freedom. The total organic carbon level is on the order of 500 μg/l.
- Water processed in hygiene water processing is assumed to meet hygiene water requirements similar to those established for Space Station Freedom. The total organic carbon level is on the order of 10,000 μg/l.
- Brines from water processing are not. processed by water management technologies. They are sent to solid waste treatment if they are to be processed.

Solid Waste Treatment:
- Feeds to solid waste treatment include brines from water processing and feces from the human habitat. Papers, kitchen wastes, spent chemical beds, filters, etc. are sent to trash and are not processed for resource recovery.

- Condensates produced from solid waste treatment must be polished by hygiene water processing with the exception of supercritical water oxidation (SCWO) : SCWO condensate is mixed with hygiene water processing product without polishing.

Mission parameter assumptions are as follows:

Mission crew size	4
Total mission duration	90 and 600 days
Resupply launches	0
Emergency backup supply storage	5 days
Use of LiOH canisters for emergencies	yes
Habitat volume (ft^3 per person)	1, 000
Gaseous trash vent or dump option	Vent
Liquid trash vent or dump option	Vent
Solid trash dump or store option	Dump

SYSTEM AND SUBSYSTEM WET WEIGHT COMPARISONS

Wet weights for all 22 cases, including a breakdown of subsystems, are given in Figures ES-1 and ES-2 for 90 days and 600 days, respectively. Wet weights include equipment, storage tanks, and the weight of stored items, such as water. Overall system weights vary between 3840 kg and 4440 kg for the 90-day mission and 13,400 kg and 18,400 kg for the 600-day mission. Note that the cases maintain their relative positions with a few exceptions. For example, in both the 90- and 600-day missions, Case 10, which pertains to the use of water vapor electrolysis technology for 0_2 generation, shows the minimum weight; however, Case 22 (supercritical water oxidation for solids waste treatment) has the maximum weight for the 90-day mission, but Case 6 (non-regenerative LiOH for $C0_2$ removal), which pertains to nonregeneration of oxygen, is the heaviest for the 600-day mission. In general, nonregenerative system/subsystem configurations would impose increasing weight penalties with increasing mission duration. The dominance of nonregenerable supplies is readily seen by a comparison of various subsystem weights constituting the total system weight. Storage subsystem weights include the weights of consumables and their containers. By keeping the crew size the same for both the 90- and 600-day missions, the differences between the two figures are entirely due to the effect that mission duration has on the demand for consumable supplies.

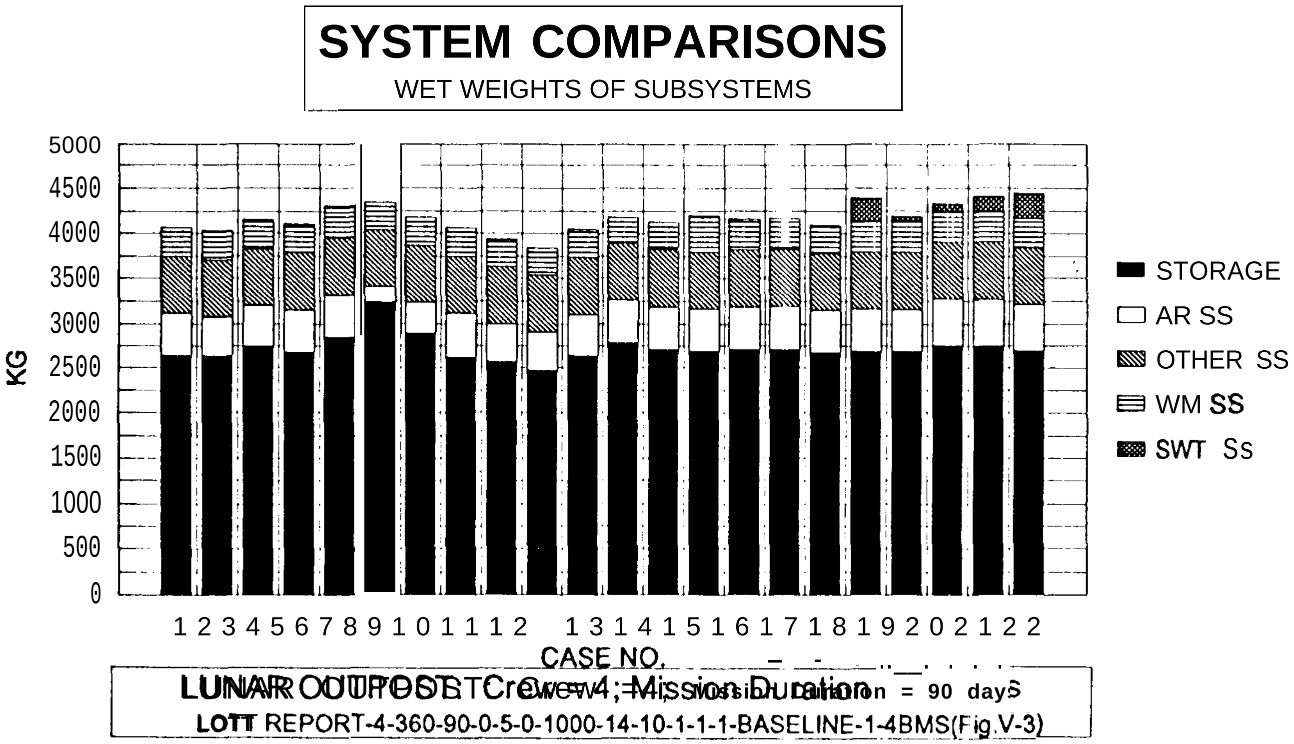


Figure ES-1. Subsystem Weight Comparisons for 90-day Mission

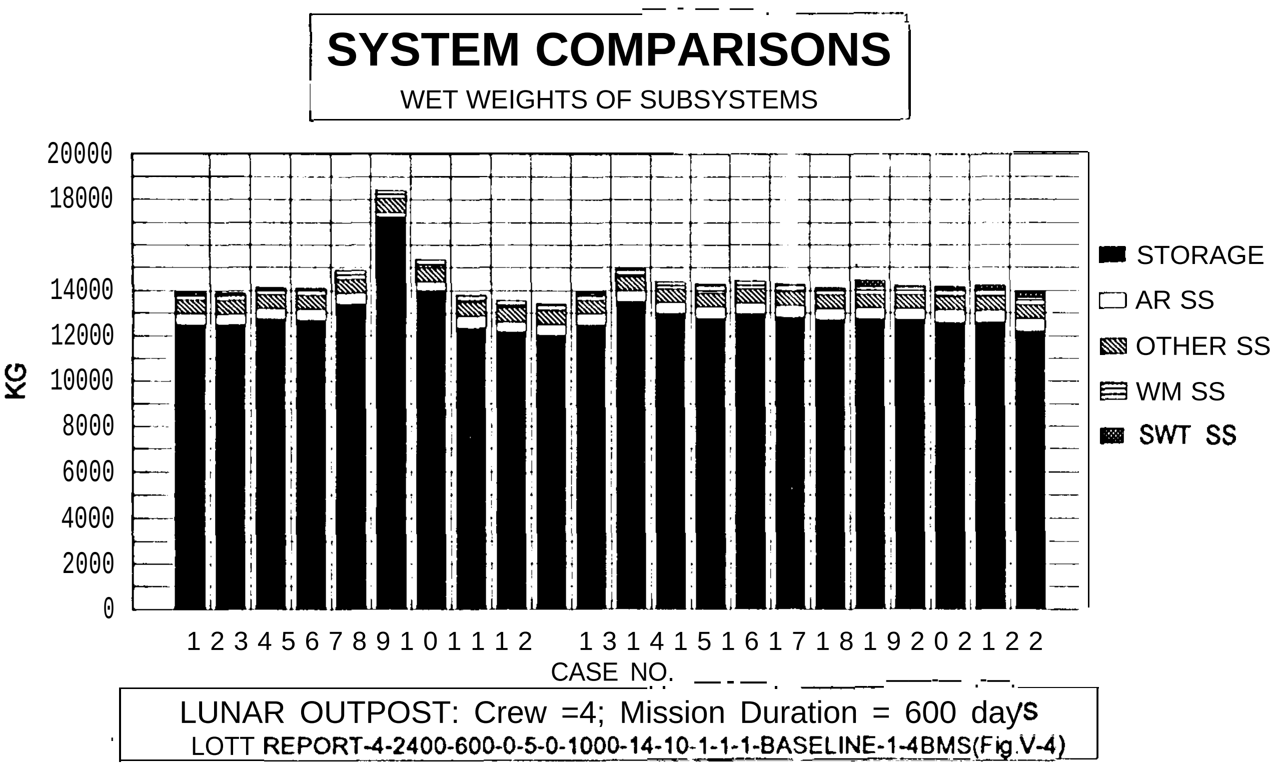


Figure ES-2. Subsystem Weight Comparisons for 600-day Mission

SYSTEM AND SUBSYSTEM POWER COMPARISONS

Since the weight of process equipment is independent of mission duration, the power demand summaries shown in Figure ES-3 are the same for either 90-day or 600-day missions. The total system power use ranges from a low of 3760 watts for Case 6 to a high of 7050 watts for Case 18. Cases 18 through 22 are significantly higher than other cases primarily due to the additional power required for the added solid waste treatment. technologies. It is clear that for all cases, the air revitalization subsystem is the largest consumer of power; the water management subsystem is roughly 1/4 to 1/2 that of the air revitalization subsystem; oxidation technologies in the solid waste treatment subsystem use less power than the water management subsystem.

