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NASA Technical Memorandum 109927

Life Support Systems Analysis and Technical Trades for a Lunar Outpost

December 1994

National Aeronautics and
Space Administration

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Life Support Systems Analysis and Technical Trades for a Lunar Outpost

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Scientific and Technical Information Program

1994

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES
(continued)

APPENDIX:

Process Flow Schematics:

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
CO2EL	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
GMFS	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
SFE	Subsystem functional element
SFWE	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

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 up 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	
	CO2 REMOVAL	CO2 REDUCTION	O2 GENERATION	POTABLE H2O PROCESSING	HYGIENE H2O 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	"	"	SFWE	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 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 (non-regenerative 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. 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.

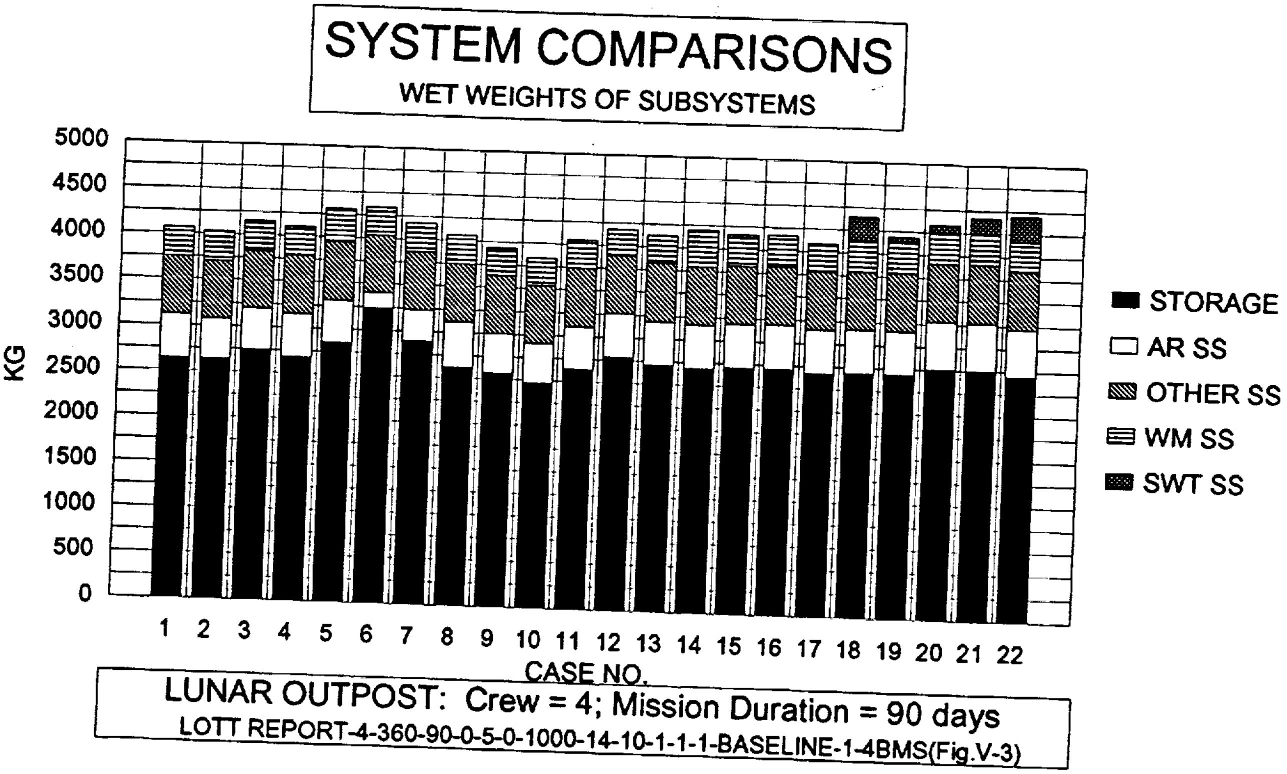


Figure ES-1. Subsystem Weight Comparisons for 90-day Mission

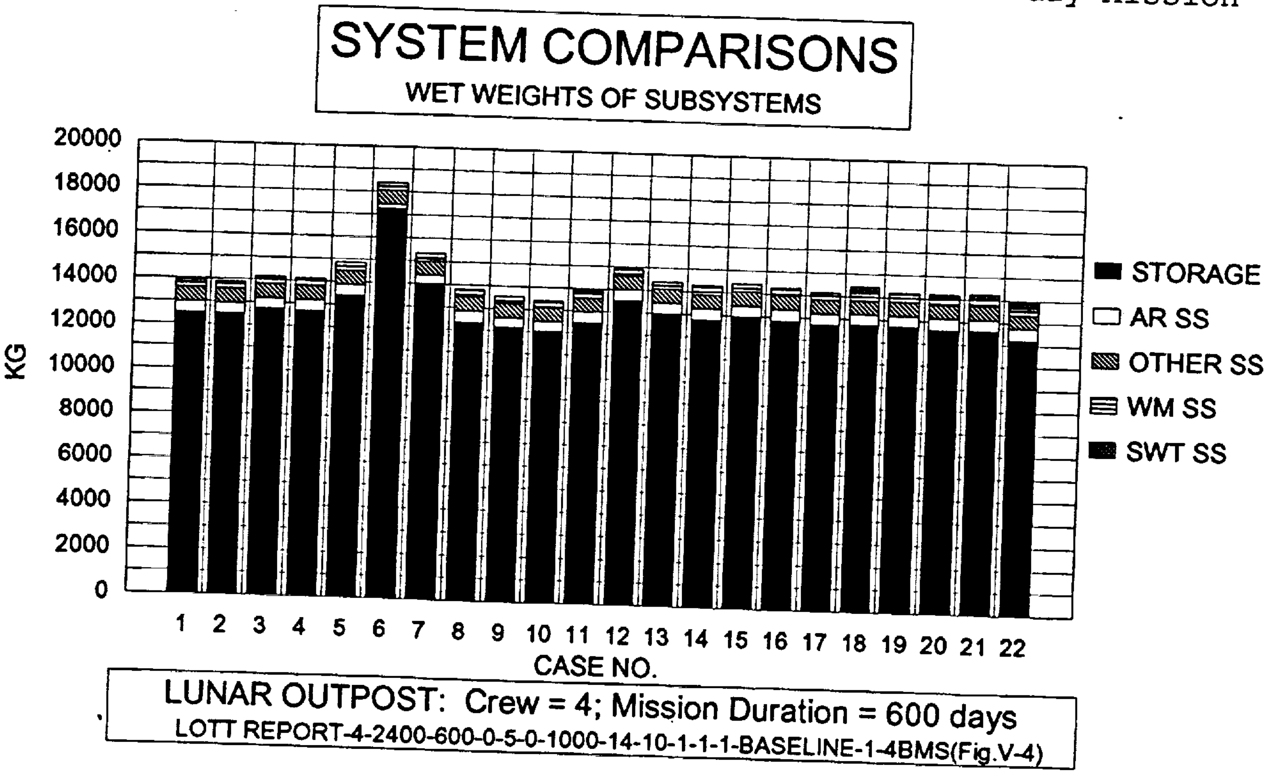


Figure ES-2. Subsystem Weight Comparisons for 600-day Mission

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.

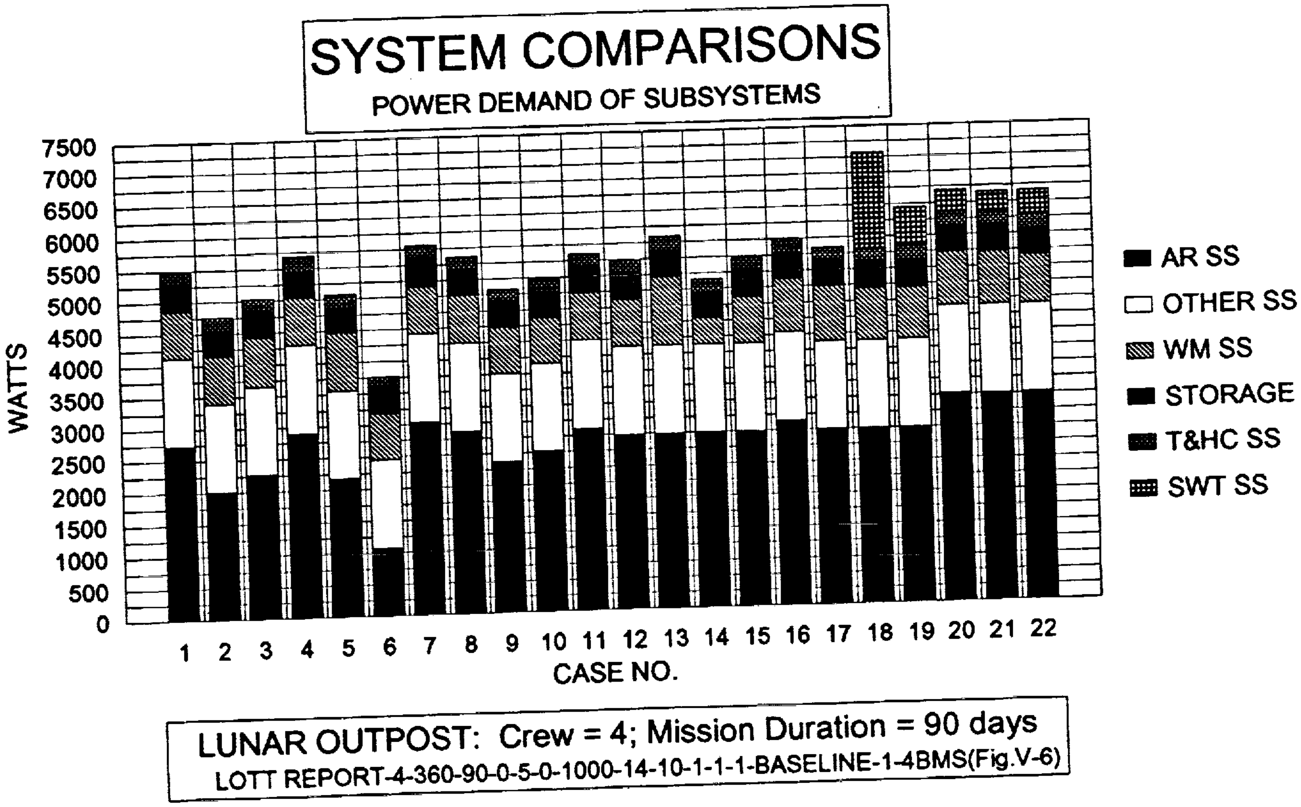


Figure ES-3. Subsystem Power Comparisons

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 desorption, CO_2 electrolysis, and multifiltration for hygiene water.

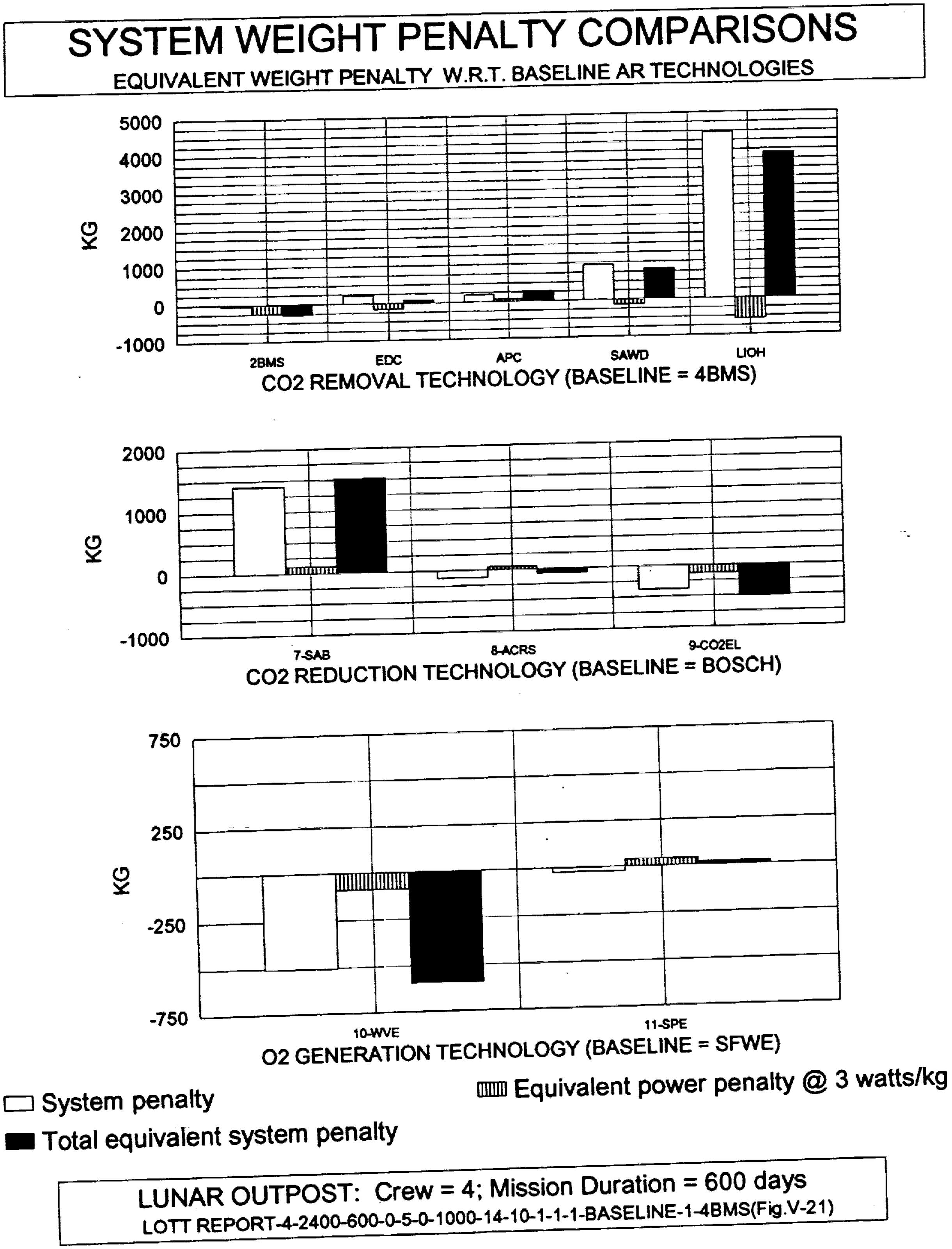


Figure ES-4. Equivalent System Weight Comparisons for Air Revitalization Technologies

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 and 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 outperform 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-1]. 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 [I-8, I-9, and I-10]. 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 II 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 [II-1] has established nominal mass values for the following:

METABOLIC INPUTS

- Dry food
- Water in food
- Drinking water
- Consumed oxygen

METABOLIC OUTPUTS

- CO_2
- Urine H_2O
- Urine Solids
- 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	0.0225		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						
1. SOLID WASTES						
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	0.0099	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

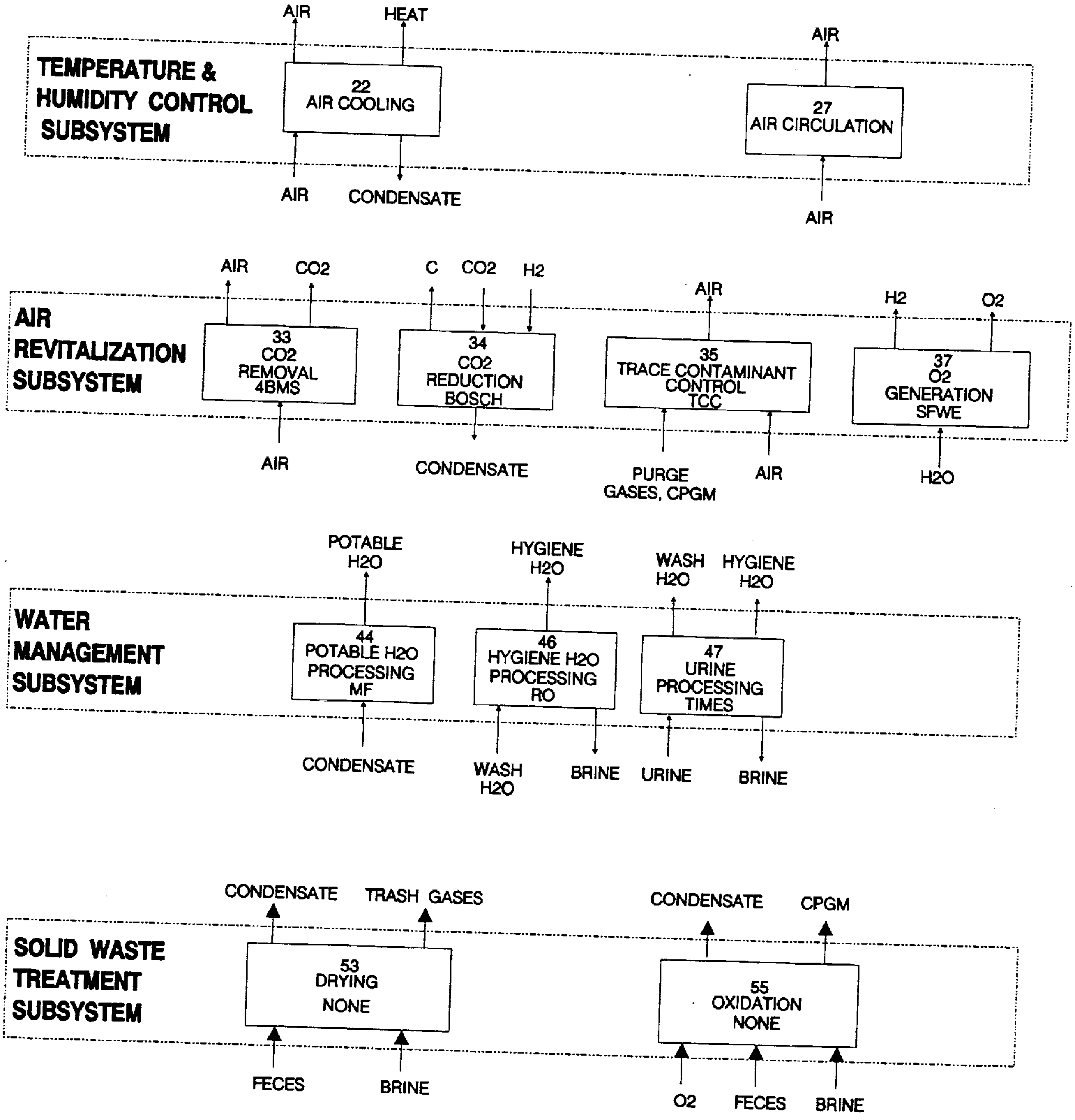


Figure II-1. Baseline Life Support System Configuration

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-TT VARIABLE NAME	VALUE
Mission crew size	MCS	4
Mission crew length	MCL	4*90 and 4*600 (<=MCS*MCL)
Total mission duration	TMD	90 and 600
Resupply launches	RSL	0
Emergency backup supply storage (days)	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	0
Habitat volume (m^3 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=0)	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 supply and waste/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 Two tanks to contain fresh supplies and one tank empty at the start of the mission. Two tanks to contain wastes and one tank empty at the end of the mission. Total storage volume is 150% of the required volume.
10	ELEVEN Ten small tanks to contain fresh supplies and one empty tank at the start of the mission. Ten tanks to contain wastes and one tank empty at the end of the mission. Total storage volume is 110% the required volume.

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. The 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 from 1 and/or 2 above
4	Estimated from high validity data for similar equipment
5	Estimated from detailed paper design for nonexistent hardware
6	Unvalidated third party estimates
7	"Engineering judgement"

Table IV-2. Air Revitalization Subsystem Technology Data Sources

SFE	TECHNOLOGY	COMPANY/CONTACT	REF. NO.	VALIDITY LEVEL
CO2 Removal	4BMS	AirResearch/ Mr. Scott Manatt	IV-2, IV-3	3
" "	2BMS	AirResearch/ Mr. Scott Manatt	IV-2	4
" "	EDC	Life Systems/Dr. Chin Lin (NASA-JSC); Ph: (713)-483-9126	IV-3, IV-4	4
" "	APC	Life Systems/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
CO2 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 Faszcza Ph: (203)-654-3350	IV-3, IV-4	4
" "	CO2EL/BD	Westinghouse / Dr. Chin Lin (NASA-JSC) Ph: (713)-483-9126	IV-2	7
O2 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 H2O 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	COMPANY/CONTACT	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-10	7
"	SCWO	MODAR,Inc./Glenn Hong ph.(508) 965-2920	IV-1, IV-9, IV-11, IV-12	7

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-1. Technology Choices

CASE NO.	AR SS			WM SS			SWT SS	
	CO_2 REMOVAL	CO_2 REDUCTN.	O_2 GEN.	POTABLE H_2O PROC.	HYGIENE H_2O PROC.	URINE PROC.	DRYING	OXIDATION
1	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	"	"	SFWE	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

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.

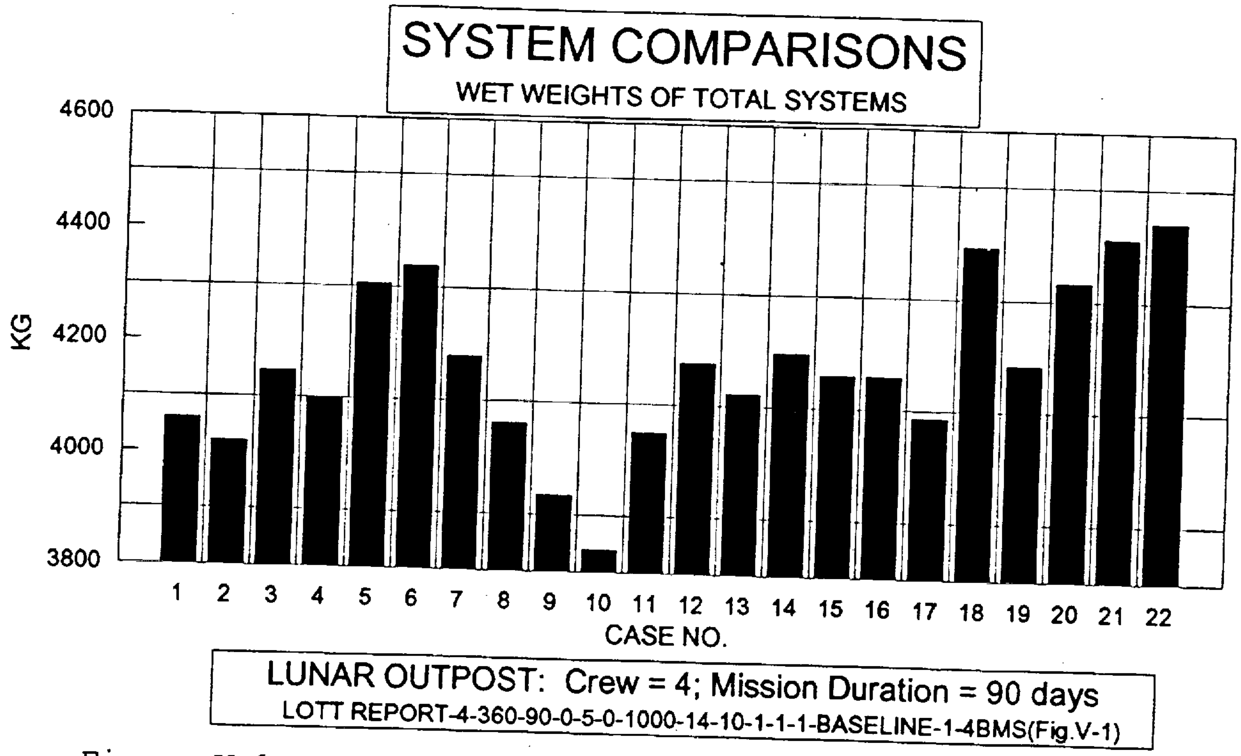


Figure V-1. Total System Weight Comparisons (90-day mission)

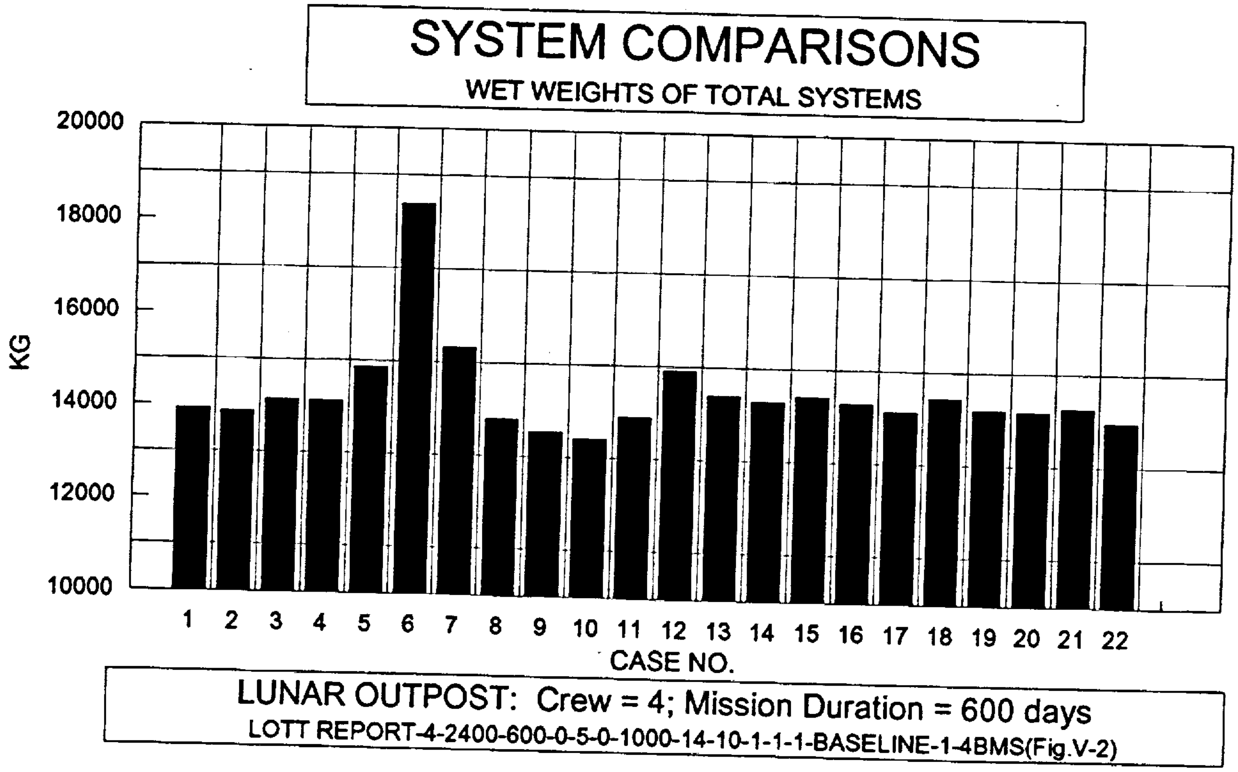


Figure V-2. Total System Weight Comparisons (600-day mission)

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.

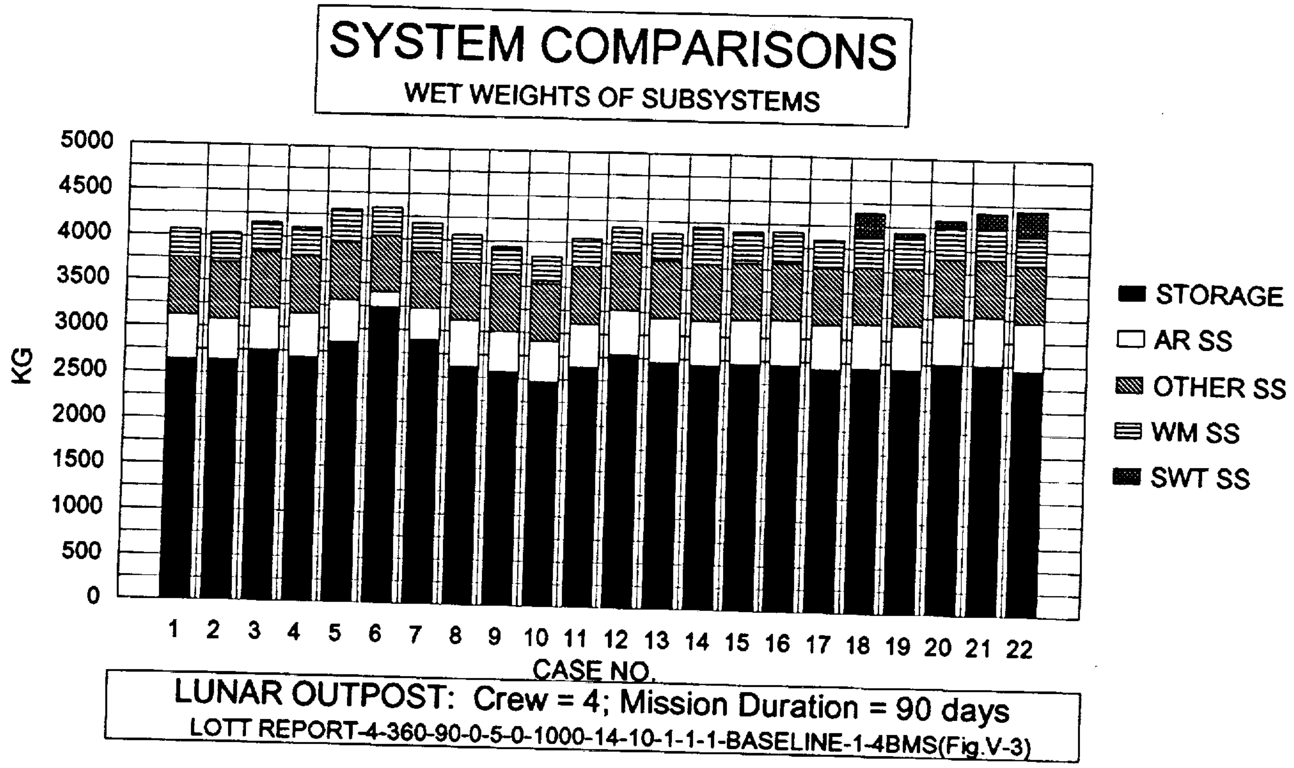


Figure V-3. Subsystem Weight Comparisons (90-day mission)

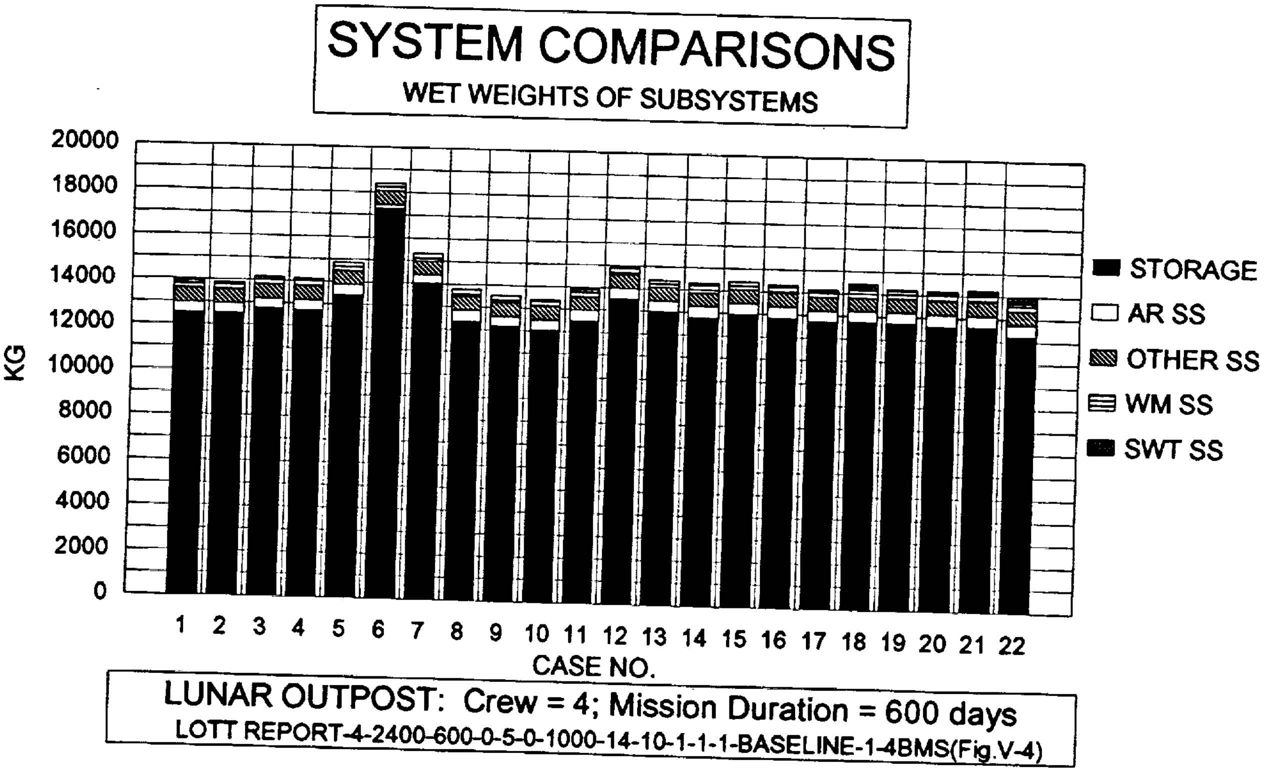


Figure V-4. Subsystem Weight Comparisons (600-day mission)

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.

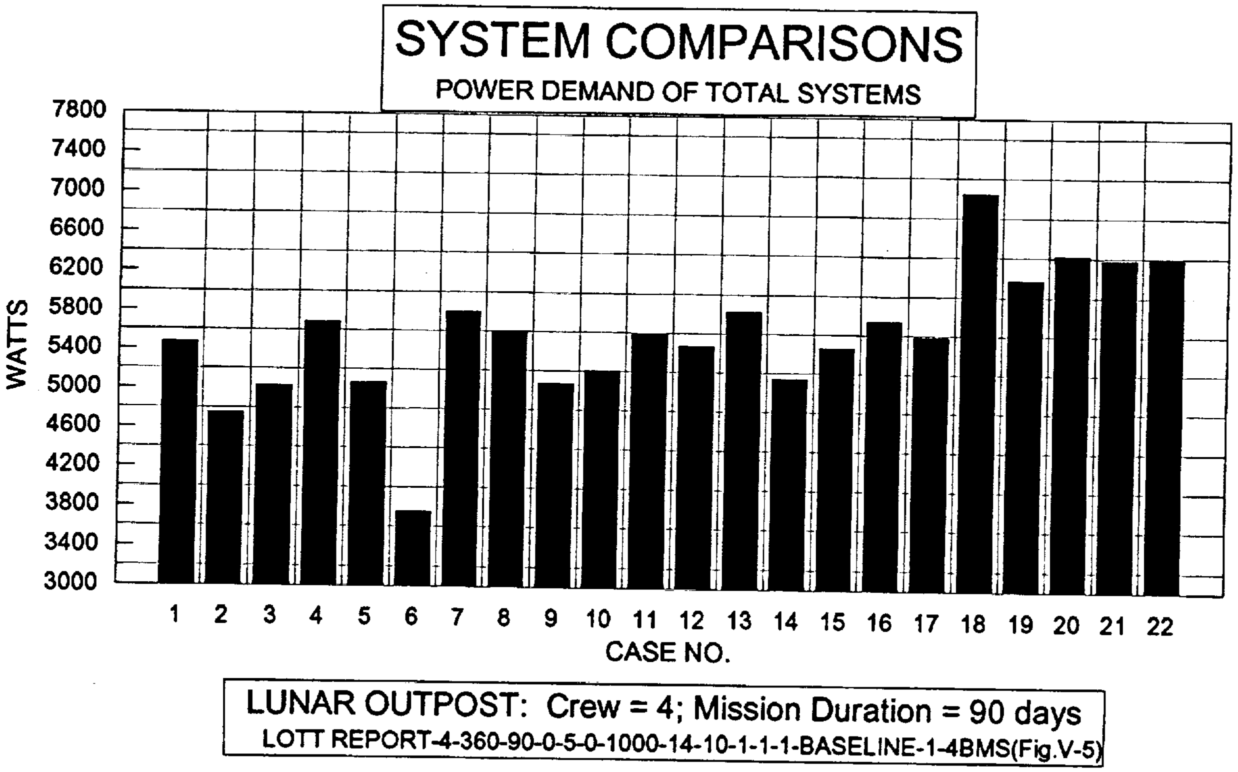


Figure V-5. System Power Comparisons (90- or 600-day mission)

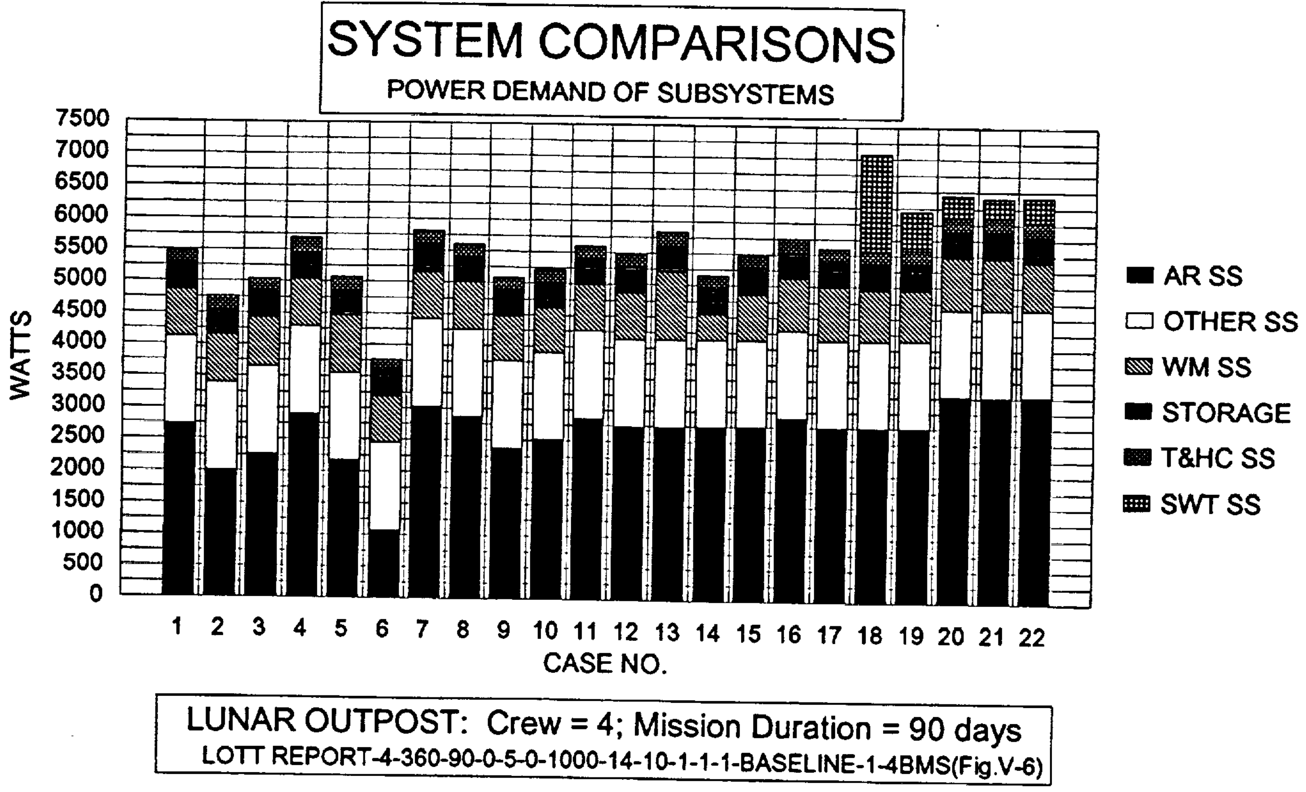


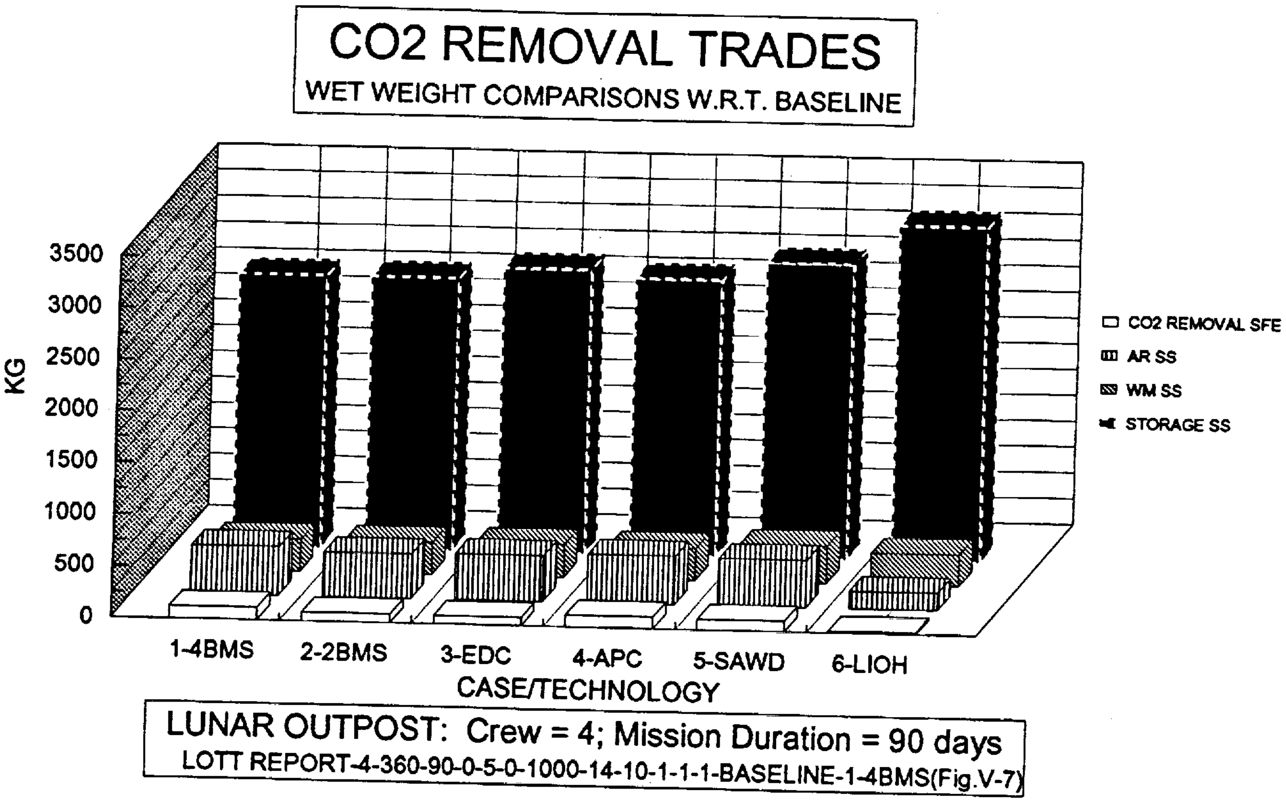
Figure V-6. Subsystem Power Comparisons (90- or 600-day mission)

2. CO_2 Removal Technology Trade

Six different technologies were included, as shown in Figure V-7 for wet weight and Figure V-8 for electrical power demand. These figures illustrate the impact of technology substitution on the various subsystems and the entire system: while a technology candidate can show significant weight or power advantages over other candidates at that functional level (e.g., CO_2 removal), the advantage may not be maintained through the subsystem (e.g., air revitalization) and through the entire life support system.