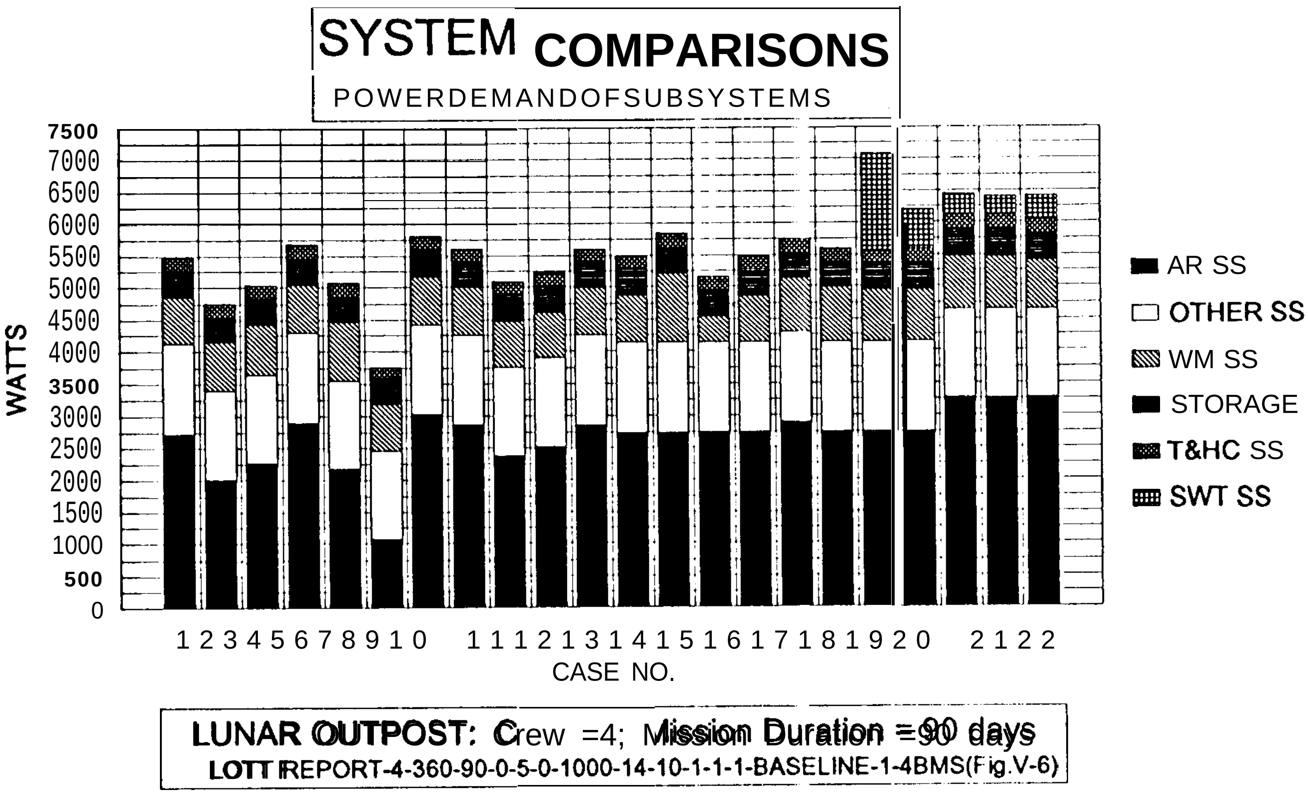


Figure ES-3. Subsystem Power Comparisons

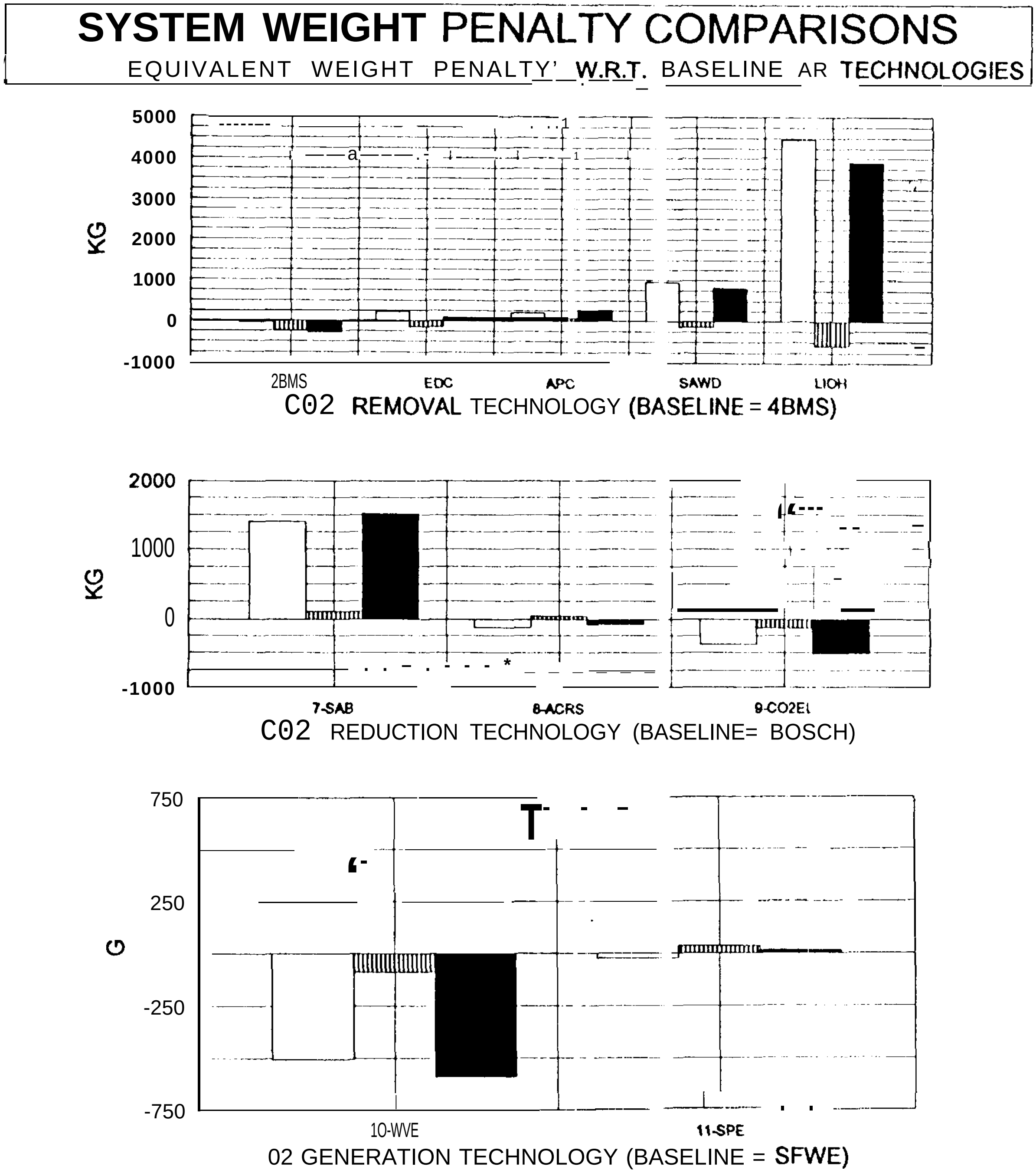
EQUIVALENT SYSTEM PENALTY WEIGHT COMPARISONS

By assigning a weight value to the incremental power required for different life support technologies, an equivalent system weight can be calculated and compared to the baseline technology used. For this report, a regenerative fuel cell technology has been assumed using a value of 3 watts/kg for the incremental power. The life support system weight is added to the equivalent power weight to represent a total equivalent life support weight. The combined effects of weight and power penalties and advantages' relative to the baseline system can be compared. The most significant advantages were found with air revitalization technologies as represented in Figure ES-4. The two-bed molecular sieve shows an advantage of 280 kg; most of these advantages are attributed to power. CO_2 electrolysis shows a total equivalent advantage of 500 kg. Water vapor electrolysis shows a significant total equivalent advantage of 600 kg. Technologies for water management and solid waste treatment do not show any total equivalent advantages. The supercritical water oxidation technology offers the advantage of reducing potentially hazardous solids waste in addition to closing the water cycle and producing an excess of water. For extremely long duration missions of over 1200 days, the supercritical water oxidation technology could offer an overall equivalent weight advantage over the baseline.