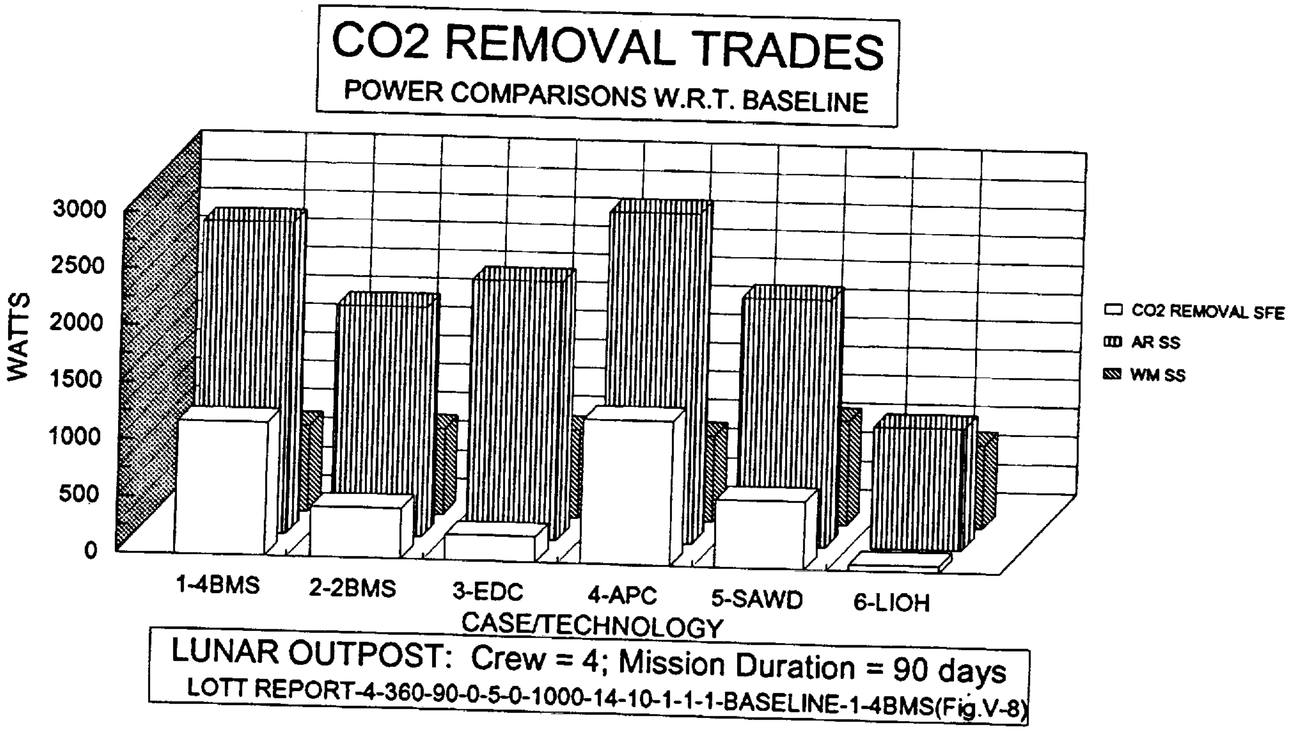
The wet weights of various systems considered for comparison of CO_2 removal technologies could differ by as much as 340 kg (for the 90-day mission) primarily due to differences in the demand for stored supplies and in the weight of process equipment. Differences in process equipment weights for the various CO_2 removal technologies are on the order of 100-300 kg. In addition to their impact on the AR subsystem, even the WM subsystem weights are seen to be affected somewhat by the choice of CO_2 removal technology. Such interactions between different subsystems cannot be recognized quantitatively by comparing the weight, power demand, etc. of individual technologies by themselves. For example, the solid amine water desorption (SAWD) process puts steam into the cabin air, which is condensed and the condensate becomes an additional load on the hygiene water processing unit, thereby increasing its weight and power demand. Because of the increased throughput, any nonregenerable chemicals used by hygiene water processing also increases and can be accounted for in the increased storage subsystem weight. The LiOH CO_2 removal technology is for nonregenerative capture of CO_2. The weight of the LiOH sorption equipment itself is small compared to the other regenerative CO_2 removal process units. However, since the process is nonregenerable, there is a high demand for LiOH canisters (as seen in the storage subsystem weight), which is directly proportional to crew size and mission duration.

Subsystem power demands also show significant differences. The power demand for the various CO_2 removal technologies is less by hundreds of watts compared to the baseline four-bed molecular sieve (4BMS) with the exception of the air polarized concentrator (APC). Even though the electrochemical depolarized concentrator (EDC) shows a marked decrease in power demand for the CO_2 removal SFE, the power advantage does not carry through exactly into the AR subsystem. EDC adversely affects the AR subsystem by requiring additional H_2 generation and thus increasing the size, throughput, and power demand on the water electrolysis unit. LiOH requires the minimum power for the SFE, AR subsystem, and the overall system since the LiOH technology has low power and the CO_2 reduction process is eliminated.


CO2 REMOVAL TRADES
WET WEIGHT COMPARISONS W.R.T. BASELINE

LUNAR OUTPOST: Crew = 4; Mission Duration = 90 days
LOTT REPORT-4-360-90-0-5-0-1000-14-10-1-1-1-BASELINE-1-4BMS(Fig.V-7)

Figure V-7. CO_2 Removal Trade Weight Comparisons


CO2 REMOVAL TRADES
POWER COMPARISONS W.R.T. BASELINE

LUNAR OUTPOST: Crew = 4; Mission Duration = 90 days
LOTT REPORT-4-360-90-0-5-0-1000-14-10-1-1-1-BASELINE-1-4BMS(Fig.V-8)

Figure V-8. CO_2 Removal Trade Power Comparisons

3. CO_2 Reduction Technology Trade

The baseline uses Bosch technology to recover O_2 as water condensate and is compared for subsystem weights and power demands to the Sabatier advanced carbon removal system (ACRS), and the CO_2 electrolysis/Boudouard (CO2EL/BD or CO2EL) process in Figures V-9 and V-10, respectively. The technology choice here has no intersubsystem impact except for the storage subsystem. The simplest of the four processes in terms of weight and power is the Sabatier process, which catalytically converts all of the CO_2 in its feed to CH_4 by reacting with H_2. However, the H_2 requirement places an additional burden on the O_2 generation SFE of the AR subsystem, thereby losing its advantage over other technologies. Since the CH_4 produced by Sabatier technology is vented as trash, the associated H_2 loss must be supplied by additional storage of hydrogen or preferably water, which is reflected in the higher storage subsystem weight. For the baseline system, using Bosch, there is a net requirement of 0.8 kg per day of makeup water for a crew of 4; with the Sabatier process, this makeup water increases to 3.7 kg per day. However, the Bosch process also requires chemical supplies in the form of canisters to collect the carbon formed in the process. These canisters account for 0.5 kg per day. Hence, the net consumables difference per day between the Sabatier and the Bosch processes is 2.4 kg, which amounts to over 200 kg for a 90-day mission. Another way of configuring the system with the Sabatier process would be to convert only part of the CO_2 produced. This scheme would take only available H_2 created from the O_2 generation SFE due to metabolic O_2 requirements. This would reduce the size of the O_2 generation unit significantly as the stoichiometric ratio of H_2/CO_2 requirement for Bosch is 2 and for Sabatier is 4 for complete CO_2 reduction. The impact would significantly affect the power requirements for the CO_2 reduction and H_2O electrolysis processes.

The ACRS and CO2EL processes show results comparable to the baseline Bosch process in terms of weight; ACRS shows slightly higher power than Bosch for both the SFE and AR subsystem, while CO2EL shows a higher SFE power but a slightly lower AR subsystem power.

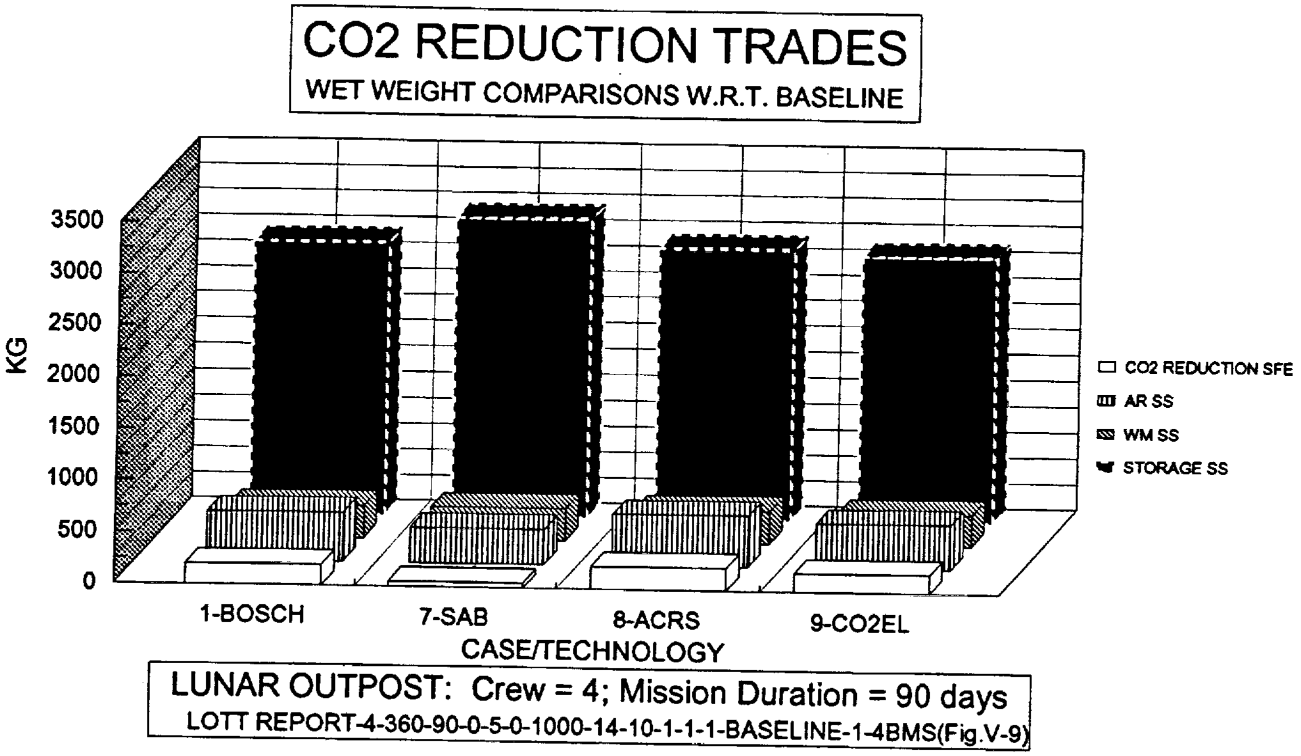


Figure V-9. CO_2 Reduction Trade Weight Comparisons

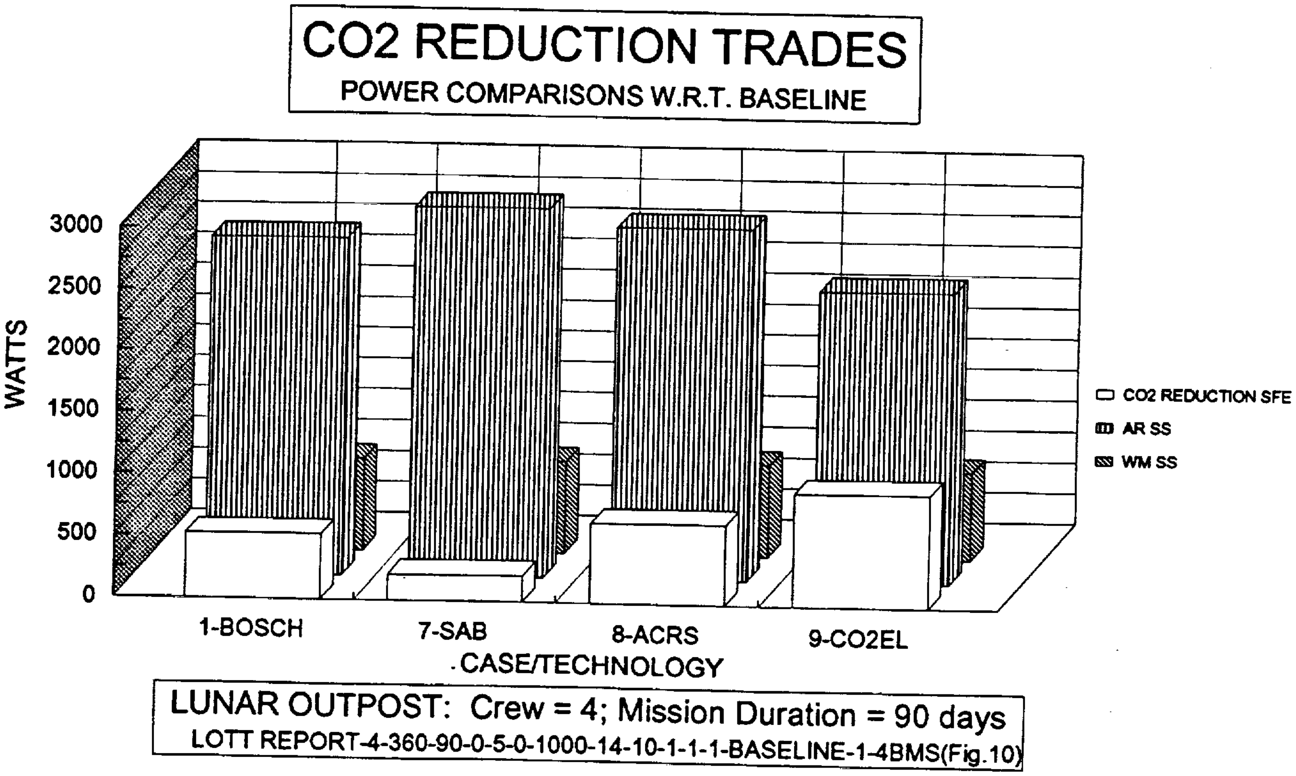


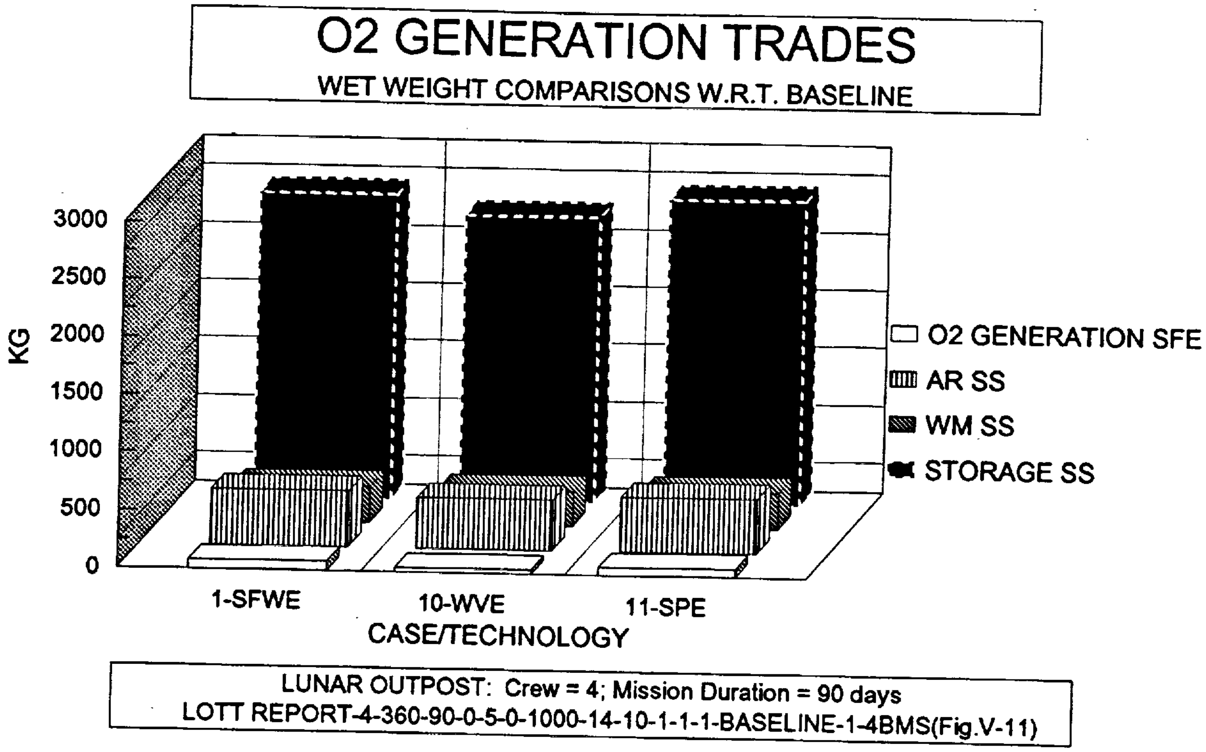
Figure V-10. CO_2 Reduction Trade Power Comparisons

4. O_2 Generation Technology Trade

The O_2 generation subsystem functional element uses the static feed water electrolysis (SFWE) process as its baseline. SFWE is compared to the subsystem weight and power parameters for water vapor electrolysis (WVE) and solid polymer electrolyte liquid feed (SPE) in Figures V-11 and V-12.

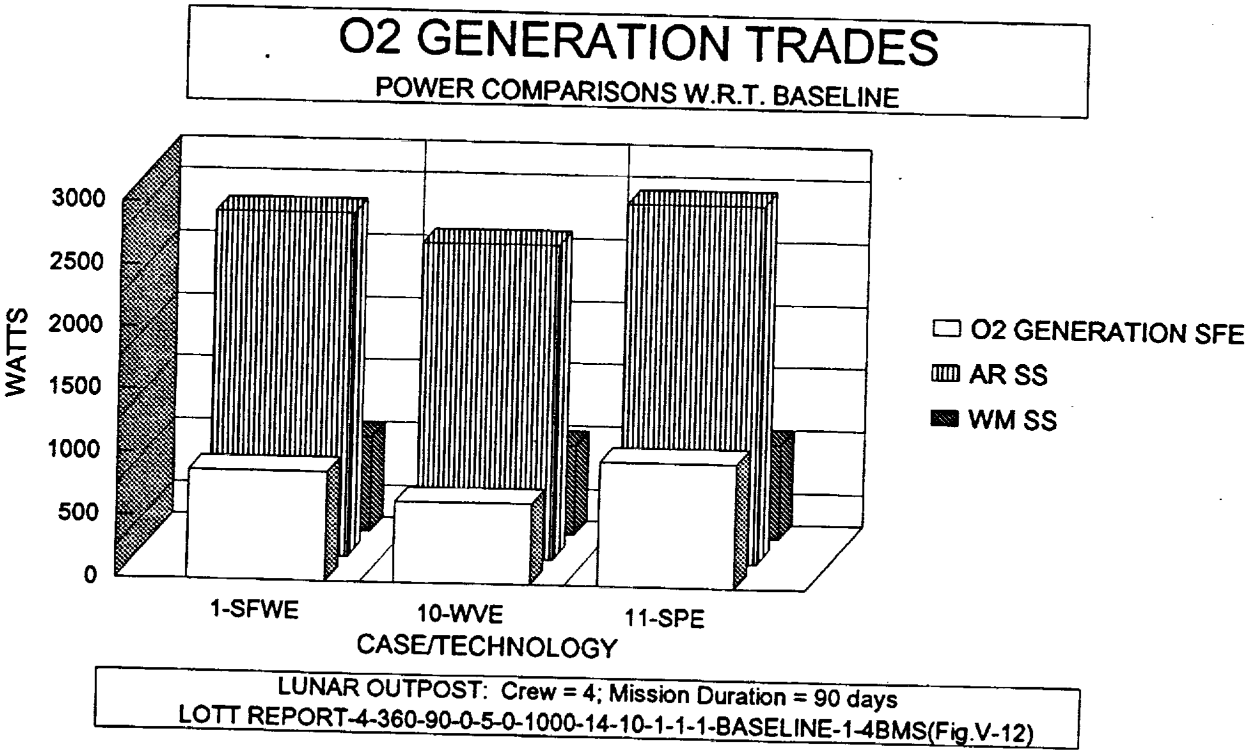
SFWE and SPE compare closely both in weight and power demand, with SFWE having only a slight advantage due to the lower weight and power demands at the SFE level. However, the WVE affects both the WM and storage subsystems because the WVE process draws water out of the cabin air and then electrolyzes the H_2O to H_2 and O_2. This avoids the condensation of atmospheric moisture and the subsequent cleaning of condensate water to standards of purity required for electrolysis. The net effect is to reduce the magnitude of condensate processing imposed on the WM subsystem and thereby reducing the WM subsystem weight, power, and chemical supplies by that required for condensate treatment. This then results in the lowest overall system weight as shown in Figures V-1 (90 days) and V-2 (600 days).

The comparison of power demand numbers shows that WVE results in significantly lower overall system power by over 200 watts. The primary reduction is seen at the O_2 generation SFE level. A slight reduction is also realized in the WM subsystem.



LUNAR OUTPOST: Crew = 4; Mission Duration = 90 days
LOTT REPORT-4-360-90-0-5-0-1000-14-10-1-1-1-BASELINE-1-4BMS(Fig.V-11)

Figure V-11. O_2 Generation Trade Weight Comparisons



LUNAR OUTPOST: Crew = 4; Mission Duration = 90 days
LOTT REPORT-4-360-90-0-5-0-1000-14-10-1-1-1-BASELINE-1-4BMS(Fig.V-12)

Figure V-12. O_2 Generation Trade Power Comparisons

5. Potable H_2O Processing Technology Trade

The subsystem functional element for potable water recovery uses multifiltration for potable water(MFPW or MF) as its baseline which is compared to the subsystem weights and power of reverse osmosis for potable water (ROPW or RO) and electrochemical deionization (ELDI) in Figures V-13 and V-14.

RO and ELDI recover less water (~90%) compared to the baseline value of 99.99%, thereby showing a higher storage subsystem weight to carry the extra makeup water not recovered; this represents about a 2 kg per day difference in water. However, the higher water recovery rate for MF is tempered by a higher demand for consumable chemicals (MF unibeds) compared to the RO. The weights computed for the potable water recovery SFE and for the WM and AR subsystem are similar for all the three processes; the storage subsystem is lowest for the MF as it recovers the most water.

Power demand for the MF and RO is essentially equal, while ELDI shows a significantly higher rate. Other SFEs and subsystems are not affected by the change in the technology candidate for potable H_2O processing. On the other hand, if it would be possible to route the RO brine from potable water processing to urine processing, then the overall water recovery could be increased at the expense of higher SFE weight and power demand of urine processing. It would also be possible to compute the mission duration for a break-even point where the reduced water supply requirement matches the increased weight and power demand (equating incremental power to weight) for urine processing.

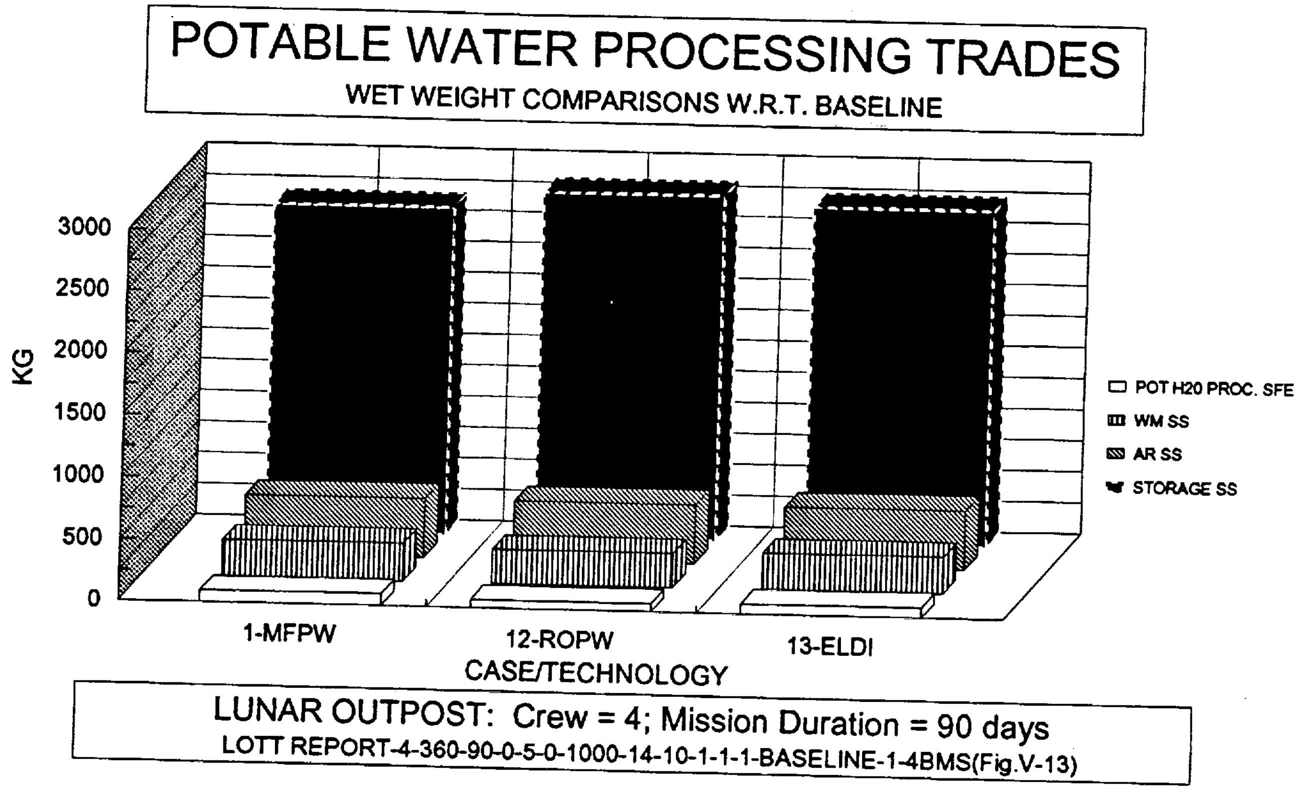


Figure V-13. Potable Water Processing Trade Weight Comparisons

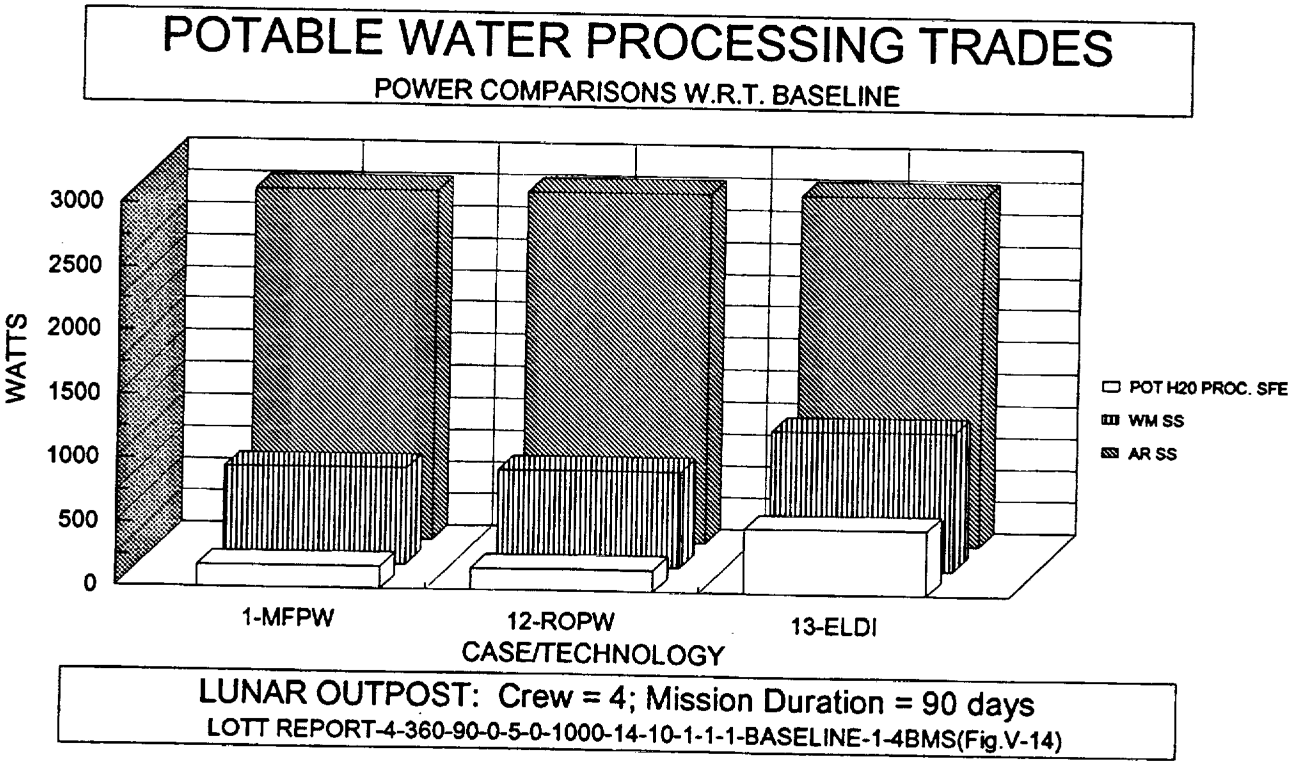


Figure V-14. Potable Water Processing Trade Power Comparisons

6. Hygiene H_2O Processing Technology Trade

The reverse osmosis for hygiene water (ROHW or RO) baseline process has a lower water recovery rate (93.5%) compared to the 99.99% recovery for multifiltration for hygiene water (MFHW or MF). By switching to MF, the system completely regenerates all the hygiene water requirement: in fact, an excess of H_2O is generated, which must be stored as trash or dumped overboard. For the baseline ROHW process, the makeup rate for four persons is 0.8 kg per day and for the MFHW process, there is no demand for makeup. However, in treating all of the wash waters, the MF process consumes an additional 1.1 kg per day of ion exchange and adsorption beds (unibeds), thereby causing a net increase in consumable supplies of 0.3 kg per day compared to the RO process. The overall impact on the storage subsystem is small (less than 50 kg). The primary weight difference between the two cases is mostly attributed to the weights of the RO and MF processes with the ROHW weighing about 100 kg more than the MFHW.

The power demands for RO and MF are compared in Figure V-16. The MF shows a power decrease relative to the RO process of over 300 watts at the SFE level. This difference accounts for the entire difference at the system level; i.e., the choice between RO and MF limits their comparison at the SFE level since neither of them have any impact on other SFEs or subsystems with respect to power demand.

An option for RO would be to route the RO brine to urine processing thereby increasing the overall H_2O recovery depending on the recovery rate of the urine processing technology selected.

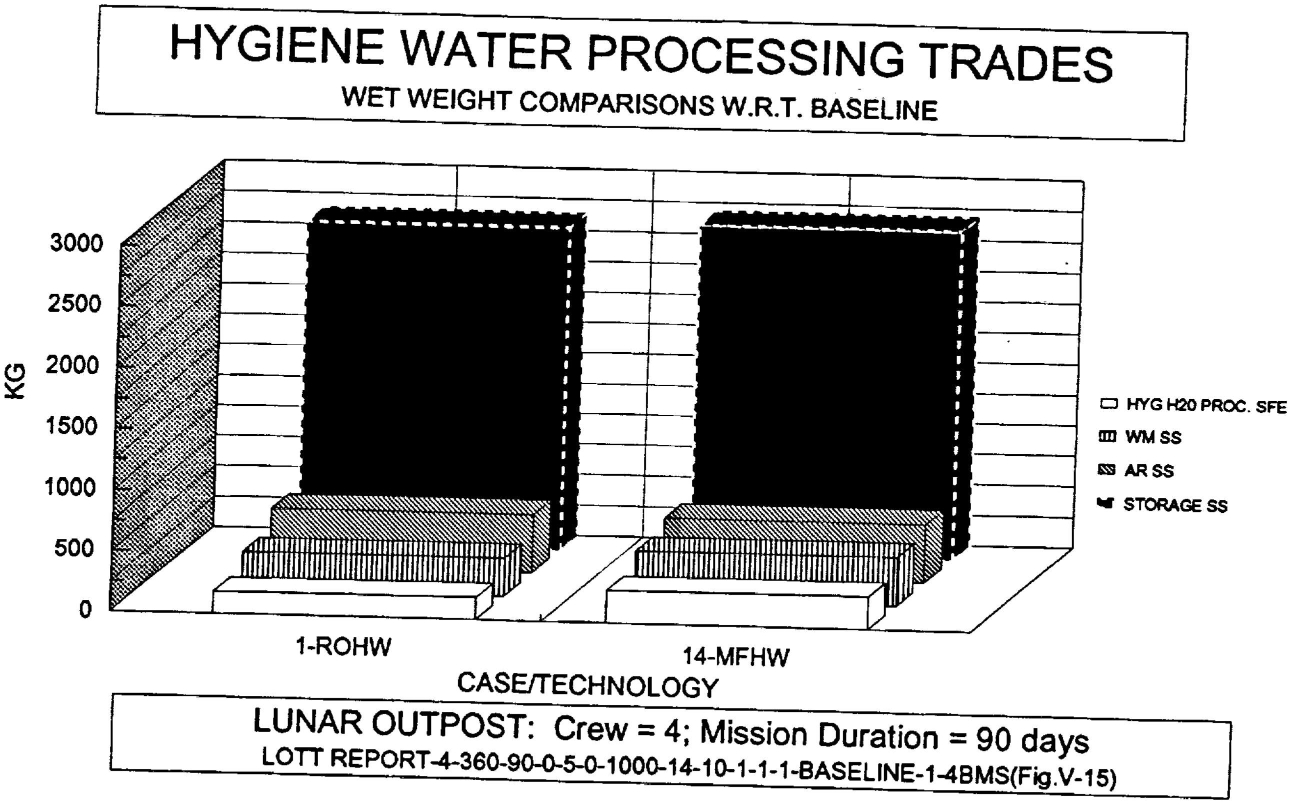


Figure V-15. Hygiene Water Processing Trade Weight Comparisons

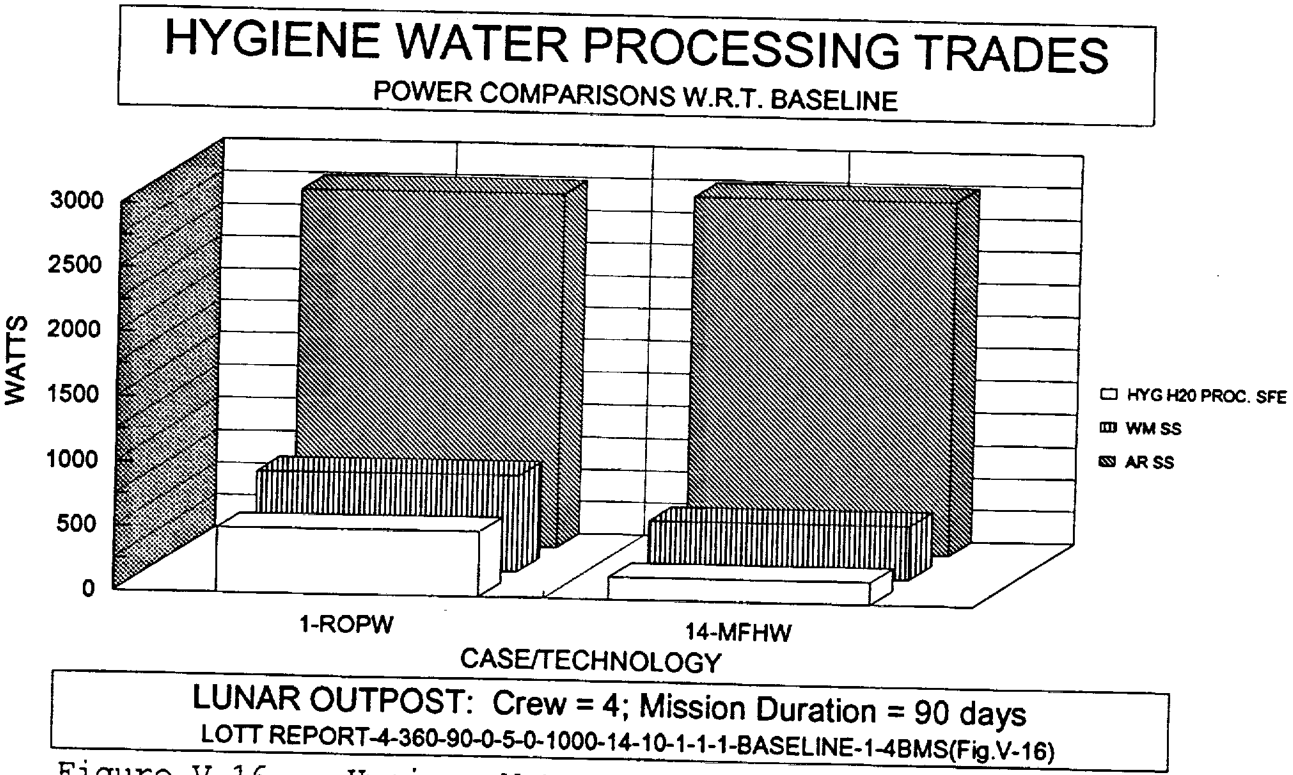


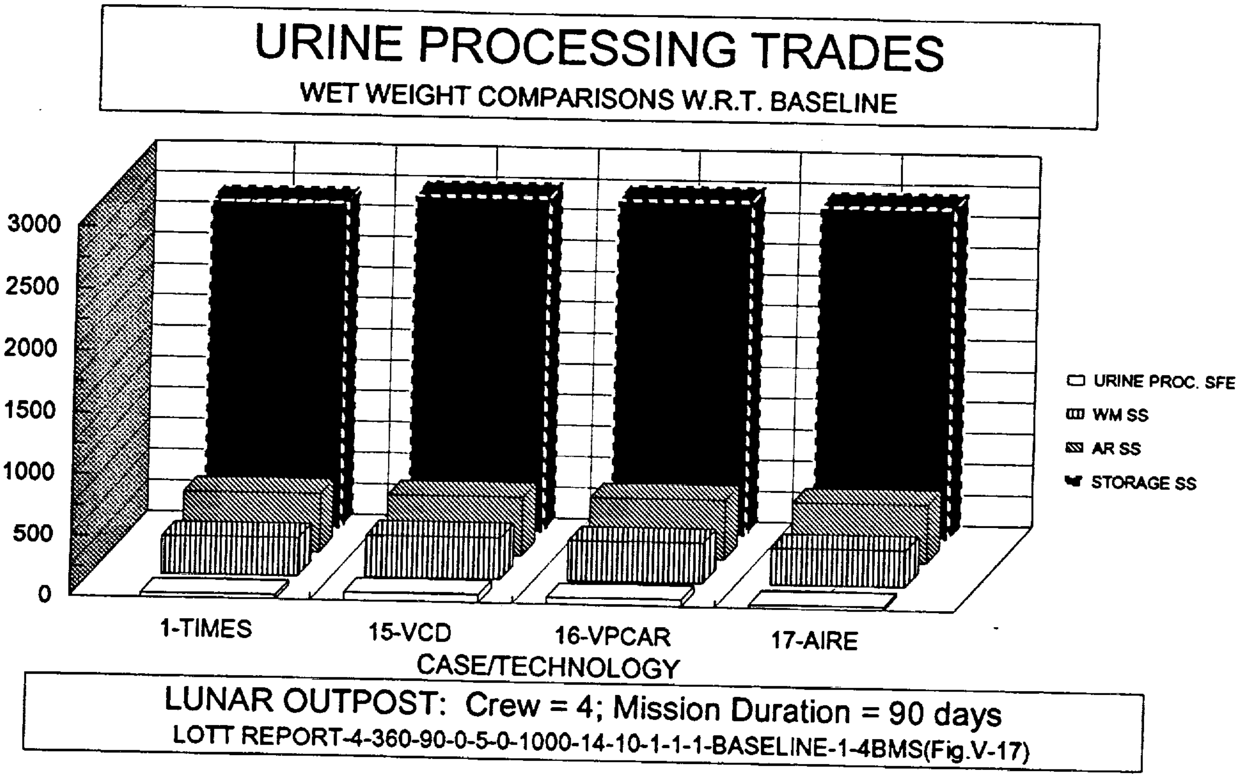
Figure V-16. Hygiene Water Processing Trade Power Comparisons

7. Urine Processing Technology Trade

Thermoelectric integrated membrane evaporation system (TIMES) technology, as the baseline for urine processing, was compared in terms of the impact of substitution with vapor compression distillation (VCD), vapor phase catalytic ammonia removal (VPCAR), and air evaporator (AIRE) processes in Figures V-17 and V-18.