CONCLUSIONS

The trade results presented in this report were obtained in 1993 and do not include new technologies and advances in technologies beyond 1993. In order to realize the advantages identified by systems analysis of an immature technology, research and development investment must be made. During the development, analysis should be continued to assess technical progress against past investment and the need for further investment.. Conclusions concerning the best technologies should be revisited following significant progress in technology development. By this iterative process of systems analysis and hardware development, the risk of investing in technology development can be significantly reduced.

1. Regenerative technologies showing significant system weight advantages include CO_2 electrolysis and water vapor electrolysis.
2. Regenerative technologies showing significant system power advantages include two-bed molecular sieve, electrochemical-depolarized concentrator, solid amine water resorption, CO_2 electrolysis, and multifiltration for hygiene water.



System penalty

Equivalent power penalty @ 3 watts/kg

Total equivalent system penalty

LUNAR OUTPOST: Crew =4; Mission Duration = 600 days
LOTT REPORT-4-2400-600-0-5-0-1000-14-10-1-1-1-BASELINE-1-4BMS(Fig.V-21)

Figure ES-4 . Equivalent System Weight Comparisons for Air Revitalization Technologies

3. When power demand is represented in terms of equivalent weight and added to the system weight, the two-bed molecular sieve, CO_2 electrolysis, and water vapor electrolysis have advantages over the baseline for long durations.

RECOMMENDATIONS FOR FURTHER WORK

Recommendations based on the results of this analysis are as follows:

1. As technologies are funded for development, contractors should be required to generate anti report data that can be utilized for quantitative technology comparisons.
2. Technology development directions should be aimed at reducing the weight of resupplies in addition to minimizing system weight and power demand.
3. Technology development should be directed to out perform the current best technology or a selected baseline technology.
4. Basic research should be directed toward identification and use of lighter construction materials, minimization or elimination of resupplies, and minimization of power demand.
5. The effects of process dynamics on technology trades should be examined thoroughly.
6. Systems analysis is an iterative and continuing process throughout the technology development cycle from concept evaluation to mission readiness. By stepping back again and again to obtain a system view following technology selections for further development or mission system design, systems analysis enables significant cost reductions in developing, designing and commissioning any complex system. LiSSA is such an analysis tool for physical- chemical life support systems.
7. Life support systems analysis should be extended to include biological systems and in situ resource utilization systems so that technologies pertaining to these systems can be traded for assessment of system impacts. The modular and architectural construction of LiSSA lends itself to performing these trades [Reference ES-l]. in addition, future trades should include power and propulsion systems to complete the picture for mission and project planners.
8. Life support systems analysis using dynamic models and integrated controllers must be undertaken to assess the operational impact of technology selections for any given system.

ACKNOWLEDGEMENT

JPL gratefully acknowledges the consistent and committed support and advocacy provided by Ms. Peggy L. Evanich of NASA/OACT for this effort, Johnson Space Center for using LiSSA during the developmental phases and providing valuable feedback, and others who participated in beta-testing, providing comments and suggestions. The research described in this report was carried out at the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California under a contract with the National Aeronautics and Space Administration.

I. INTRODUCTION

A life support systems analysis tool has been developed at the Jet Propulsion Laboratory for the National Aeronautics and Space Administration to enable synthesis and evaluation of system and technology options for advanced human missions. The tool is called LiSSA, which stands for Life Support Systems Analysis. LiSSA consists of two parts: the LiSSA-Simulation Tool (LiSSA-ST) and the LiSSA-Trade Tool (LiSSA-TT) . LiSSA-ST models the life support system based on a steady-state, one-person, daily basis in ASPEN PLUS. LiSSA-TT uses data generated from a LiSSA-TT simulation and mission parameters that are selected in a spreadsheet format (Lotus 1-2-3) to yield system analysis results. The model and its GMFS architecture has been described in several publications [references I-1 through I-7] . A more detailed description of LiSSA is given in Appendix A. For a complete description and explanation of how to use LiSSA, the reader is referred to user and developer manuals [1-8, I-9, and I-lo] . LiSSA uses a modular, top-down hierarchical breakdown of a physical/chemical closed-loop life support (P/C CLLS) system into subsystems, and further breakdowns of subsystems into subsystem functional elements (SFEs); these SFES can be realized in hardware by specific processing technologies. This architecture is called the Generic Modular Flow Schematic (GMFS) .

Section 11 includes a description of a baseline system that will be used as a reference to compare alternative technologies. Included in this section is a discussion of the derivation of the metabolic loads used in the life support simulation model. The metabolic balance is broken down into an elemental balance including C, H, O, N, and ash for human input and output streams. A hygiene water load model is presented based on literature sources. The baseline life support system configuration that is described in this section does not represent any optimized or NASA baseline; it is given here for the purpose of making trade comparisons in this report.

Section III includes assumptions used in all the life support system modeling in LiSSA-ST. Mission parameter choices are also given and defined as they are used in the trade model (LiSSA-TT).

In Section IV, the sources of information and the degree of validity are shown for the various air, water and solid waste treatment technologies to be traded against their counterparts in the baseline system configuration.

In Section V, a case matrix is set up that identifies the substitution of technologies for the baseline. Comparisons of all the cases relative to system and subsystem weight and power are presented in detail, and a system level comparison is discussed. Technology trade results and short discussions of these results are provided for carbon dioxide removal , carbon dioxide reduction, oxygen generation, potable water recovery, hygiene water recovery, urine water recovery, and solid waste treatment technologies. Power equivalent weight. is given by assuming a regenerative fuel cell with an equivalent weight of 3 watts/kg. Overall system equivalent weights, including system weight and equivalent weight of power, are presented. Results of the effect of changing the food water content is given also.

Based on these results, some significant conclusions and recommendations are provided in Section VI.

A list of references cited in the main body of the report is given in Section VII.

Appendix A includes a brief description of the LiSSA tool. References to detailed descriptions and uses of LiSSA are given.

Appendix B gives brief process descriptions and schematics of the technologies used for the trades.

II. BASELINE SYSTEM DEFINITION FOR TECHNOLOGY TRADES

1. Metabolic Load Basis

A metabolic mass balance has been established and is presented in Table II-1. This balance is the result of combining several literature sources into a consistent elemental balance that is sufficiently detailed to perform systems analysis using the LiSSA-ST with ASPEN PLUS.

Space Station Freedom [11-1] has established nominal mass values for the following:

METABOLIC INPUTS	METABOLIC OUTPUTS
Dry food	CO_2
Water in food	Urine H_2O
Drinking water	Urine Solids
Consumed oxygen	Feces H_2O
	Feces solids
	Respiration & Perspiration H_2O
	Sweat solids

In addition, there is also a nominal value specified by Space Station Freedom for metabolic heat release rate.

However, the elemental compositions of the waste solids are not specified. If chemical processing and transformation (e.g., oxidation of feces and urine wastes) are to be performed, this information must be known. Wydeven[II-2] and Golub[II-3] have collected chemical compositions of various human waste streams including trace compounds. However, the data collected is not correlated to the composition of food ingested by the human crew. Volk[II-4] presented mass balance relationships by establishing representative chemical formulas for food and waste streams as follows:

Food protein	C_4H_5ON
Food carbohydrate	$C_6H_{12}O_6$
Food fat	$C_{16}H_{32}O_2$
Urine solids	$C_2H_6O_2N_2$
Feces solids	$C_{42}H_{69}O_{13}N_5$
Wash solids (no soap)	$C_{13}H_{28}O_{13}N_2$.