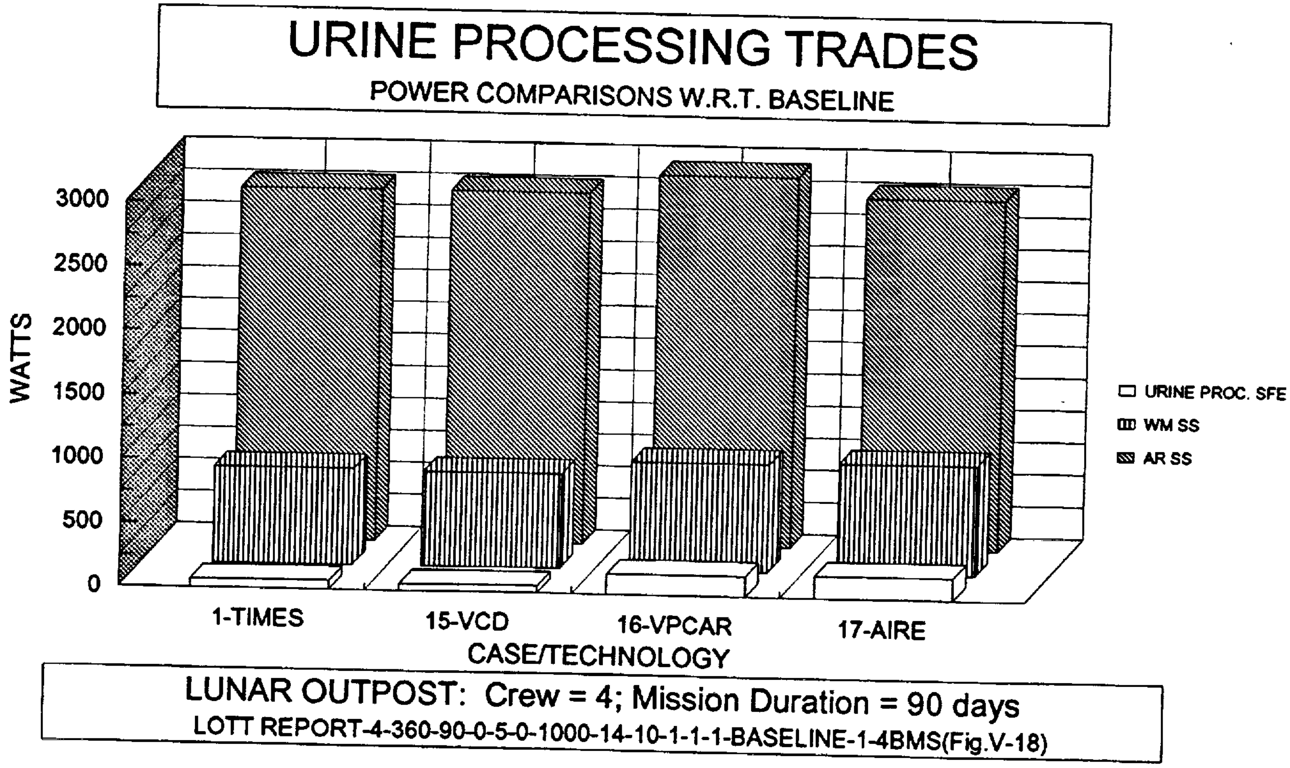
Water recovery rates for the TIMES baseline, VCD, VPCAR, and AIRE range from 90% for VCD and VPCAR to 99.9% for the AIRE process, respectively, resulting in small differences in storage subsystem weights relating to makeup water requirement. Makeup water for the TIMES baseline is 0.8 kg per day for a crew of 4; for VCD, VPCAR, and AIRE, the makeup rates are 1.5, 1.4, and 0.7 kg per day, respectively. While the AIRE has the highest water recovery, there is a significant weight associated with the use of wicks as a nonregenerable chemical supply that amounts to 0.6 kg per day. The overall weight effect is that the TIMES and AIRE cases are similar and the VCD and VPCAR are slightly higher due to lower water recoveries.

Power demand shows the AIRE and the VPCAR processes requiring about 100 watts more than the TIMES and the VCD for the urine processing SFE. VPCAR also requires slightly more power from the AR subsystem, as it requires additional oxygen generation for NH_3 oxidation.


URINE PROCESSING TRADES
WET WEIGHT COMPARISONS W.R.T. BASELINE

LUNAR OUTPOST: Crew = 4; Mission Duration = 90 days
LOTT REPORT-4-360-90-0-5-0-1000-14-10-1-1-1-BASELINE-1-4BMS(Fig.V-17)

Figure V-17. Urine Processing Trade Weight Comparisons


URINE PROCESSING TRADES
POWER COMPARISONS W.R.T. BASELINE

LUNAR OUTPOST: Crew = 4; Mission Duration = 90 days
LOTT REPORT-4-360-90-0-5-0-1000-14-10-1-1-1-BASELINE-1-4BMS(Fig.V-18)

Figure V-18. Urine Processing Trade Power Comparisons

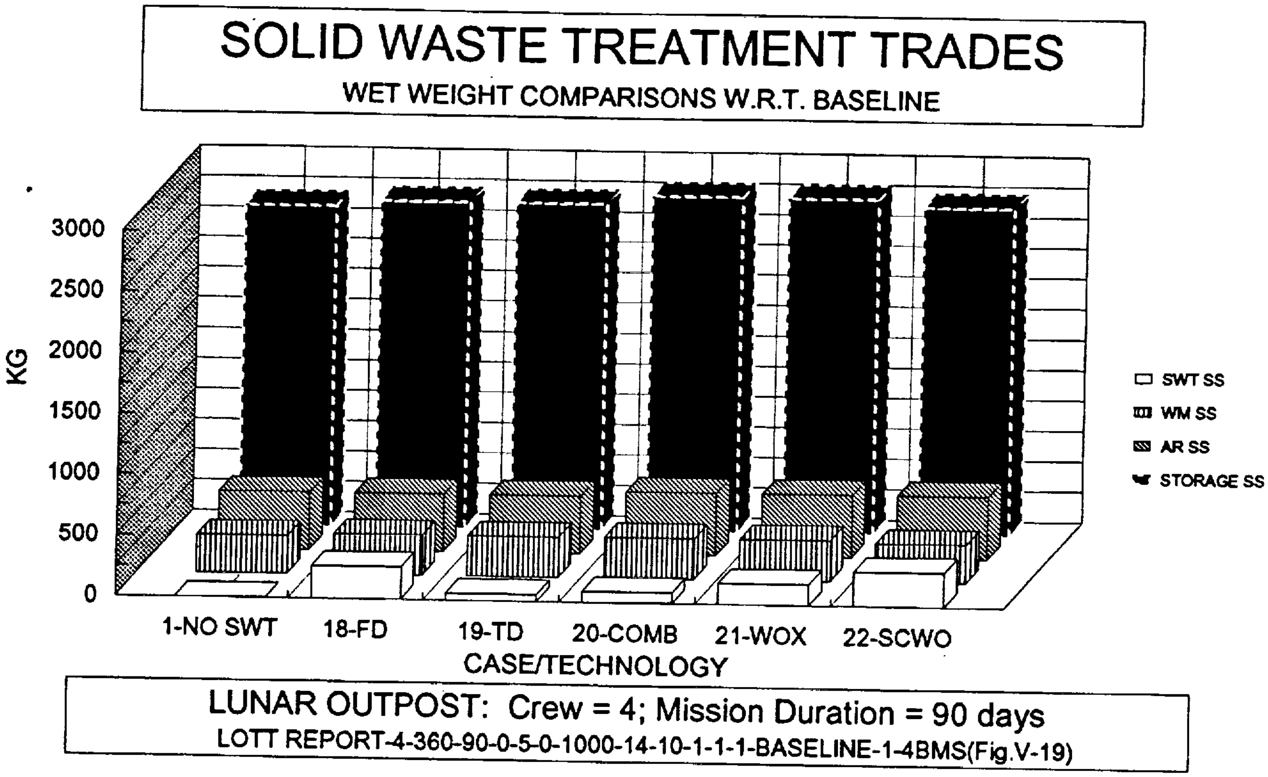
8. Solid Waste Treatment Technology Trade

The baseline system does not use solids waste treatment. In Figures V-19 and V-20, it is compared to subsystem weight and power demand for freeze drying (FD), thermal drying (TD), combustion (COMB), wet oxidation (WOX), and super critical water oxidation (SCWO).

System weight increases over the baseline are 260, 60, 90, 170, and 280 kg for FD, TD, COMB, WOX, and SCWO, respectively. For the FD and TD processes, the weight increases are mostly attributed to the weight of the drying equipment, as shown in Figure V-19. The drying processes produce water condensate that must be treated in the WM subsystem. In the case of the oxidation processes, additional condensate is produced by the oxidation of organic solids. The CO_2 and trace pollutant gases released by oxidation are considered to be a concentrated polluted gas stream that must be treated by trace contaminant control in the AR subsystem for pollutant oxidation, carbon rejection, and oxygen recovery. Hence, the oxidation processes affect both the WM and AR subsystems, while the drying processes impact the WM subsystem only.

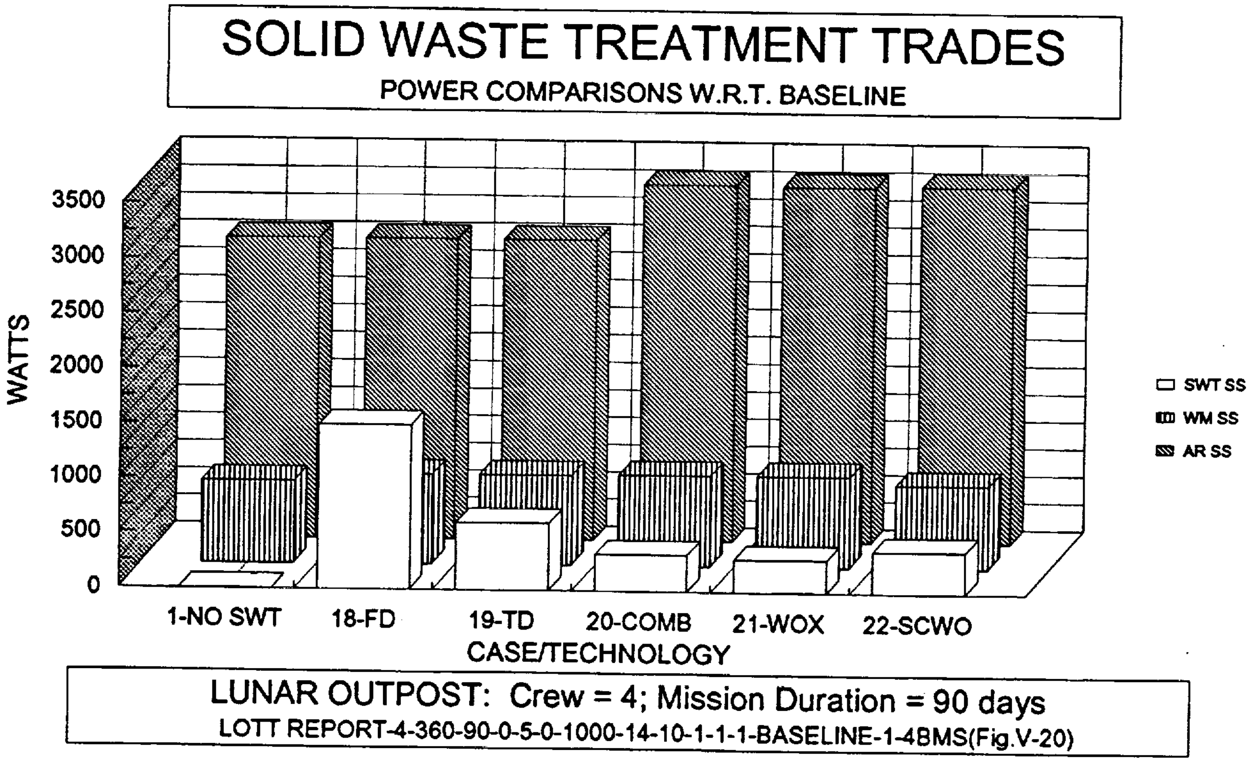
For the SCWO process, it has been reasonably assumed that the condensate produced from the process can be routed directly to the potable water bus where it could be mixed with other water produced from the WM subsystem such that an acceptable average water quality for potable water is achieved.

Storage subsystem weights are slightly higher (about 40 kg) than the baseline for the drying processes. The weight savings in makeup water is offset by the additional chemical supplies required for the SWT and WM subsystems. For the oxidation processes, the storage subsystem weights are higher by 110 kg for COMB and WOX and by only 50 kg for the SCWO process. Similar to the drying processes, the savings in makeup water weight is offset by the additional chemical supplies for SWT and WM subsystems; for SCWO, no additional chemical supplies for WM is required as its condensate is sent directly to the potable water bus without having it processed in the WM subsystem. However, since the oxidation process requires additional gas processing, storage weights of several waste gases (such as O_2, CO_2, H_2, and Concentrated Polluted Gas Mix) are slightly increased.


SOLID WASTE TREATMENT TRADES
WET WEIGHT COMPARISONS W.R.T. BASELINE

LUNAR OUTPOST: Crew = 4; Mission Duration = 90 days
LOTT REPORT-4-360-90-0-5-0-1000-14-10-1-1-1-BASELINE-1-4BMS(Fig.V-19)

Figure V-19. Solid Waste Treatment Trade Weight Comparisons


SOLID WASTE TREATMENT TRADES
POWER COMPARISONS W.R.T. BASELINE

LUNAR OUTPOST: Crew = 4; Mission Duration = 90 days
LOTT REPORT-4-360-90-0-5-0-1000-14-10-1-1-1-BASELINE-1-4BMS(Fig.V-20)

Figure V-20. Solid Waste Treatment Trade Power Comparisons

Increases in power demand over the baseline are 1580, 700, 950, 910, and 920 watts for FD, TD, COMB, WOX, and SCWO, respectively. The additional power demands attributed to the SWT subsystem alone are 1490, 600, 330, 290, and 370 watts, respectively. For the drying processes, the power increases are predominantly due to the drying processes themselves with a slight contribution from the WM subsystem for processing of additional water condensate. For the oxidation processes, more than half of the power increase can be attributed to the additional gas processing required of the AR subsystem; the power demand for oxidation contributes slightly less than half of the additional power required. For COMB and WOX, there is a slight additional power demand on the WM subsystem similar to the drying processes; for SCWO, there is no additional load placed on the WM subsystem as its product condensate goes directly to the potable water bus.

Surplus Water and Food-Water:

Feed to the SWT subsystem includes feces from the human habitat and brines from the WM subsystem. All SWT cases provide for additional water recovery leading to a surplus of water developed which must be trashed. For the drying processes (FD and TD), the surplus amounts to 5.7 kg per day for a crew size of 4. Table V-2 illustrates a metabolic balance for a crew size of 4. Note that the ratio of food-water content to dry-food constituents is 1.83. With this quantity of water contained in the stored food, there is an excess of water produced as a result of using solids waste processing. If it is assumed that stored food can be reduced significantly to levels such as freeze-dried food, then the weight of stored food and the amount of excess water produced will decrease accordingly.

Table V-2. Metabolic Balance for Crew of 4:
(1.83 food-water-to-dry-food ratio)

INPUTS:	CARBON (kg)	HYDROGEN (kg)	OXYGEN (kg)	NITROGEN (kg)	ASH (kg)	TOTALS (kg)
1. DRY FOOD						
Protein, C4H5ON	0.3080	0.0324	0.1028	0.0896		0.5328
Carbohydrate, C6H12O6	0.5956	0.1000	0.7936			1.4892
Fat, C16H32O2	0.3432	0.0576	0.0572			0.4580
Minerals, Ash					0.0380	0.0380
2. LIQUIDS (WATER)						
Drink		0.7208	5.7192			6.4400
Food Preparation		0.3536	2.8064			3.1600
Food Water Content (1.83*dry food)		0.5148	4.0852			4.6000
3. GASES						
Oxygen			3.3436			3.3436
INPUT SUMS	1.2468	1.7792	16.9080	0.0896	0.0380	20.0616
OUTPUTS:						
1. SOLID WASTES						
Urine, C2H6O2N2	0.0640	0.0160	0.0852	0.0748	0.0308	0.2708
Feces, C42H69O13N5	0.0708	0.0096	0.0292	0.0096	0.0072	0.1264
Sweat, C13H28O13N2	0.0296	0.0056	0.0396	0.0052		0.0800
2. LIQUIDS (WATER)						
Urine		0.6776	5.3764			6.0540
Feces		0.0408	0.3224			0.3632
Sweat & Perspiration		1.0296	8.1716			9.2012
3. GASES						
Carbon dioxide	1.0824		2.8836			3.9660
OUTPUT SUMS	1.2468	1.7792	16.9080	0.0896	0.0380	20.0616
Potable water recycled:		1.0744	8.5256			9.6000
Potable water with stored food:		0.5148	4.0852			4.6000
Total water in:		1.5892	12.6108			14.2000
Total water out:		1.7480	13.8704			15.6184
Net water metabolized:		0.1588	1.2596			1.4184
Excess water produced (HD):		0.6418	5.0940			5.7358

Lowering the Food Water Content:

Table V-3 shows the same metabolic balance using a ratio of 0.01 food-water-to-dry-food (0.01 is used here for illustration purposes and is not meant as a suggested food composition). In both tables, the crew is ingesting the same water and food and producing the same outputs. Decreasing the food water content requires an increase in the recycled potable water from 9.6 to 14.2 kg per day while decreasing the excess water produced from 5.7 kg to 0.5 kg per day if thermal drying is used for solid waste treatment. Note that 1.4 kg of water are created metabolically regardless of the food water content.

For the oxidation processes, the surplus is 6.2 kg per person day for the higher food water content. Creating this surplus comes at the expense of weight and power. The oxidation processes effectively create more water by oxidizing the solids waste to CO_2 and H_2O.

Table V-3. Metabolic Balance for Crew of 4:
(0.01 food-water-to-dry-food ratio)

INPUTS:	CARBON (kg)	HYDROGEN (kg)	OXYGEN (kg)	NITROGEN (kg)	ASH (kg)	TOTALS (kg)
1. DRY FOOD						
Protein, C4H5ON	0.3080	0.0324	0.1028	0.0896		0.5328
Carbohydrate, C6H12O6	0.5956	0.1000	0.7936			1.4892
Fat, C16H32O2	0.3432	0.0576	0.0572			0.4580
Minerals, Ash					0.0380	0.0380
2. LIQUIDS (WATER)						
Drink		0.7208	5.7192			6.4400
Food Preparation		0.8656	6.8692			7.7348
Food Water Content (0.01* dry food)		0.0028	0.0224			0.0252
3. GASES						
Oxygen			3.3436			3.3436
INPUT SUMS	1.2468	1.7792	16.9080	0.0896	0.0380	20.0616
OUTPUTS:						
1. SOLID WASTES						
Urine, C2H6O2N2	0.0640	0.0160	0.0852	0.0748	0.0308	0.2708
Feces, C42H69O13N5	0.0708	0.0096	0.0292	0.0096	0.0072	0.1264
Sweat, C13H28O13N2	0.0296	0.0056	0.0396	0.0052		0.0800
2. LIQUIDS (WATER)						
Urine		0.6776	5.3764			6.0540
Feces		0.0408	0.3224			0.3632
Sweat & Perspiration		1.0296	8.1716			9.2012
3. GASES						
Carbon dioxide	1.0824		2.8836			3.9660
OUTPUT SUMS	1.2468	1.7792	16.9080	0.0896	0.0380	20.0616
Potable water recycled:		1.5864	12.5884			14.1748
Potable water with stored food:		0.0028	0.0224			0.0252
Total water in:		1.5892	12.6108			14.2000
Total water out:		1.7480	13.8704			15.6184
Net water metabolized:		0.1588	1.2596			1.4184
Excess water produced (HD):		0.0507	0.4039			0.4546

9. 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 [reference V-1] 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. In this manner, penalties relative to the baseline system weights are compared for air revitalization, water management, and solid waste treatment technologies. Penalties therefore represent additional mass that must be lifted to the lunar surface relative to baseline technologies used in Case 1.

Air Revitalization Technologies:

Figure V-21 shows all of the AR technologies for the 4-person/600-day mission. For the CO_2 removal processes, the largest penalty relative to the baseline 4BMS is associated with LiOH. The 2BMS shows an advantage (negative penalty value) of 280 kg; most of these advantages are attributed to power.