Table II-1. Metabolic Mass Balance
(kg/person-day)

INPUTS	CARBON	HYDROGEN	OXYGEN	NITROGEN	ASH	TOTALS
1. DRY FOOD						
Protein, C_4H_5ON	0.0770	0.0081	0.0257	0.022?5		0.1332
Carbohydrate, $C_6H_{12}O_6$	0.1489	0.0250	0,1984			0.3723
Fat, $C_{16}H_{32}O_2$	0.0858	0.0144	0.0143			0.1145
Minerals, Ash					0.0095	0.0095
2. LIQUIDS (WATER)						
Drink		0.1802	1.4298			1.6100
Food Preparation		0.0884	0,7016			0,7900
Food Water Content		0.1287	1.0213			1.1500
3. GASES						
Oxygen			0.8359			0.8359
INPUT SUMS	0.3118	0.4448	4.2270	0.0225	0.0095	5.0155
OUTPUTS						
I.SOLIDWASTES						
Urine, $C_2H_6O_2N_2$	0.0160	0.0040	0.0213	0,0187	0.0077	0.0678
Feces, $C_{42}H_{69}O_{13}N_5$	0.0177	0.0024	0.0073	0.0024	0.0018	0.0318
Sweat, $C_{13}H_{28}O_{13}N_2$	0,0074	0.0014	00099	0.0013		0.0200
2. LIQUIDS (WATER)						
Urine		0.1693	1.3440			1.5133
Feces		0.0102	0.0806			0.908
Sweat & Perspiration		0.2574	2.0429			2.3003
3. GASES						
Carbon dioxide	0.2706		0.7209			0.9915
OUTPUT SUMS	0.3118	0.4448	4,2270	0.0225	0.0095	5.0155

These representative formulas were developed to account for the major elements, C, H, N, and o found in human and biological components (e.g., edible and inedible plants) . The elemental compositions were necessary to estimate oxygen requirements in a waste processor that would oxidize human and plant wastes. These food and waste chemical formulas have been used as indicated in Table II-1. These compounds were used in the LiSSA-ST using the Property Constant Estimation System (PCES) of the chemical process simulation package called ASPEN PLUS.

In addition to the elements C,H,N, and O, other elements appearing in human wastes include P, S, Ca, Mg, K, and others. These elements are all treated as ash, which is taken in with the food and rejected as ash wastes. In the LiSSA-ST modeling, these ash constituents will be distributed as 80% leaving with urine solids and 20% leaving with feces solids. The relative ash distribution was based on elemental compositions of freeze-dried urine and feces (II-2) .

Trace compounds, such as alcohols, ammonia, and methane generated by the human metabolic function, could significantly affect the sizing of trace contaminant control units and other processes interacting with them. These compounds would also impose consumable demands associated with processes for their removal. LiSSA uses reasonable estimates for the anticipated levels of release of these compounds into the human habitat. without any explicit correlation with the composition of ingested food.

2. Hygiene Load Basis

Hygiene water use and waste load estimates based on reference II-2 are as follows for a 1 person-day basis:

Water Use:	(kg)
Oral hygiene H_2O	0.36
Hand/face Wash H_2O	1.81
Shower H_2O	5.44
Clothes wash H_2O	12.47
Dish wash H_2O	5.44
Flush H_2O	0.49

	26.01

Waste Loads:	
Hygiene H_2O	7.17
Latent hygiene H_2O	0.44
Clothes wash H_2O	11.87
Latent clothes wash H_2O	0.60
Dish wash H_2O	5.41
Latent dish wash H_2O	0.03
Flush H_2O	0.49

	26.01

3. Baseline System Configuration

In order to perform technology trades, a baseline system to trade against was chosen. Baseline technologies in this report are not baselined identically in any known life support system design nor do they represent an optimal system configuration. They have been arbitrarily chosen as representatives of the technology functions constituting a physical-chemical life support system. Figure II-1 shows the baseline system.

BASELINE LSS CONFIGURATION

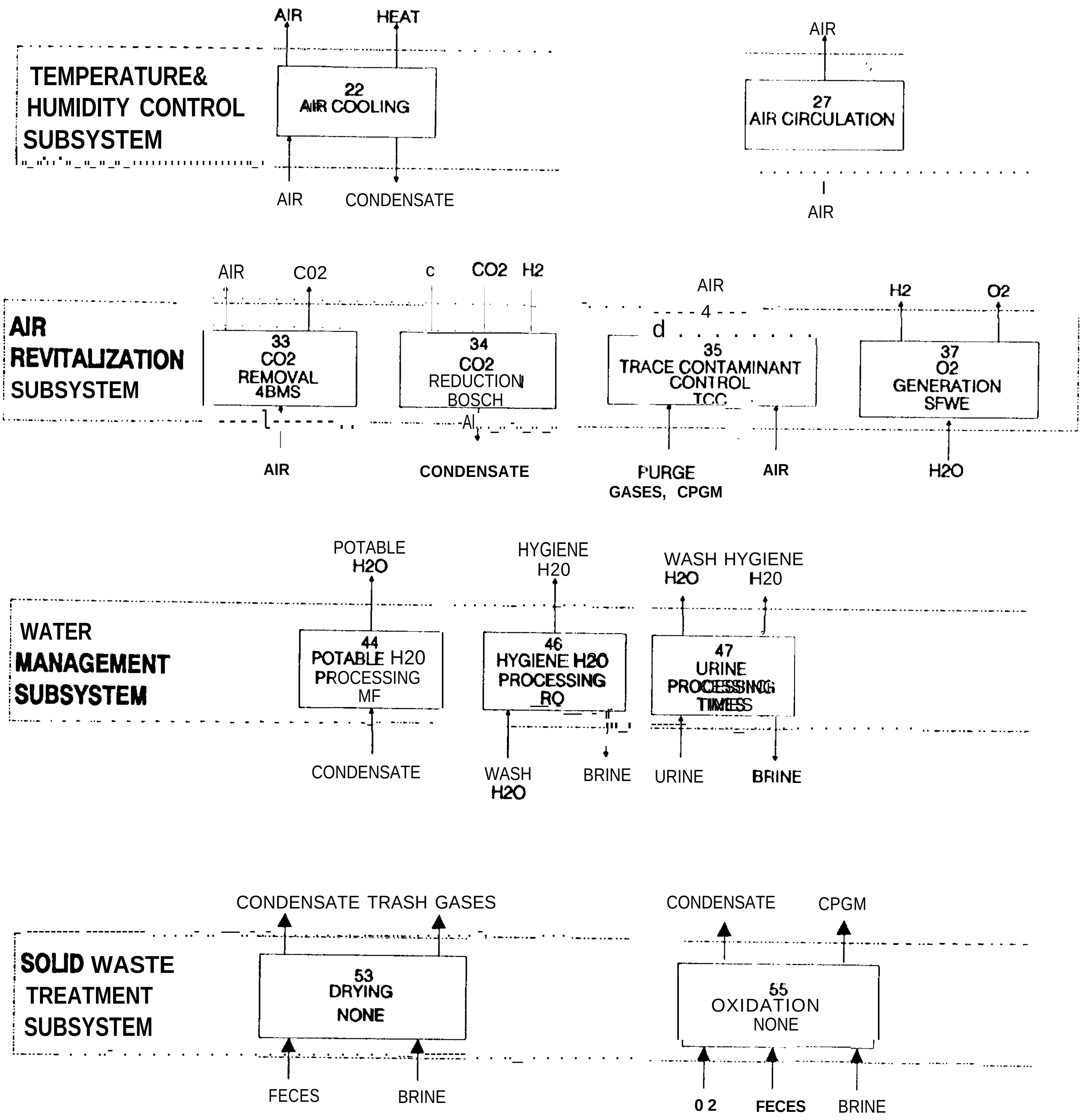


Figure II-1. Baseline Life Support System Configuration

This page left intentionally blank

III. SYSTEM AND MISSION ASSUMPTIONS

1. Life Support System Modeling Assumptions

Assumptions used in the life support simulation are as follows:

Air Revitalization and Cabin Air:

- Cabin pressure = 1 atmosphere.
- Cabin air maximum temperature = 27°C.
- Cabin air minimum temperature = 16°C.
- Maximum CO_2 partial pressure ≈ 2.7 mm Hg.
- All CO_2 recovered from CO_2 removal is sent to CO_2 reduction.
- Oxygen used in the life support system is generated via water electrolysis.
- Potable water purity levels are required for O_2 generation via electrolysis.
- Trace contaminants in the cabin air are assumed to be equivalent to methane and ethanol as they impact the oxygen required for catalytic oxidation in the trace contaminant control process.
- The cabin air leakage rate is assumed to be very small (0.0005 kg/day).

Water Management and Purity:

- Water processed in potable water processing is assumed to meet potable water requirements similar to those established for Space Station Freedom. The total organic carbon level is on the order of 500 μg/l .
- Water recovered as cabin air condensate and process condensates is routed to potable water processing.
- Water recovered as hygiene wash water wastes is routed to hygiene water processing.
- Water processed in hygiene water processing is assumed to meet hygiene water requirements similar to those established for Space Station Freedom. The total organic carbon level is on the order of 10,000 μg/l.
- Water recovered from urine processing is mixed with water from wash water processing to make hygiene water. It is assumed that the combined quality of product water from hygiene water processing and urine processing meets the hygiene water purity requirements.
- Brines from water processing are not processed by water management technologies. They are sent to solid waste treatment if they are to be processed.
- The life support system will process all water streams

that are available regardless of the requirement of potable and hygiene water required. In some cases, this leads to an excess of potable and/or hygiene water. Excess potable water (i.e., water produced in excess of the hygiene water requirement) is used for hygiene water; if excess hygiene water is produced, it is sent to trash storage or dumped.

Solid Waste Treatment:

- Feeds to solid waste treatment include brines from water processing and feces from the human habitat. Papers, kitchen wastes, spent chemical beds, filters, etc. are sent to trash and are not processed for resource recovery.
- Condensates produced from solid waste treatment must be polished by hygiene water processing with the exception of supercritical water oxidation: its condensate is mixed with hygiene water processing product without polishing.

2. Mission Parameter Definitions and Assumptions

Mission parameters chosen are given in Table III-1 and are defined as follows:

MAXIMUM CREW SIZE (MCS) is the maximum number of people that would occupy the human habitat at any time during the mission. This number is required to size the processing equipment.

MISSION CREW LOADING (MCL) is the sum of the products of crew size and corresponding durations spent in the human habitat during the mission. For example, during a 100-day mission, if a crew of four occupy the habitat for 25 days and a crew of two for 75 days, the crew loading for the entire 90-day mission would be 250 person-days(4x25 + 2x75). MCL can never exceed the product of maximum crew size and total mission duration.

TOTAL MISSION DURATION (TMD) is calculated as the sum of one-way, return and planetary surface duration quantities in days.

RESUPPLY LAUNCHES (RSL) is set to zero for no follow-on launches for resupply, as it is assumed that the lunar outpost is completely supplied at the beginning of its mission for the total mission duration. Resupply includes all materials that will not be regenerated by the life support system including provisions for leakage and emergencies.

HABITAT VOLUME (HABVOL) is the value for habitat volume per person in cubic meters.

Table III-1. LiSSA-TT Parameter Choices

PARAMETER	LISSA-TTVARIABLE NAME	VALUE
Mission crew size	MCS	4
Mission crew length	MCL	4*90 and 4*800 (<= MCS*MCL)
Total mission duration	TMD	90 and 800
Resupply launches	RSL	o
Emergency backup supply storage	EBSS	5
Use of LiOH canisters for emergencies (1 =yes, 0=no)	ELIOH	1
Emergency backup supply storage for air if air used rather than LiOH (hrs)	EBSSA	o
Habitat volume (m’ per person)	HABVOL	28.3 (1000 ft^3)
Leak fraction (= fraction of HABVOL x 10^{6})	LEAKFRAC	0.000014
Exhaust storage factor (%)	ESF	10
Gaseous trash venting option (vent=1 or store=O)	GTVO	1
Liquid trash venting option (vent = 1 or store=0)	LTVO	1
Solids trash dumping option (dump= 1 or store=0)	STDO	1

EMERGENCY BACKUP STORAGE SPECIFICATION (EBSS) is the amount of emergency backup storage of regenerated materials, except air, in number of days required to handle the longest life support system emergency anticipated for the mission. Additional storage will be accounted for the various materials in the storage subsystem in proportion to this number.

EMERGENCY LITHIUM HYDROXIDE (ELIOH) is set to 1 in this study to specify the use of lithium hydroxide sorption technology for emergency CO_2 removal. This is in addition to the selection of nonregenerative LiOH technology or any other technology for continual CO_2 removal.

EMERGENCY BACKUP STORAGE SPECIFICATION-AIR (EBSSA) is specified in hours instead of days, as an option to supply fresh air and vent cabin air during emergencies pertaining to CO_2 removal. This specification will be disregarded if is set to 1.

HABITAT LEAKAGE FRACTION (LEAKFRAC) is the fraction of the habitat volume that is leaked per day to space.

EXHAUST STORAGE FACTOR (ESF) provides for the distribution of materials stored in a number of identical storage tanks or containers to enable reuse of supply storage tanks for waste storage. ESF is specified in this study to be 10%. The use of ESF is illustrated in Table III-2.

The gaseous trash venting option (GTVO), liquid trash venting option (LTVO) , and solids trash dumping option (STDO) are set in this study such that gaseous, liquid, and solid trash streams are vented or dumped rather than stored. Hence, there will not be any storage requirements for these trash streams.

Table III-2. Esf and Its Relation to Number of Storage Tanks

ESF	Number of identical storage tanks for supplyandwaste/trash
0	ONE This is impractical, since wastes have to be stored in same tank as fresh supplies. Total storage volume is 100% of the required volume.
100	TWO One tank to contain fresh supplies and one tank to store wastes. Total storage volume is 200% of the required volume.
50	THREE Twotanksto contain fresh supplies andonetankempty at the start of the mission. Two tanks to contain wastes and onetankempty attheend of the mission. Total storage volume is 150% of the required volume.
10	ELEVEN Ten small tanks to contain fresh supplies and one ernptytankatthe start of the mission. Ten tanks to contain wastes and onetankempty at the end of the mission. Total storage volume is 110% the requkedvolume.

IV. TECHNOLOGIES

Technologies are grouped as subsystem functional elements (SFES) within subsystems. The SFE functions traded in this study include CO_2 removal, CO_2 reduction, and O_2 generation for the air revitalization (AR) subsystem; potable water (PW) processing, hygiene water (HW) processing, and urine processing for the water management (WM) subsystem; and drying and oxidation for the solid waste treatment (SWT) subsystem. Data sources for technologies included in this report are included in this section in Tables IV-2 , IV-3, and IV-4. Technology developer companies and contacts are listed wherever applicable. If no contact. was available, the data from references was utilized. Also, a "validity level," as described in Table IV-1 below, is attributed to each technology based on the authors' judgement. This validity level can be viewed as a relative uncertainty associated with the data for each technology. Scale-up formulas used to calculate the wet weight, dry weight, power, and volume of each technology is included in the LiSSA-TT spreadsheet. 'I'he methodology of scale-up has been described in reference IV-1. Brief functional descriptions and schematics of each technology included in this report can be found in Appendix B.

Table IV-1. Validity Level Definitions

VALIDITY LEVEL	DESCRIPTION
1	Measurement
2	Calculated from a dimensioned drawing with known materials of construction
3	Estimated from scaling procedure using data froml and/or2 above
4	Estimated from high validity data for similar equipment
5	Estimated from detailed paper designfor nonexistent hardware
6	Invalidated third party estimates
7	"Engineeringjudgement"

Table IV-2. Air Revitalization Subsystem '1'ethnology Data Sources

SFE	TECHNOLOGY	COMPANY/CONTACT	REF. NO.	VALIDITY LEVEL
C02 Removal	4BMS	AirResearch/ Mr. Scott Manatf	IV-2, IV-3	3
"	2BMS	AirResearch/ Mr. Scott Manatf	IV-2	4
"	EDC	LifeSystems/Dr.Chin Lin (NASA-JSC); Ph: (713)-463-9126	IV-3, IV-4	4
"	APC	LifeSystems/Dr.Chin Lin (NASA-JSC); Ph: (713)-483-9126	IV-3, IV-4	7
"	SAWD	Hamilton Standard /Mr. Jeff Faszcza Ph: (203)-654-3350	IV-3	7
"	LiOH	Hamilton Standard /Mr. Jeff Faszcza Ph: (203)-654-3350	IV-5	3
C02 Reduction	Bosch	Life Systems/Mr. Paul Weiland MSFC Ph: (205)-544-7215	IV-3, IV-4	3
"	Sabatier	Hamilton Standard /Mr. Jeff Faszcza Ph: (203)-654-3350	IV-3, IV-4	3
"	ACRS	Hamilton Standard /Mr. Jeff F aszcza Ph: (203)-654-3350	IV-3, IV-4	4
"	CO2EL/BD	Westinghouse / Dr. Chin Lin (NASA-JSC) Ph: (71 3)-463-9126	IV-2	7
02 Generation	SFWES	Life Systems/Mr. Paul Weiland MSFC Ph: (205)-544-7215	IV-3, IV-4	3
"	WVE	—	IV-2	7
"	SPELF	Hamilton Standard /Mr. Jeff Faszcza Ph: (203)-654-3350	IV-3, IV-4	7