For the CO_2 reduction processes, SAB shows a significant weight penalty relative to the Bosch baseline, while ACRS and CO2EL show total equivalent advantages of 80 and 500 kg respectively.
For the O_2 generation technologies, the WVE shows a significant total equivalent advantage of 600 kg relative to the SFWE baseline. This advantage is mostly attributable to lower storage supplies for water processing of condensate; the WVE process effectively removes moisture from the air, thereby reducing the amount of condensate to be treated in potable water processing. SPE is essentially identical to SFWE.

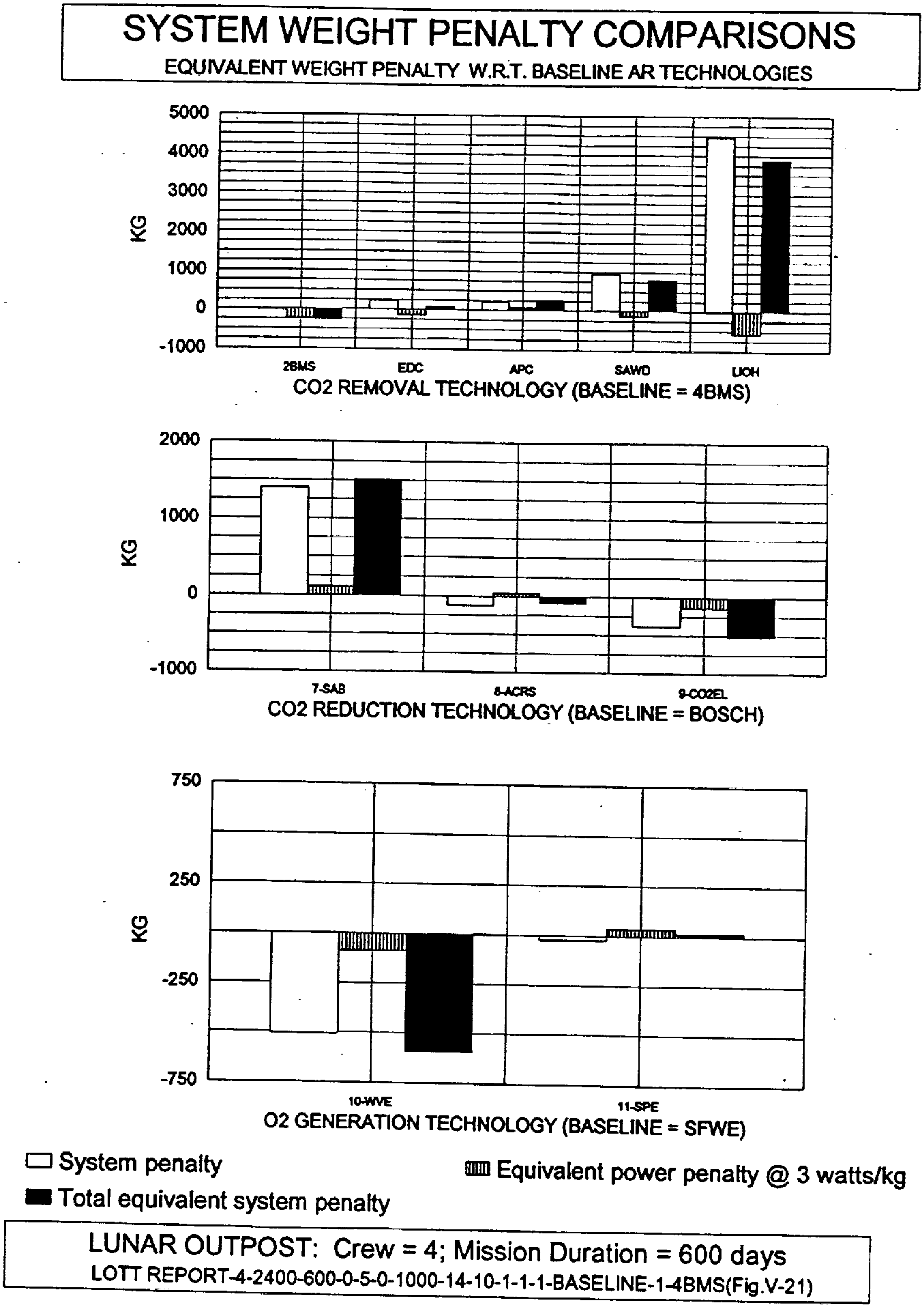


Figure V-21. Equivalent System Weight Comparisons: Air Revitalization Technologies

Water Management Technologies:

Figure V-22 shows the total equivalent system penalties for all of the WM technologies. For the potable water processes, the weight disadvantages are due to lower water recoveries; since brines are not processed in this configuration, unrecovered water must be made up from storage.

For the hygiene water processes, there is a penalty of using MF relative to RO for using additional unibed material (which shows up as a consumable item in the storage subsystem). However, there is a power advantage of the MF system that roughly decreases the disadvantage of storage supplies by one-third.

For the urine processing technologies, equivalent power weights are similar to the baseline at the system level. Differences in system level penalties for VCD and VPCAR are attributed to water recoveries. For the AIRE process, even though the water recovery is nearly 100%, there is a penalty associated with expendable wicks amounting to over 200 kg.

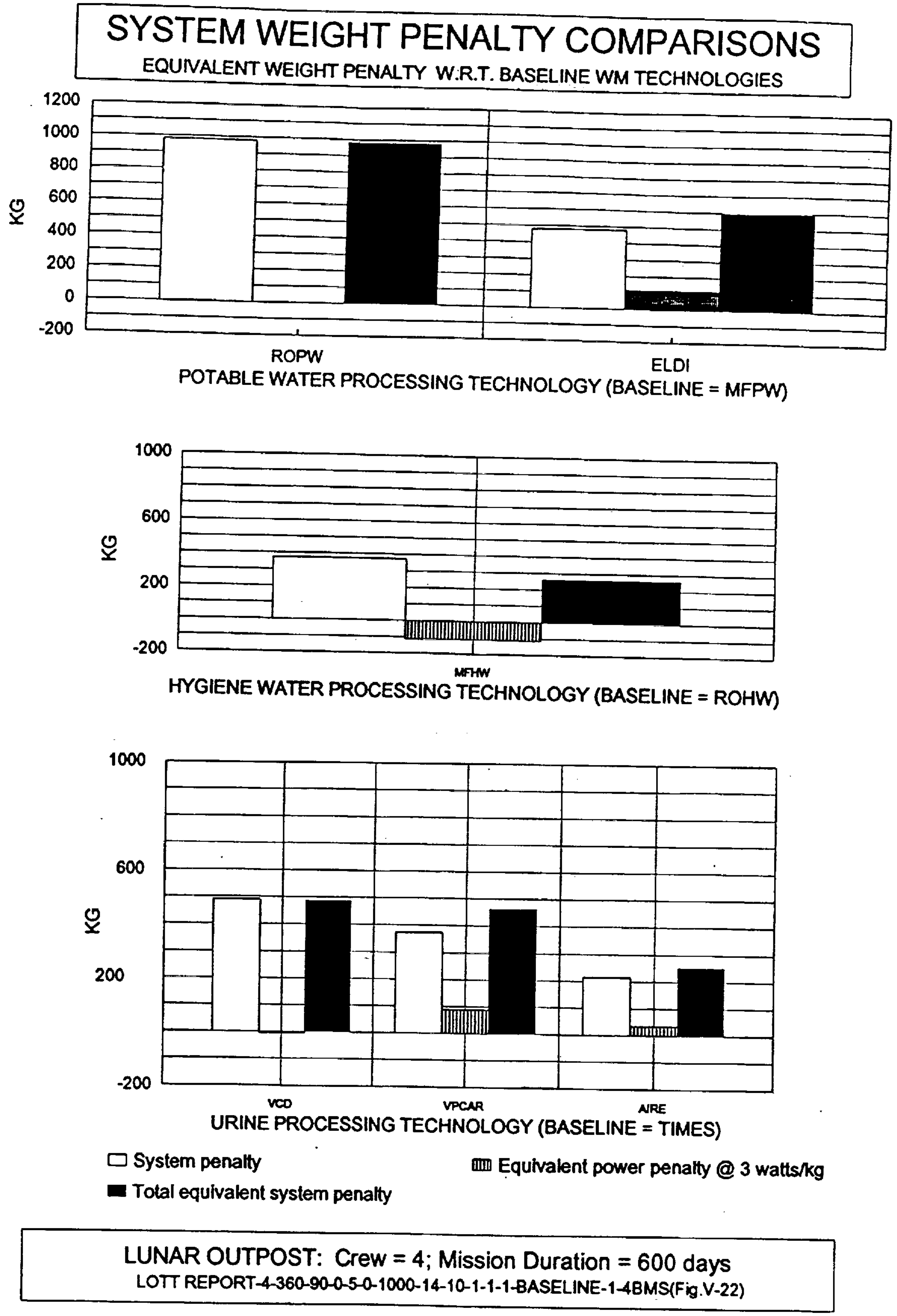


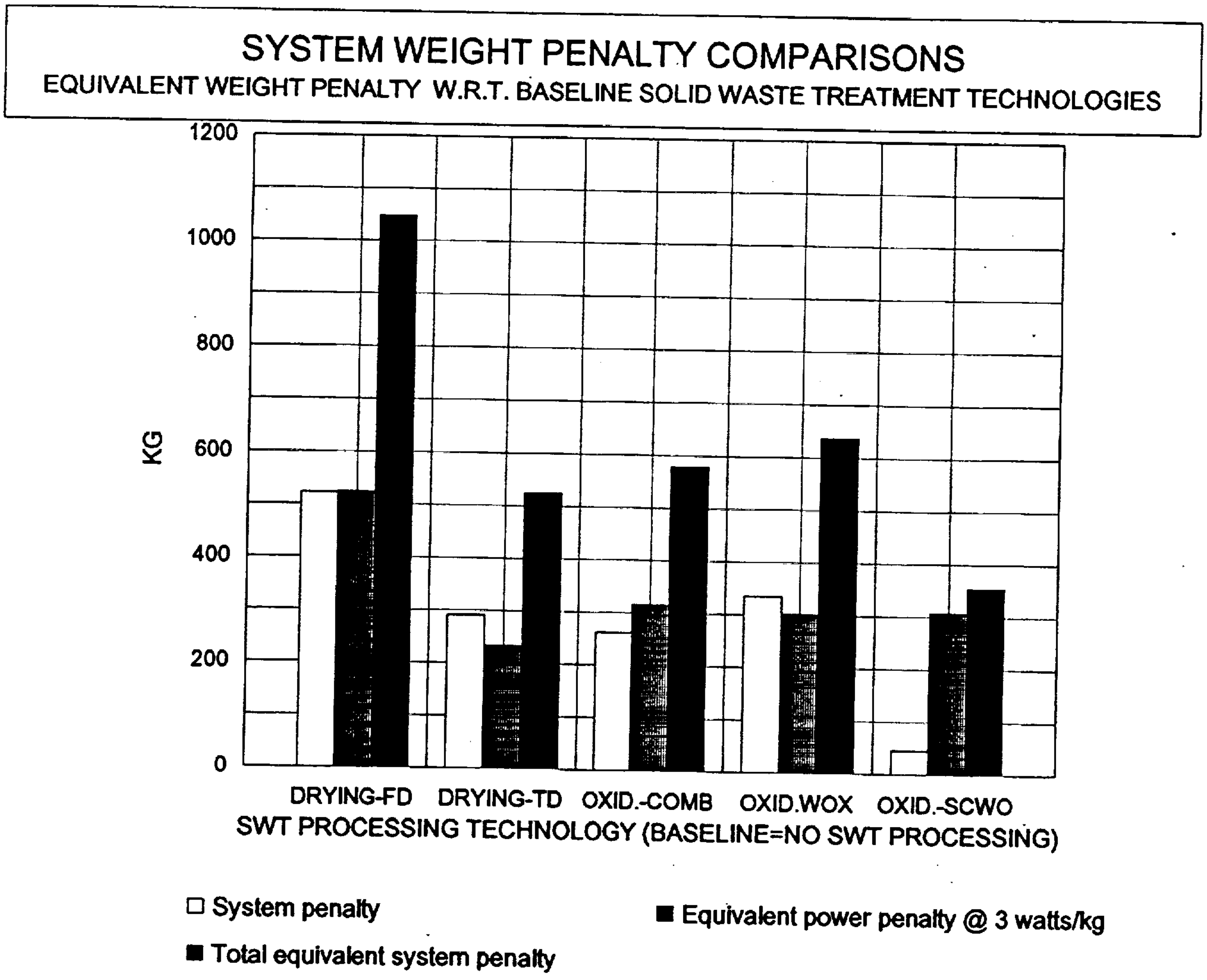
Figure V-22. Equivalent System Weight Comparisons: Water Management Technologies

Solid Waste Treatment Technologies:

Figure V-23 shows the total equivalent system penalties for all of the SWT technologies. The drying processes (FD and HD) and the oxidation processes (COMB, WOX, SCWO) are compared to the baseline, which has no solid waste treatment.

SWT technologies show total equivalent penalties ranging from 350 kg to over 1050 kg. As discussed above, by introducing SWT processing, a surplus of clean water is produced; this surplus could be reduced by decreasing the amount of water in stored food. Power equivalent for the oxidation processes are similar (300 kg); however, due to the reported ability of SCWO to create near-potable quality water, system weight of the SCWO is lowest.

The weight advantage for SCWO is dependent upon the mission duration and the assumption that SCWO condensate does not require further treatment. At 90 days, the weight of the SCWO hardware dominates any weight advantage gained by producing clean condensate as shown in Figure V-24. At 90 days, the overall SCWO system weight penalty (excluding the equivalent power penalty) is 480 kg; when the mission length is increased to 600 days, the use of SCWO results in the penalty decreasing to 50 kg over the baseline as shown in Figure V-23. By increasing the mission duration to 700 days, the system weight penalty for SCWO goes to zero and becomes an advantage. However, the power penalty would still result in the SCWO having a total equivalent weight penalty of about 300 kg. In order for SCWO to have a weight advantage, mission lengths of about 1200 days for a crew size of four would be required. However, if it is assumed that the SCWO condensate requires additional cleanup before being accepted as either potable or hygiene water, then it is unlikely that any system weight advantages will be realized.



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-23)

Figure V-23. Equivalent System Weight Comparisons: Solid Waste Treatment Technologies

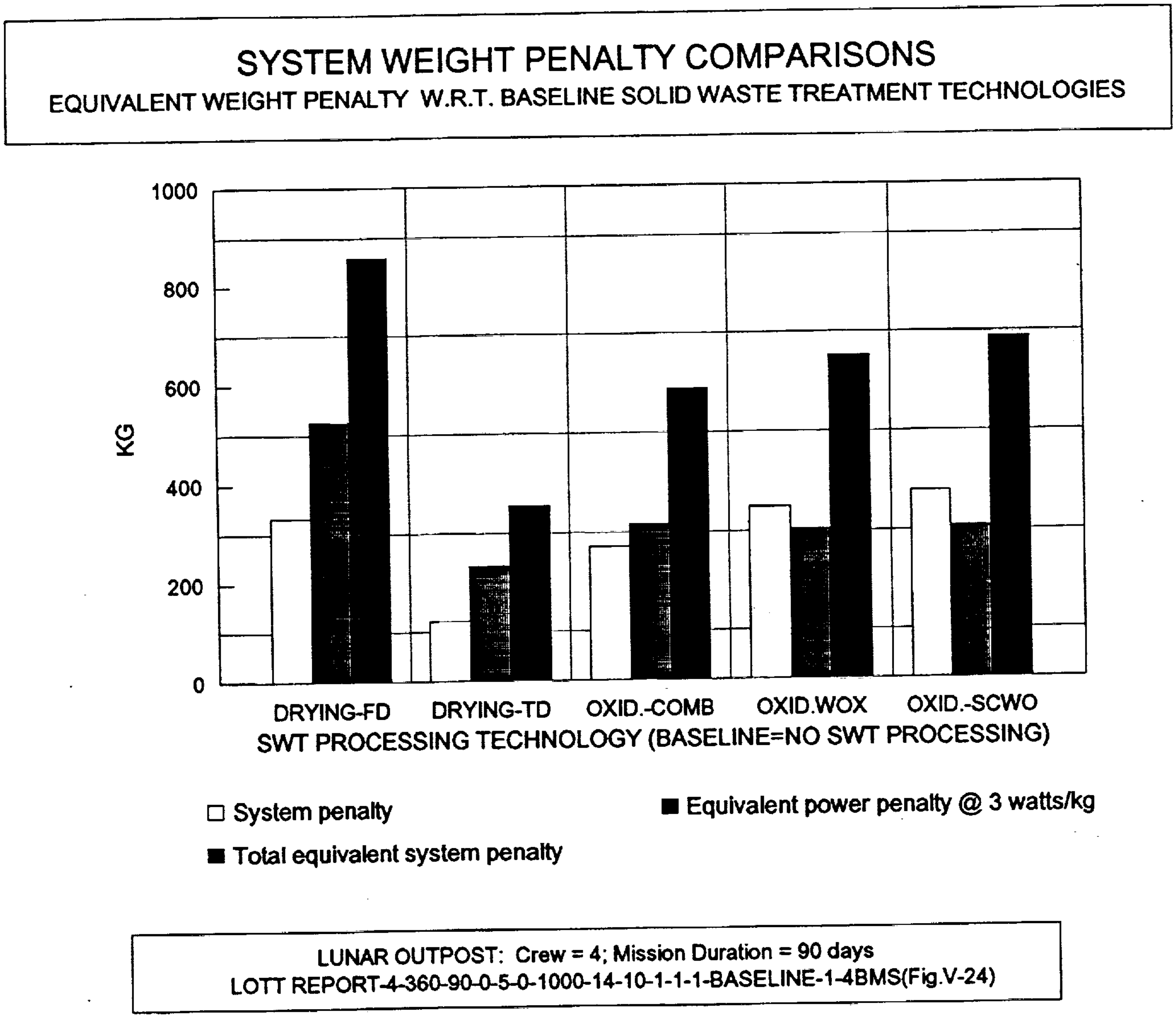


Figure V-24. Equivalent System Weight Comparisons: Solid Waste Treatment Technologies (90 days)

VI. CONCLUSIONS AND RECOMMENDATIONS

1. Conclusions

As all of the regenerative technologies used in this study are still under development, conclusions concerning the best technologies must be revisited following significant progress in technology development. Hence, identifying a less-developed technology as having an advantage over a more-developed technology must be seen only as identifying a potential advantage that could be realized only by further investment in technology development. Some of the technologies are currently included in the design of the Space Station and therefore represent considerable technological maturity. Some technologies are conceptual in nature with varying degrees of uncertainty associated with the data collected on these technologies; the degree of data uncertainty is qualitatively represented by the validity level ranking.

A baseline set of technologies has been used against which comparisons have been made with a crew size of four. The baseline technologies are:

- Air Revitalization Subsystem:
  - CO_2 Removal: Four Bed Molecular Sieve
  - CO_2 Reduction: Bosch
  - O_2 Generation: Static Feed Water Electrolysis
- Water Management Subsystem:
  - Potable Water Processing: Multifiltration
  - Hygiene Water Processing: Reverse Osmosis
  - Urine Processing: Thermoelectric Integrated Membrane Evaporation System
- Solid Waste Treatment Subsystem:
  - Drying: None
  - Oxidation: None.

For the 21 regenerative cases run (Case 6, using lithium hydroxide is considered nonregenerative), overall regenerative system weights vary from a -5 to a +9 weight% relative to the baseline weight of 4060 kg for 90 days; for 600 days, the variation from the baseline weight of 13,920 kg varied from a -4 to a +10 weight%. For the nonregenerative case where lithium hydroxide was used for CO_2 removal, the system weight penalty was 7 weight% for 90 days and 32 weight% for 600 days.

Overall system power varied from a -8% to a +29% relative to the baseline power of 5470 watts (excluding the nonregenerative LiOH case). When comparing only air revitalization and water management technologies, the variation narrows to -8 to +6%.

Regenerative technologies showing significant weight advantages include CO_2 electrolysis/Boudouard and water vapor electrolysis. Regenerative technologies showing significant power advantages include two bed molecular sieve, electrochemical depolarized concentrator, solid amine water desorption, co_2 electrolysis/Boudouard, and multifiltration hygiene water.

When power is equated to equivalent weight (3 watts/kg for a regenerative fuel cell system) and added to the system weight, the two bed molecular sieve, co_2 electrolysis/Boudouard, and water vapor electrolysis have advantages over the baseline for long durations.

For mission durations below 700 days, there are no overall weight advantages realized by solid waste treatment processing. The decision to include solid waste treatment must therefore be based on considerations other than system weight reduction. For mission durations beyond 700 days, supercritical water oxidation technology is attractive relative to the baseline as it may produce a high quality water condensate. However, the high power and safety issues arising from the high pressure operation of the supercritical water oxidation must be balanced against its weight advantages. Total equivalent weight advantages of supercritical water oxidation relative to the baseline would require extremely long durations of over 1200 days.