Table IV-3. Water Management Subsystem Technology Data Sources

SFE	TECHNOLOGY	COMPANY/CONTACT	REF. NO.	VALIDITY LEVEL
Potable H2O Processing	MF	Hamilton Standard /Mr. Jeff Faszcza Ph: (203)-654-3350	IV-2, IV-3	3
" "	RO	Hamilton Standard /Mr. Jeff Faszcza Ph: (203)-654-3350	IV-2	3
" "	ELDI	—	IV-2	7
Hygiene H20 Processing	RO	Hamilton Standard /Mr. Jeff Faszcza Ph: (203)-654-3350	IV-3, IV-4	3
" "	MF	Hamilton Standard /Mr. Jeff Faszcza Ph: (203)-654-3350	IV-3	3
Urine Processing	TIMES	Hamilton Standard /Mr. Jeff Faszcza Ph: (203)-654-3350	IV-3, IV-4	3
" "	VCD	Life Systems/Mr. Paul Weiland MSFC Ph: (205)-544-7215	IV-3, IV-4	3
" "	VPCAR	—	IV-3, IV-4	7
" "	AIRE	—	IV-2	7

Table IV-4 . Solid Waste Treatment Subsystem Technology Data Sources

SFE	TECHNOLOGY	COMPANYICONTACT	REF. NO.	VALIDITY LEVEL
Drying	FD	Labconco Corp.	IV-6	7
"	TD	—	IV-7	7
Oxidation	COMB		IV-8, IV-9	7
	Wox		IV-9, Iv-1o	7
"	Scwo	MODAR,Inc./Glenn Hong ph.(508) 965-2920	Iv-1, IV-9, W-11, IV-12	7

This page left intentionally blank

V. TECHNOLOGY TRADE RESULTS

1. Case Matrix

Twenty-two cases were run with technology choices substituted for the baseline technology, as identified in Table V-1:

Table V-l.. Technology Choices

CASE	AR SS			WM SS			SWT SS	
NO.	C02 REMOVAL	C02 REDUCTN.	02 GEN.	POTABLE H20 PROC.	HYGIENE H2O PROC.	URINE PROC.	DRYING	OXIDATION
1	4BMS	BOSCH	SFWE	MF	RO	TIMES	NONE	NONE
2	2BMS	"	.	"	"	"	"	"
3	EDC	"	.	"	"	"	"	.
4	APC	"	"	.	"	"	w	"
5	SAWD	"	"	.	"	"	w	.
6	LIOH	NONE	"	.	"	"	"	.
7	4BMS	SABATIER	"	"	"	"	.	.
8	.	ACRS	.	.	.	"	.	"
9	"	CO2EL/BD	"	"	"	.	"	"
10	"	BOSCH	WVE	"	"	"	.	.
11	.	"	SPELF	"	"	"	.	"
12	"	"	SFWE	RO	.	"	.	"
13	.	"	"	ELDI	.	.	"	"
14	.	"	"	MF	MF	"	"	.
15	.	.	.	"	RO	VCD	"	.
16	"	.	.	.	.	VPCAR	.	"
17	.	"	.	"	"	AIRE	.	"
18	"	.	.	"	.	TIMES	FD	.
19	"	.	W	.	.	.	TD	.
m	"	.	.	.	.	.	NONE	COMB
21	"	.	.	.	.	.	.	Wox
22	.	"	.	"	"	.	"	Scwo

System Weight Comparisons:

The results of the technology substitutions in terms of system wet weights for the 22 cases are presented in Figures V-1 and V-2 for mission durations of 90 days and 600 days. The impact of technology substitutions on subsystem wet weights are 'shown in Figures V-3 and V-4. Similar comparisons in terms of overall system power demand and subsystem power demand are shown in Figures V-5 and V-6, respectively.

Overall system weights vary between 3840 kg and 4440 kg for the 90-day mission and from 13,400 kg to 18,400 kg for the 600-day mission, as seen in Figures V-1 and V-2, respectively. Note that the cases maintain their relative positions with a few exceptions. For example, in both the 90--day mission and 600-day missions, Case 10, which pertains to the use of water vapor electrolysis technology for O_2 generation, shows the minimum weight; however, Case 22 (supercritical water oxidation for solids waste treatment) has the maximum weight for the 90-day mission, but Case 6 (nonregenerative LiOH for CO_2 removal), which pertains to nonregeneration of oxygen, is the heaviest for the 600-day mission. In general, nonregenerative system/subsystem configurations would impose increasing weight penalties with increasing mission duration. On the other hand, Case 7, which provides for the regeneration of oxygen using Sabatier technology to recover O_2 in the form of condensate from CO_2, turns out to be the second heaviest system as the mission duration is increased to 600 days. This is due to the need to trash hydrogen in the form of methane and the consequent need to store water to provide for this continual trashing operation (water is used to generate hydrogen and oxygen in the oxygen generation SFE). As mission duration is increased, the weight of consumable supplies to be stored at the start of the mission increasingly dominates over process equipment weight.

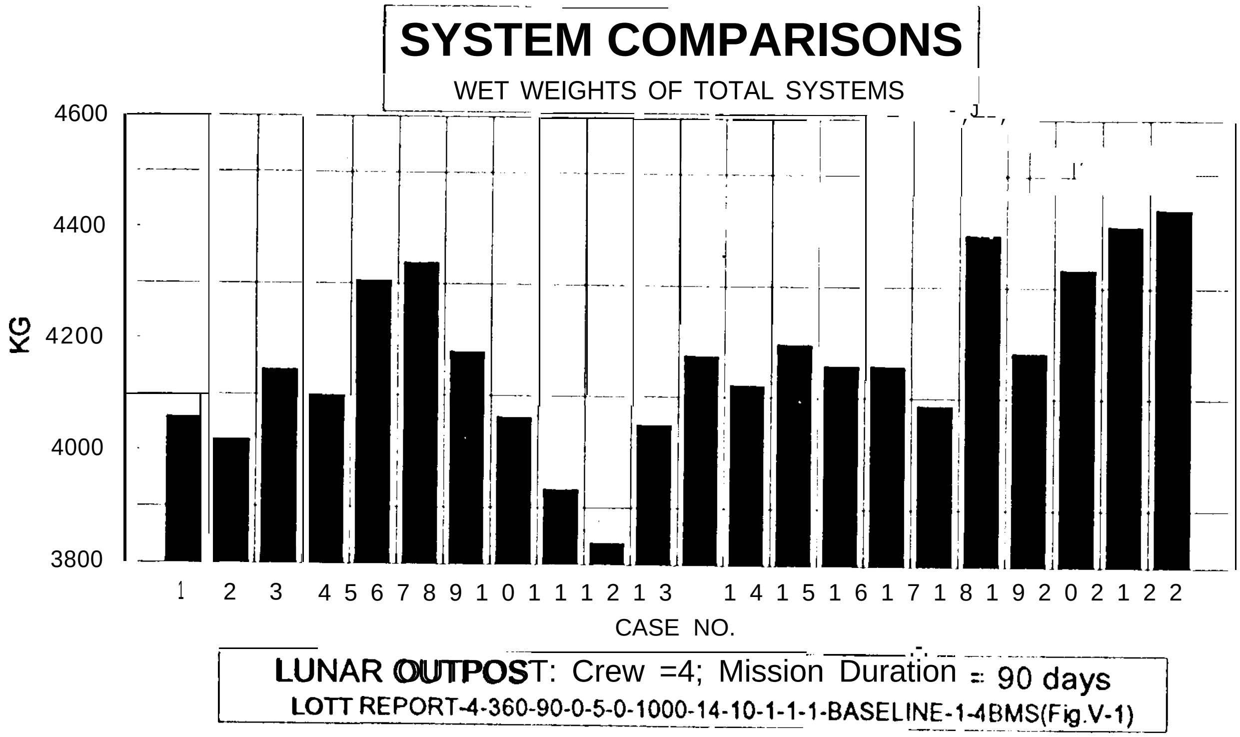


Figure V-1 . Total System Weight Comparisons (90-day mission)

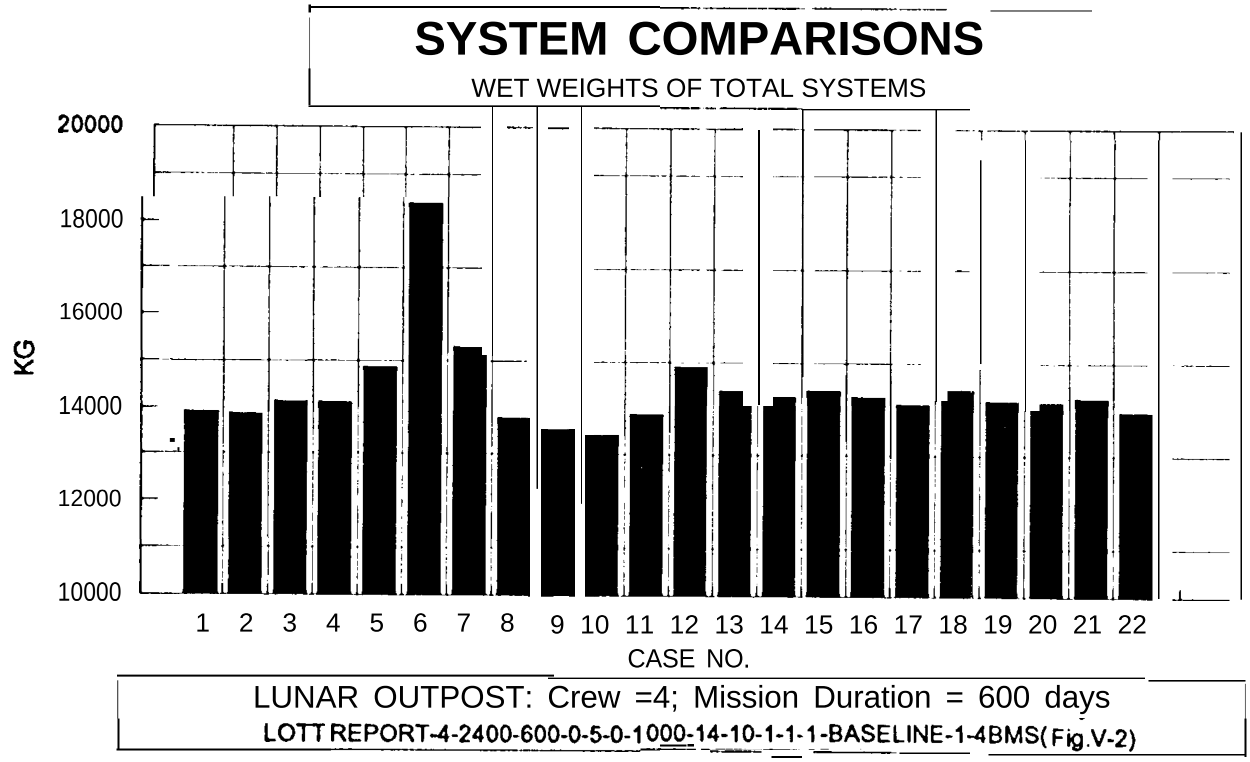


Figure V-2 . Total System Weight Comparisons (600-day mission)

Subsystem Weight Comparisons:

The dominance of nonregenerable supplies is readily seen by a comparison of various subsystem weights constituting the total system weight as shown in Figures V-3 and V-4. In these figures, storage subsystem weights include the weights of consumables and their containers. By keeping the crew size the same for both the 90- and 600-day missions, the differences between the two figures are entirely due to differences in the demand for consumable supplies. The weight of process equipment, being a function of crew size and independent of mission duration, is the same for the two figures.

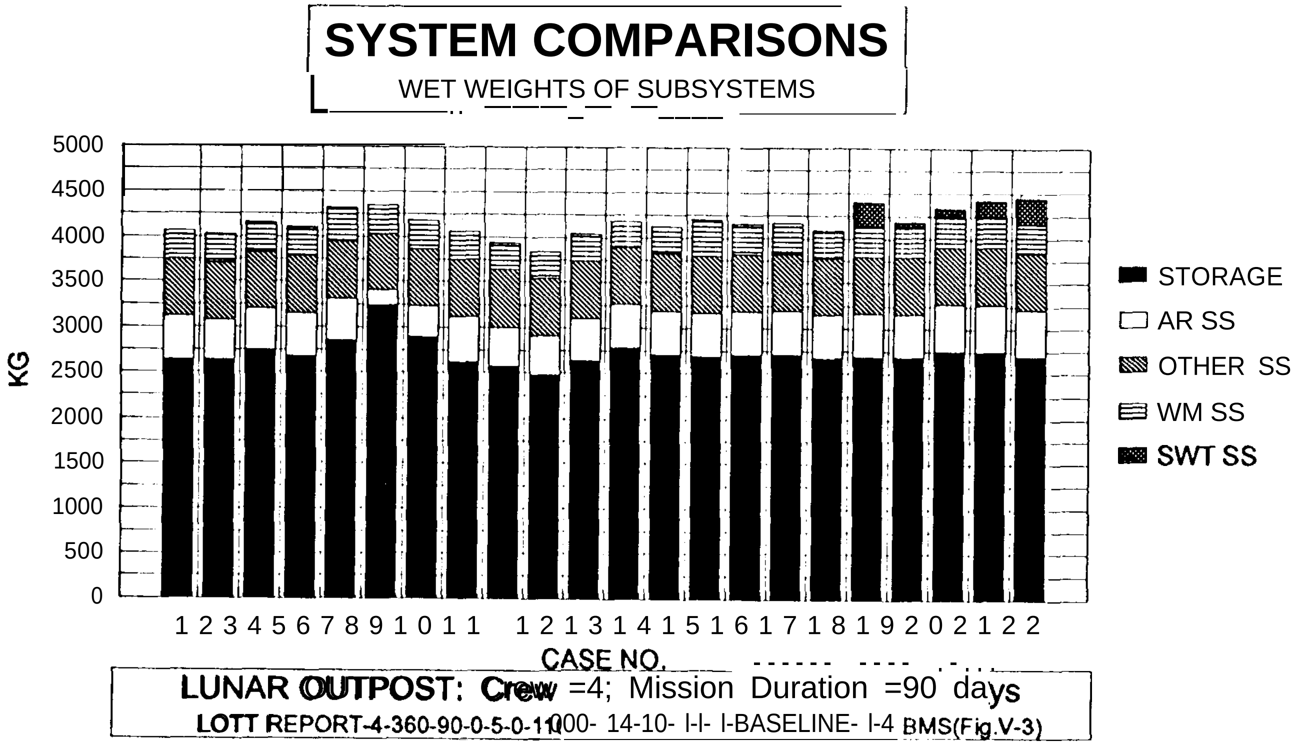


Figure V-3 . Subsystem Weight Comparisons (90-day mission)

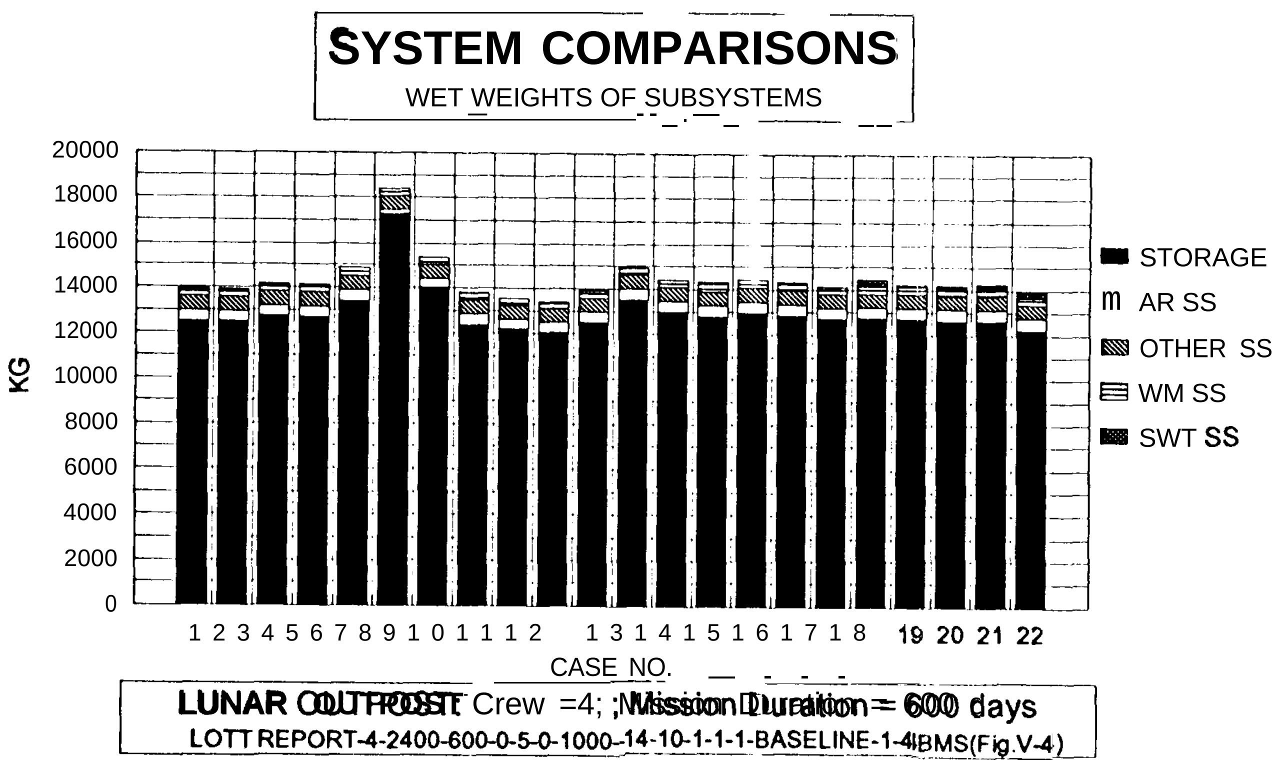


Figure V-4. Subsystem Weight Comparisons (600-day mission)