Table VI-1 summarizes advantages, disadvantages, and validity levels of the technology choices for the CO_2 removal, CO_2 reduction, and O_2 generation functions.

Table VI-1. Comparisons of Air Revitalization Subsystem Technologies

SFE	TECHNOLOGY	ADVANTAGES	DISADVANTAGES	VALIDITY LEVEL
CO_2 Removal	Four Bed Molecular Sieve	Maturity; Space Station development	SFE Power	3
" "	Two Bed Molecular Sieve	SFE weight SFE power	Maturity	4
" "	Electrochemical Depolarized Concentrator	SFE power	Effect on AR power Maturity H2 Required	4
" "	Air Polarized Concentrator	---	Maturity	7
" "	Solid Amine Water Desorption	SFE power	Effect on WM-consumables Maturity	7
" "	Lithium Hydroxide	SFE power; AR power; Maturity	Nonregenerative, consumables	3
CO_2 Reduction	Bosch	Carbon and oxygen recovery	Catalyst activity Consumable canister	3
" "	Sabatier	Maturity: Space Station development SFE simplicity	Effect on AR subsystem High H_2 to CO_2 ratio	3
" "	Advanced Carbon Reactor System	Low consumables	Maturity Two reactors, complexity	4
" "	CO2 Electrolysis/ Boudouard	Produces oxygen; Low consumables due to WM subsystem effect; Low AR power	Maturity High SFE power	7
O2 Generation	Static Feed Water Electrolysis	Maturity:Space Station development	High SFE power	3
" "	Water Vapor Electrolysis	Low SFE and AR subsystem power; Low consumables due to WM subsystem effect	Maturity	7
" "	Solid Polymer Electrolyte	Stable long term cell activity; Maturity (submarines)	Slightly higher SFE power	7

Note: SFE = Subsystem Functional Element
AR = Air Revitalization
WM = Water Management

Table VI-2 summarizes advantages, disadvantages and validity levels of the technology choices for the potable water processing, hygiene water processing, and urine processing functions.

Table VI-2. Comparisons of Water Management Subsystem Technologies

SFE	TECHNOLOGY	ADVANTAGES	DISADVANTAGES	VALIDITY LEVEL
Potable Water Processing	Multifiltration	H_2O recovery Maturity: Space Station development	Consumables	3
" "	Reverse Osmosis	Low consumables; Maturity (H_2O desalinization)	H2O recovery	3
" "	Electrochemical Deionization	H_2O recovery	Maturity; SFE Power	7
Hygiene Water Processing	Reverse Osmosis	Maturity: water desalinization	Power	3
" "	Multifiltration	Maturity: Space Station development; H_2O recovery	Consumables	3
Urine Processing	Thermoelectric Integrated Membrane Evaporation System	H_2O recovery	Maturity; Membrane fouling	3
" "	Vapor Compression Distillation	Maturity: Space Station development	Complexity (mechanical)	3
" "	Vapor Phase Catalytic Ammonia Removal	Volatiles treatment	H2O recovery; SFE power; Maturity	7
" "	Air Evaporation	High H_2O recovery	Maturity; Consumables	7

Note: SFE = Subsystem Functional Element

Table VI-3 summarizes advantages, disadvantages and validity levels of the technology choices for the drying and oxidation functions within the solid waste treatment subsystem.

Table VI-3. Comparisons of Solid Waste Treatment Subsystem Technologies

SFE	TECHNOLOGY	ADVANTAGES	DISADVANTAGES	VALIDITY LEVEL
Drying	Freeze Drying	Condensate quality; Maturity (other medical lab applications)	Maturity; SFE weight; SFE power; Unreacted solids disposal	7
"	Thermal Drying	Potential to use low grade heat	Condensate purity; Maturity; SFE weight; SFE power; Unreacted solids disposal	7
Oxidation	Combustion	Low pressure; Minimizes hazardous solids	Maturity; SFE weight; SFE power; High temperature; Condensate quality	7
"	Wet Oxidation	Maturity (other waste water applications); Minimizes hazardous solids	High pressure ; Maturity; SFE weight; SFE power	7
"	Super Critical Water Oxidation	Condensate quality; Minimizes WM consumables; Maturity (other waste water applications); Minimizes hazardous solids; Nearly complete organic destruction	High pressure; High temperature; Maturity; SFE weight; SFE power	7

Note: SFE = Subsystem Functional Element
AR = Air Revitalization
WM = Water Management

2. Recommendations

The following recommendations are based on the authors' observations not only during the performance of this study but also as the LiSSA tool was being developed:

1. ***As technologies are funded for development, it is important to require contractors to generate and report data that can be utilized for quantitative technology comparisons.*** Estimates of heat and material balances, equipment weights, power, volumes, and scaleup parameters should be a part of the technology development effort. It is suggested that NASA technical monitors add a "NASA Perspective" summary page to the final report such that any overly optimistic or conservative estimates or performances can be identified.

2. ***In general, technology development directions should be aimed at reducing the weight of resupplies.*** Nonregenerable supplies impose additional weight to be carried by a spacecraft plus additional manpower required for resupply operations.

3. ***Technology development should be directed to outperform the current best technology or a carefully selected baseline technology.*** Baseline technologies should be identified that have well documented weights, power usage, volume, feed and product characterizations, in addition to quantitative scaleup procedures.

4. ***Basic research should be directed towards identification and use of lighter materials of construction, minimization or elimination of resupplies, and minimization of power demand.*** Basic research is needed, for example, in the regeneration of sorption beds and membrane fouling for water purification, and Bosch carbon deposition kinetics and catalysts for air revitalization.

5. ***The effects of process dynamics on technology trades should be examined.*** Most of the processes investigated do not operate in a continuous mode and must deal with fluctuating feed rates and compositions. However, processes that can be designed to be continuous tend to be lighter and energy efficient. If the dynamics of the process and the fluctuating feed rates and compositions can be modeled so that effective control strategies are possible, the advantages of a continuous process design can be realized.

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. An example of extending LiSSA to biological systems in shown in Reference ES-1, and trade studies for different lunar habitats are presented in Reference VI-1. 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.***

VII. REFERENCES

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APPENDIX A

DESCRIPTION OF LiSSA TOOL

The potential complexity of future life support systems for manned missions necessitates the development of the appropriate systems analysis capability within NASA as a guide to technology and systems development (Evanich et al., 1991). The life support system (LSS) most appropriate for a given human exploration of outer space must be chosen from candidates ranging from a very simple, nonregenerative LSS to a very complex, integrated physical-chemical, and possibly biological, closed-loop LSS. There are many regenerative processes that are potential candidates to provide a particular function as part of the overall LSS. To synthesize an LSS, all of the processes must be integrated to perform certain generic life support functions such as air revitalization and water recovery.

A GMFS architecture has been developed to enable synthesis, analysis, and eventual selection of system and technology options for defined missions. The architecture consists of a modular, top-down hierarchical break-down of the physical-chemical closed loop life support (P/C CLLS) system into subsystems, and a further break-down of subsystems into subsystem functional elements (SFEs) representing individual processing technologies. This approach allows for modular substitution of technologies and subsystems and for the traceability of parameters through all the hierarchical levels, which is useful in comparing systems or technologies rapidly and accurately. The GMFS is the central feature utilized by the Life Support Systems Analysis (LiSSA) tool created by JPL as illustrated in Figure A-1.

A series of papers, describing the technique and results, titled "Human Life Support During Interplanetary Travel and Domicile" (Parts I,II,III,IV, and V), have been presented at recent International Conference on Environmental Systems (ICES) meetings. (It should be noted that the acronym LiSSA was adopted in early 1992 and therefore will not be found in earlier papers.) Another paper presented at the 21st ICES conference described hardware scaleup procedures used in the LiSSA trade tool (Rohatgi et al., 1991a). A paper was presented at the March 1993 American Institute of Chemical Engineers meeting that illustrated how the tool can be utilized to do technology trades and system optimization investigations.

LiSSA APPROACH AND CALCULATION SCHEME

A schematic of the LiSSA methodology is given in Figure A-1. To initiate the analysis, the system matrix, technology matrix, system specifications, and mission specifications are first chosen.

The system matrix includes the types of life-support systems that are of interest. It could include non-waste-processing, open-loop systems, systems that process cabin air for carbon dioxide removal only, and closed-loop systems with varying degrees of closure of the oxygen and water loops. "Closing the loops" for oxygen and water is accomplished by processes that regenerate pure oxygen and clean water from waste streams generated by the crew. The amounts of oxygen and water regenerated depend on the efficiency of the regeneration processes selected for the system.

The technology matrix includes the processing technologies that would be utilized to regenerate oxygen and water. From this matrix, a baseline set of technologies can be chosen for configuring the various systems in the system matrix. Currently, this includes technologies under consideration for Space Station Freedom (SSF) and some additional advanced technologies.

System specifications include metabolic and hygiene inputs and outputs pertaining to the crew. These specifications are required as input parameters to the GMFS module integration and computer simulation. Mission specifications are required as parametric inputs to the LiSSA Trade Tool.

For all the technology candidates considered, performance data must be acquired and utilized to model technologies as modules using the ASPEN PLUS chemical process simulation package. Once all the ASPEN PLUS modules are written, they are stored in an insert library. The modules are integrated into the GMFS architecture by calling them from the library using insert statements in the ASPEN input file. The complete input-code package represents the LiSSA Simulation Tool to produce output as an American Standard Code for Information Interchange (ASCII) file (with the *.PRN extension) that is used as input to the LiSSA Trade Tool.

The link between the LiSSA Simulation Tool and the LiSSA Trade Tool is accomplished by a spreadsheet macro which processes and loads the ASCII file from the simulation output into the Trade Tool. The Trade Tool uses simulation output, mission specifications, and JPL-developed scaleup formulas for weight, power, and volume. The entire spreadsheet represents the systems analysis output with a variety of tables and graphs.

LiSSA CALCULATION SCHEME

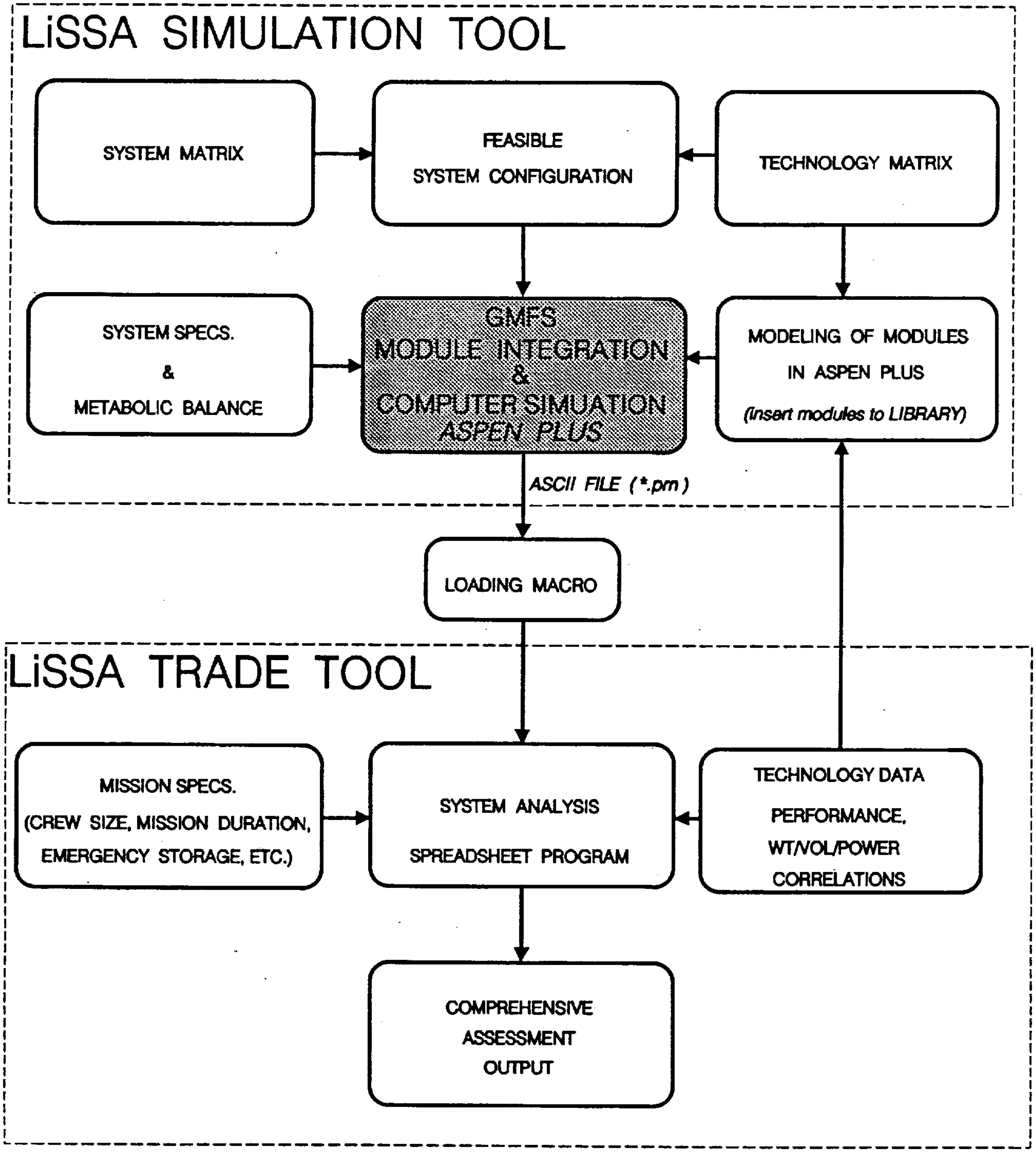

Figure A-1. LiSSA Methodology

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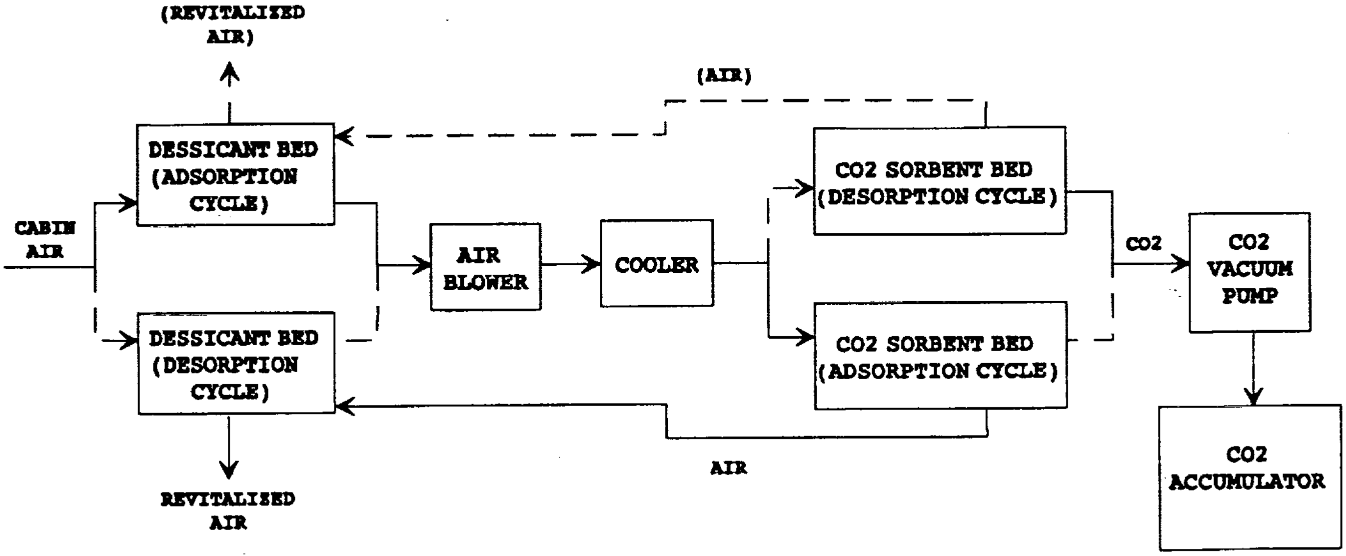
APPENDIX B

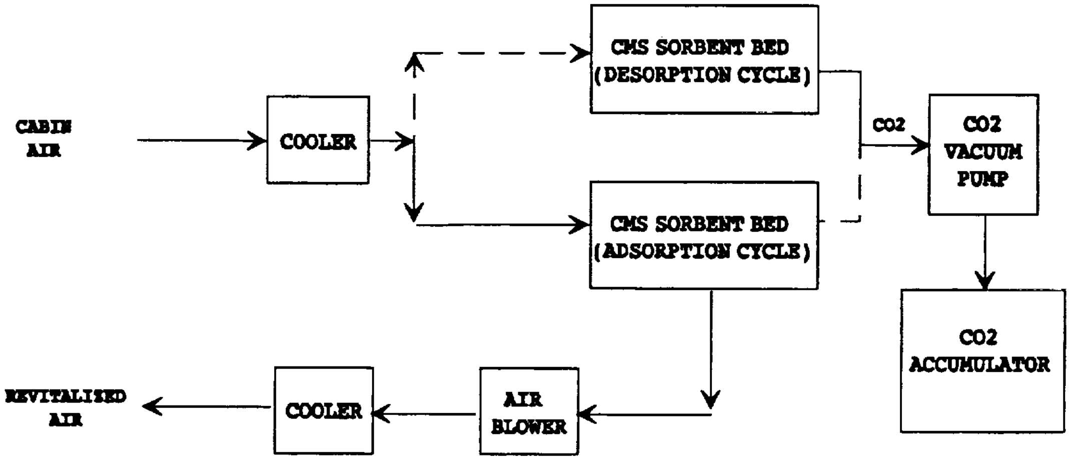
DESCRIPTIONS AND PROCESS FLOW SCHEMATICS OF PHYSICAL/CHEMICAL LIFE SUPPORT TECHNOLOGIES

The Subsystem Functional Element (SFE) functions included in this Appendix are 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 are given in Tables IV-2, IV-3, and IV-4. Functional schematics and brief descriptions of the technologies used for the trades presented in the report are included.



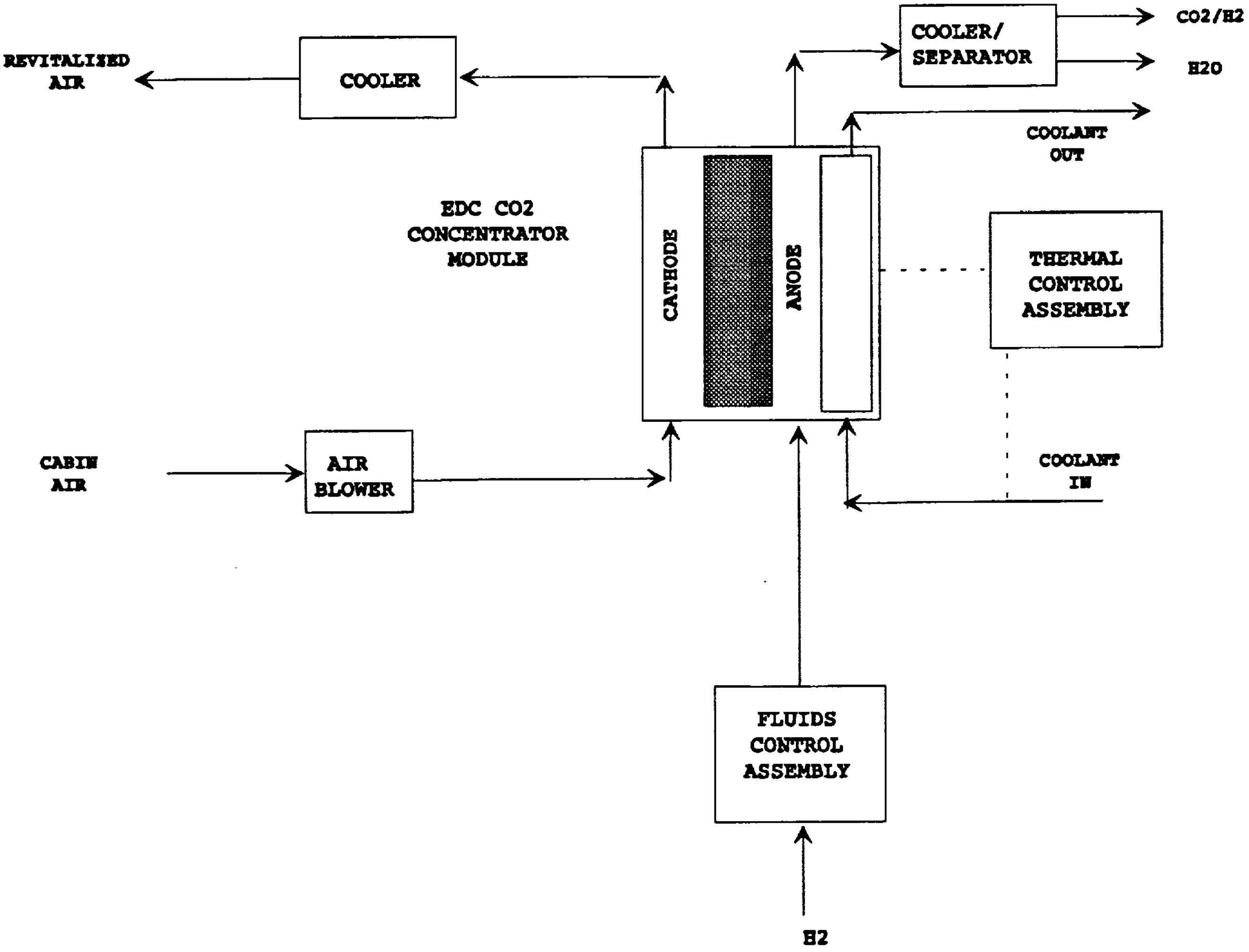
Process Flow Schematic for Four-Bed Molecular Sieve

The Four-Bed Molecular Sieve (4BMS) removes CO_2 from the inlet air stream via an adsorption process. Water is removed from the inlet air stream in an adsorbent bed packed with a mixture of silica gel and zeolite 13X. The dry air stream is then cooled and fed to a CO_2 adsorbent bed packed with zeolite 5A. Additionally, previously adsorbed water and CO_2 sorbent beds are in a desorption cycle. Desorbed water is used to rehydrate processed air, and desorbed CO_2 is pumped to an accumulation tank. Dotted lines demonstrate flow for adsorption/desorption cycling initiated when the adsorption capacity of a bed has been reached.