System and Subsystem Power Comparisons:

Since process equipment is identical with respect to mission duration, the power demand summaries shown in Figures V-5 and v-6 are identical for either 90-day or 600-day missions. Figure V-5 gives a total system power comparison, while Figure V-6 shows individual subsystem power comparisons. The total system power use ranges from a low of 3760 watts for Case 6 to a high of 7050 watts for Case 18. Cases 18 through 22 are significantly higher than other cases primarily due to the additional power required for the added solid waste treatment technologies. From Figure V-6, it is clear that for all cases, the air revitalization (AR) subsystem is the largest consumer of power. The water management (WM) subsystem is roughly 1/4 to 1/2 that of the AR subsystem; oxidation technologies in the solid waste treatment subsystem use less power than the WM subsystem.

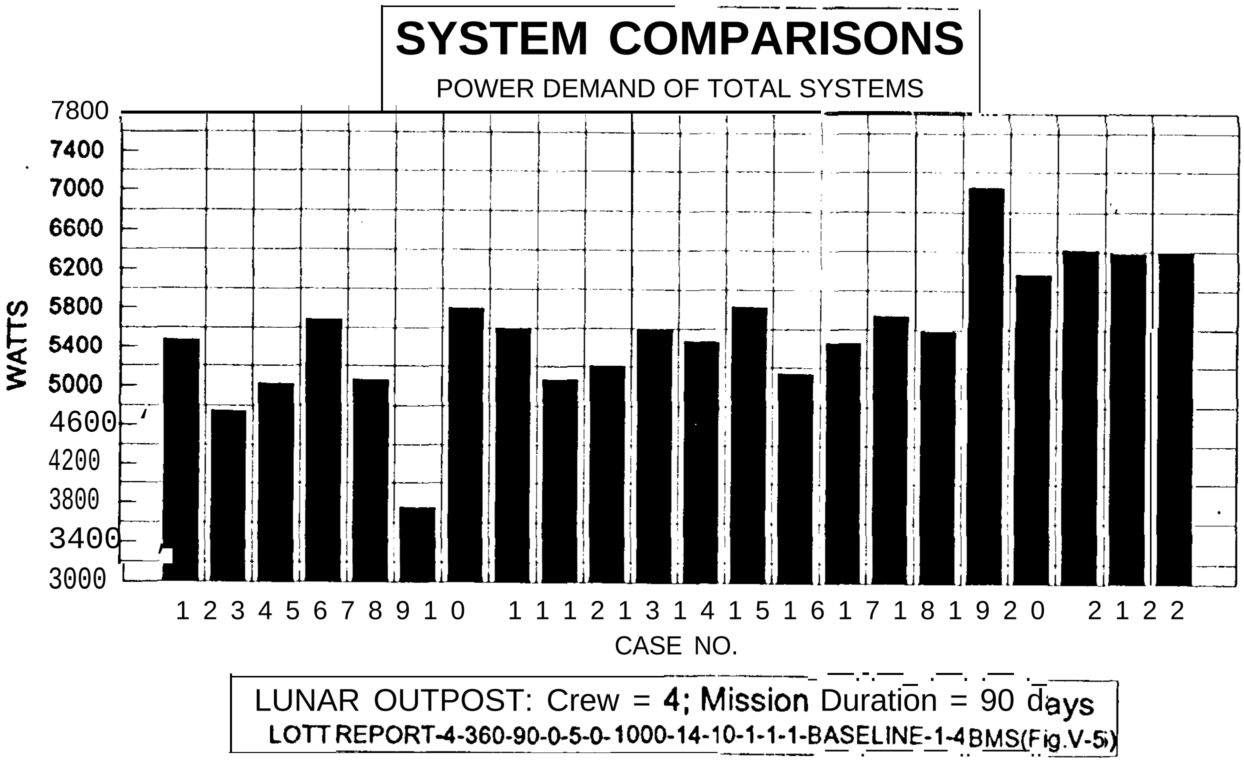


Figure V-5 . System Power Comparisons (90- or 600-day mission)

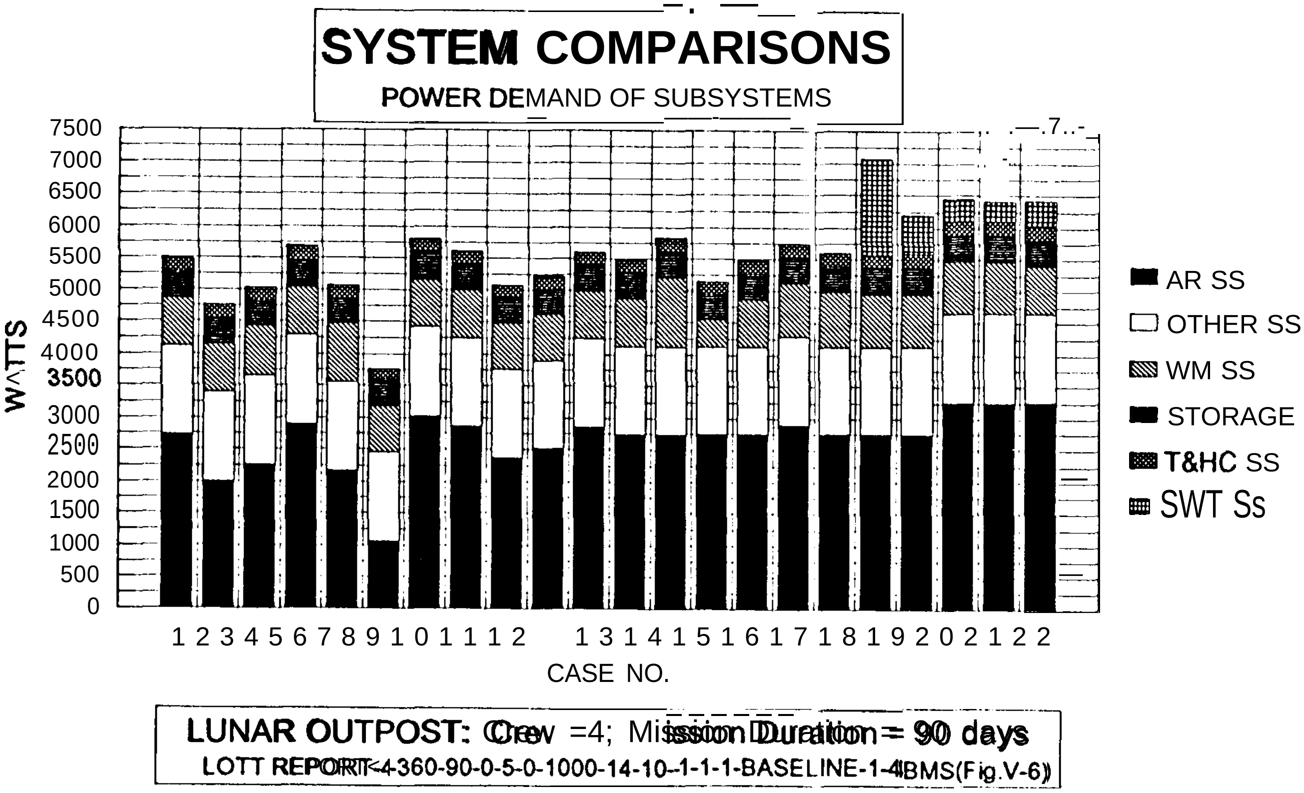


Figure v-6. Subsystem Power Comparisons (90- or 600-day mission)