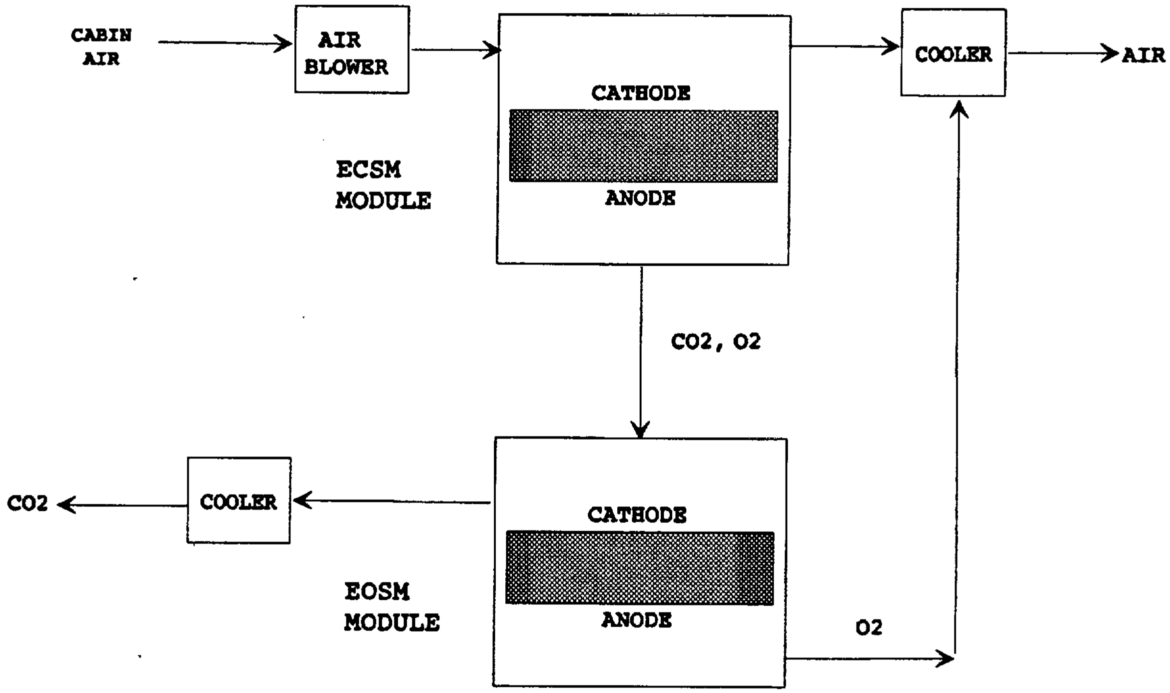
Process Flow Schematic for Two-Bed Molecular Sieve

The Two-Bed Molecular Sieve (2BMS) removes CO_2 from the inlet air stream via an adsorption process using a carbon molecular sieve (CMS). Unlike the zeolites of the 4BMS, the CMS is not affected by the moisture in the process stream. The 2BMS eliminates the requirement of desiccant beds; in addition, it also desorbs at a lower temperature than zeolites, thereby reducing regenerating power requirements. Dotted lines demonstrate flow for adsorption/desorption cycling initiated when the adsorption capacity of a bed has been reached.



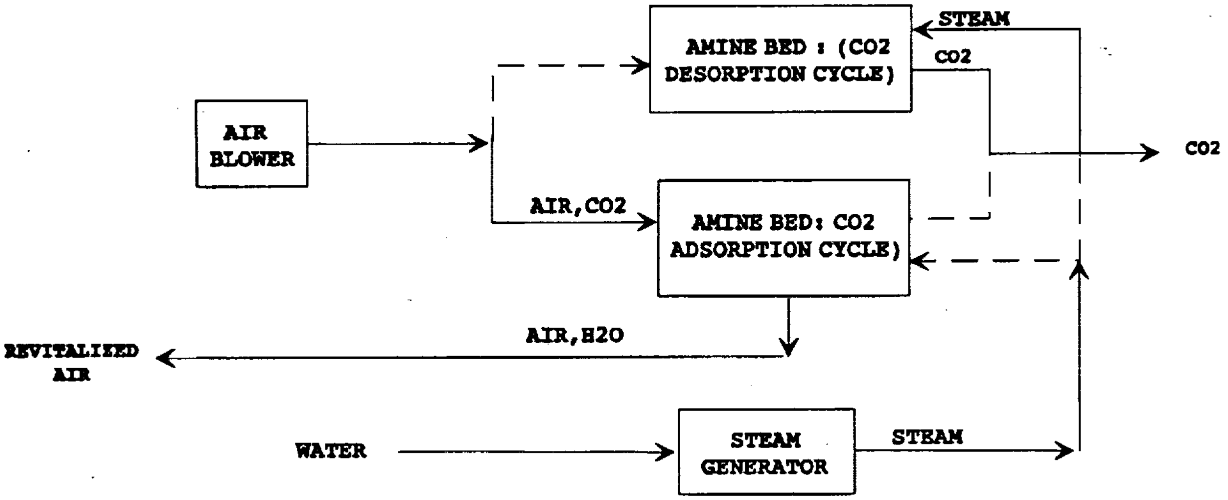
Process Flow Schematic for Electrochemical Depolarized CO_2 Concentrator

The Electrochemical Depolarized CO_2 Concentrator (ED) treats cabin air in an electrochemical cell. Air containing CO_2 passes through the cathode of an electrochemical cell utilizing an aqueous electrolyte. The CO_2 diffuses to the electrolyte-air interface where it is absorbed and reacted with hydroxyl (OH) ions to form carbonate (CO_3) and bicarbonate (HCO_3) ions. The carbonate and bicarbonate ions migrate to the cathode where CO_2 is released. When H_2 is supplied to the anode side, H_2O is also released; heat and electrical power are generated by the cell. The process requires a blower, fluids control assembly, and a thermal control assembly to remove heat from the cell.



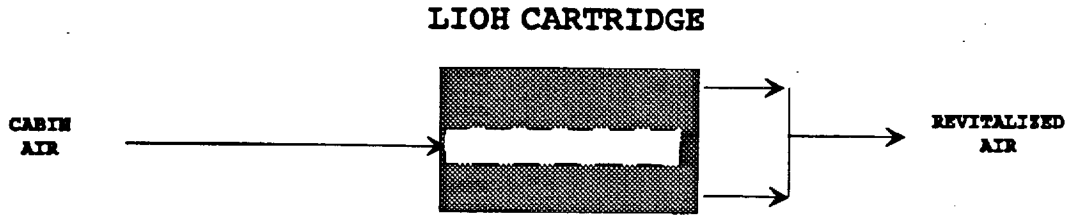
Process Flow Schematic for Air Polarized CO_2 Concentrator

The Air Polarized CO_2 Concentrator (APC) combines an electrochemical CO_2 separation module (ECSM) and an electrochemical O_2 separation module (EOSM) to remove CO_2 from cabin air. The ECSM is similar to the electrochemical cell used in the ED process; CO_2 diffuses to the electrolyte-air interface where it is absorbed and reacted with hydroxyl (OH) ions to form carbonate (CO3) and bicarbonate(HCO3) ions. The carbonate and bicarbonate ions migrate to the cathode where CO_2 is released. However, H_2 is not supplied to the ABC process; some of the O_2 in the air migrates via the electrochemical process to the anode where it is evolved with the CO_2. The O_2 and CO_2 are fed to the EOSM to remove most of the O_2 from the CO_2 stream using an acid-electrolyte cell. The process requires a blower, fluids control assembly, and a thermal control assembly to remove heat similar to the ED process.



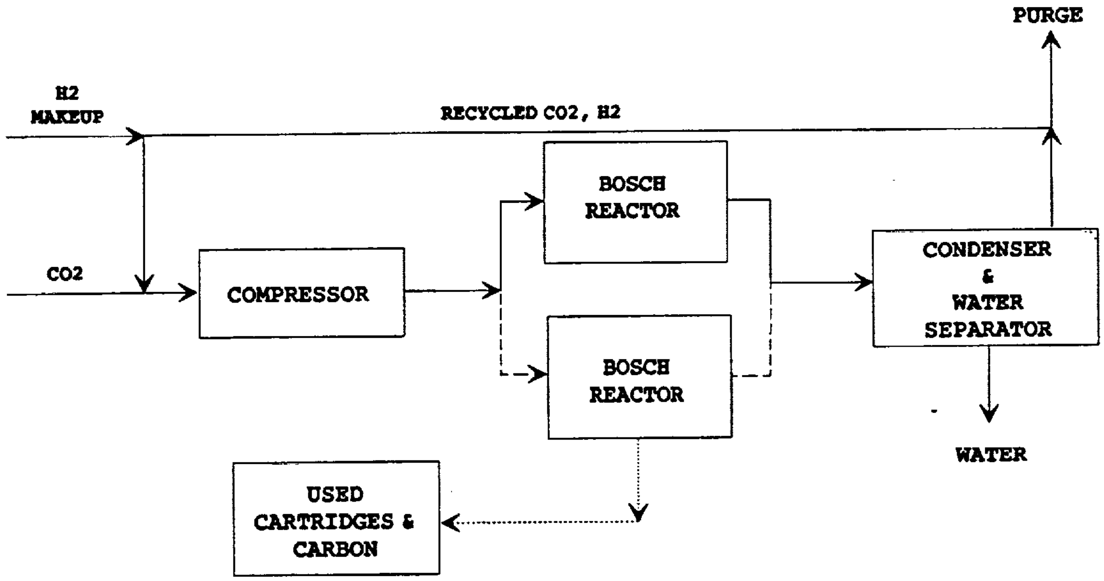
Process Flow Schematic for Solid Amine Water Desorption

The Solid Amine Water Desorption process (SAWD) removes CO_2 from the inlet air stream via an adsorption process. Dotted lines demonstrate flow for adsorption/desorption cycling initiated when the absorption capacity of a bed has been reached. Steam is used to desorb the CO_2 from the amine bed. During CO_2 absorption, the CO_2 replaces the adsorbed H_2O from the previous desorption cycle; the water removed from the bed places an additional load on the temperature and humidity control subsystem as it must condense the water vapor. Regeneration can take place at cabin pressure; i.e., vacuum conditions are not required.



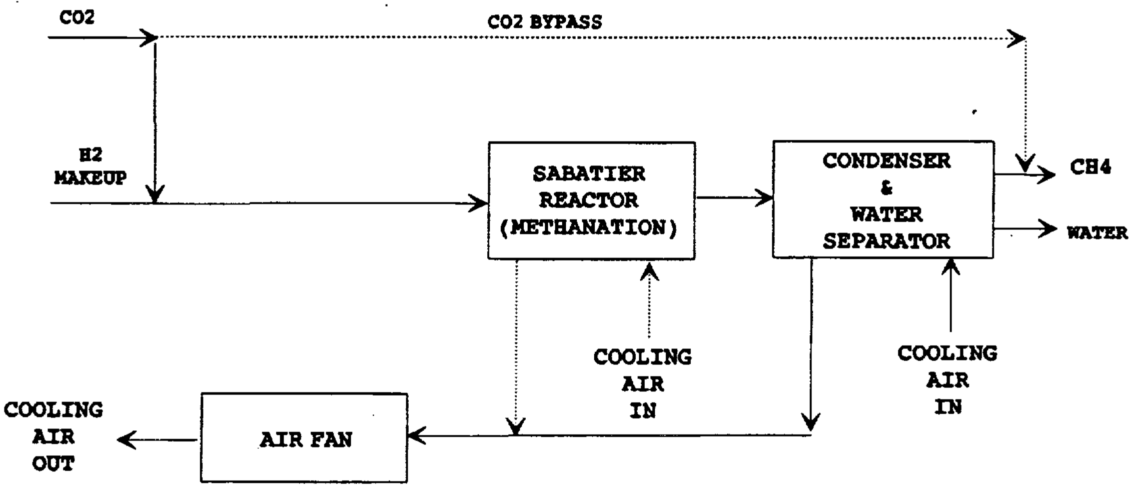
Process Flow Schematic for Lithium Hydroxide CO_2 Removal

This process uses a nonregenerable LiOH cartridge to remove CO_2. The cartridge consists of a radial flow cylindrical cartridge containing LiOH which is designed for ease of replacement after the absorber capacity has been reached. The cartridge also contains activated charcoal to control trace contaminant constituents in the cabin atmosphere. Cabin air enters the canister through a center tube and flows radially from the center through the charcoal bed where odor is removed, then through the LiOH, and finally through a particulate filter for dust removal before exiting the canister. Efficient absorption of CO_2 involves an initial H_2O absorption to form lithium hydroxide monohydrate ($LiOH-H_2O$); this is followed by absorption of CO_2 by the monohydrate forming the final carbonate (Li_2CO_3) and releasing H2O. The overall process actually is a net producer of H_2O and heat.



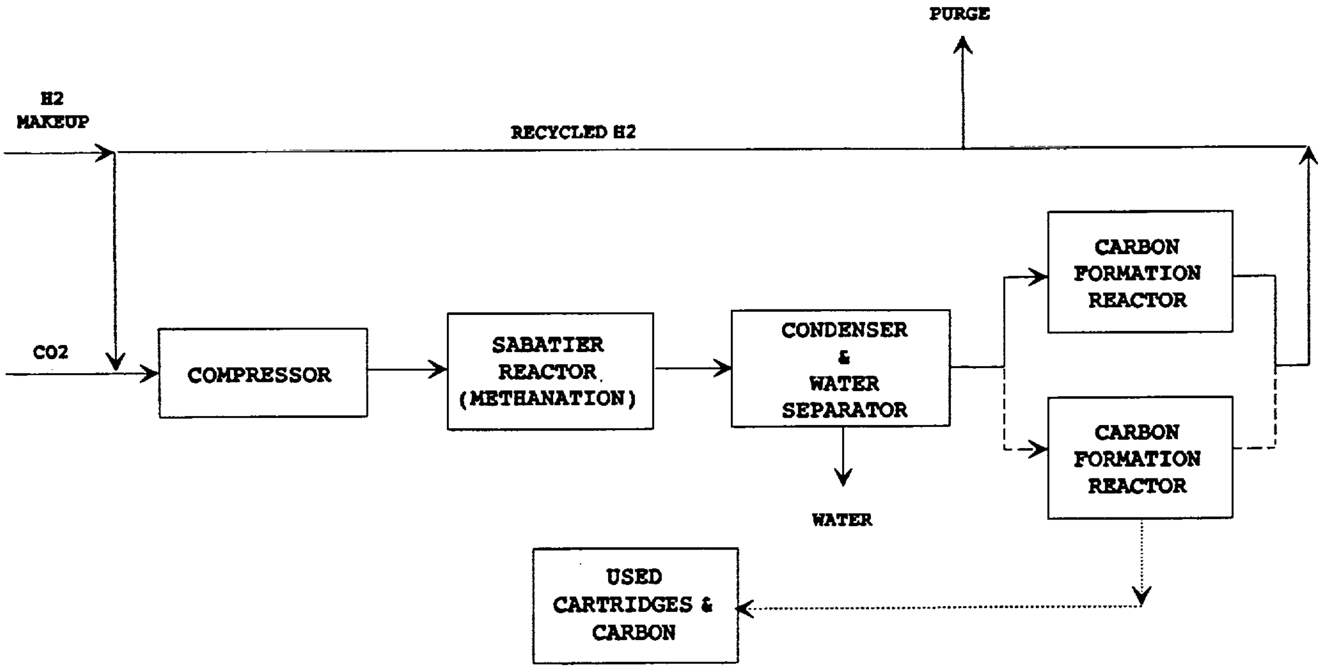
Process Flow Schematic for Bosch Reactor

The Bosch process reacts CO_2 with hydrogen in the presence of a steel wool catalyst to produce solid carbon and potable water. Less than 10% of the input CO_2 is reduced with a single pass through the Bosch reactor, but 100% conversion can be obtained by recirculating the process gases with continuous deposition of carbon and removal of water. CO_2 is directly reduced to carbon and water at 650°C in an expendable cartridge with iron catalyst. Two such reactors are required to maintain continuous operation and allow for cartridge replacement.



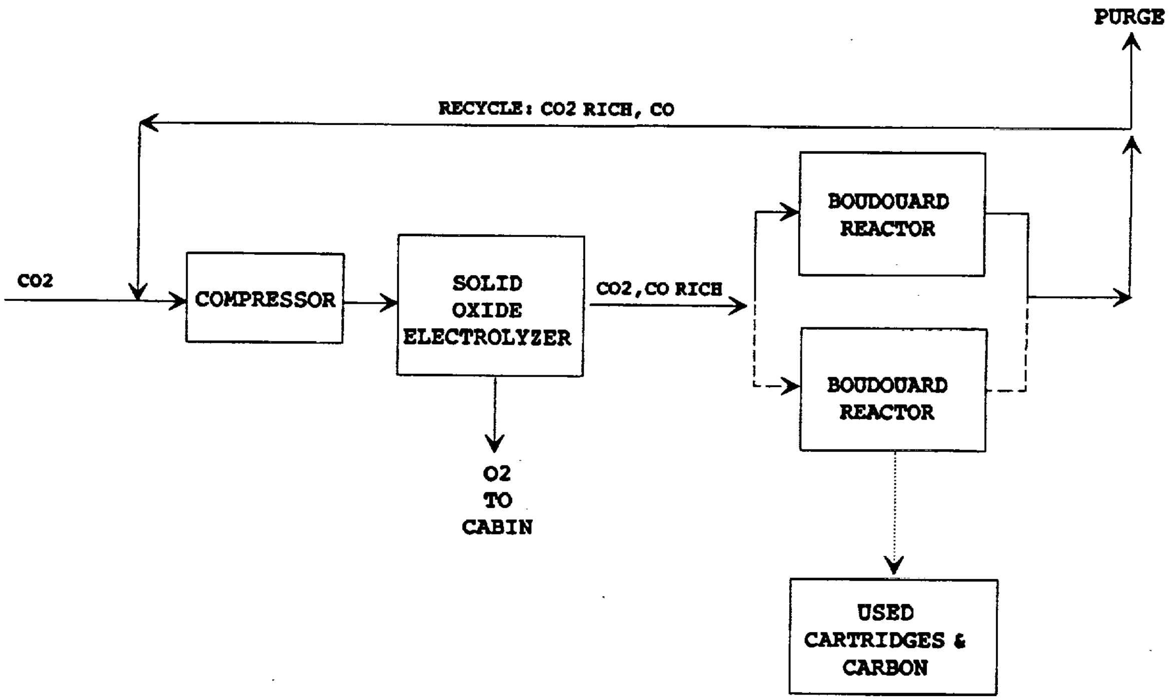
Process Flow Schematic for Sabatier Reactor

CO_2 is methanated with H_2O at temperatures from 180°C to 530°C in the presence of a ruthenium catalyst on a granular substrate. The reactor produces CH4 and H_2O with a stoichiometric reactor feed ratio of 4 moles H_2 to 1 mole of CO_2. The reactor itself is equipped with electric start up heaters. The methanation reaction is exothermic; reactor feed gas enters one end of the reactor and flows down a central tube where it is regeneratively heated by the reactor product gases. The reactor is designed so that the feed gases flow back down the catalyst bed which is located in the annulus between the center tube and reactor housing. The reactor is designed to create a favorable temperature profile with high temperatures in the catalyst bed inlet (260° to 430°C) and lower temperatures in the outlet (90° to 260°C). The gases leave the reactor between 90° and 150°C and are cooled to condense and separate the H_2O vapor product. The reactor includes air cooling to prevent overheating at elevated CO_2 reduction rates.



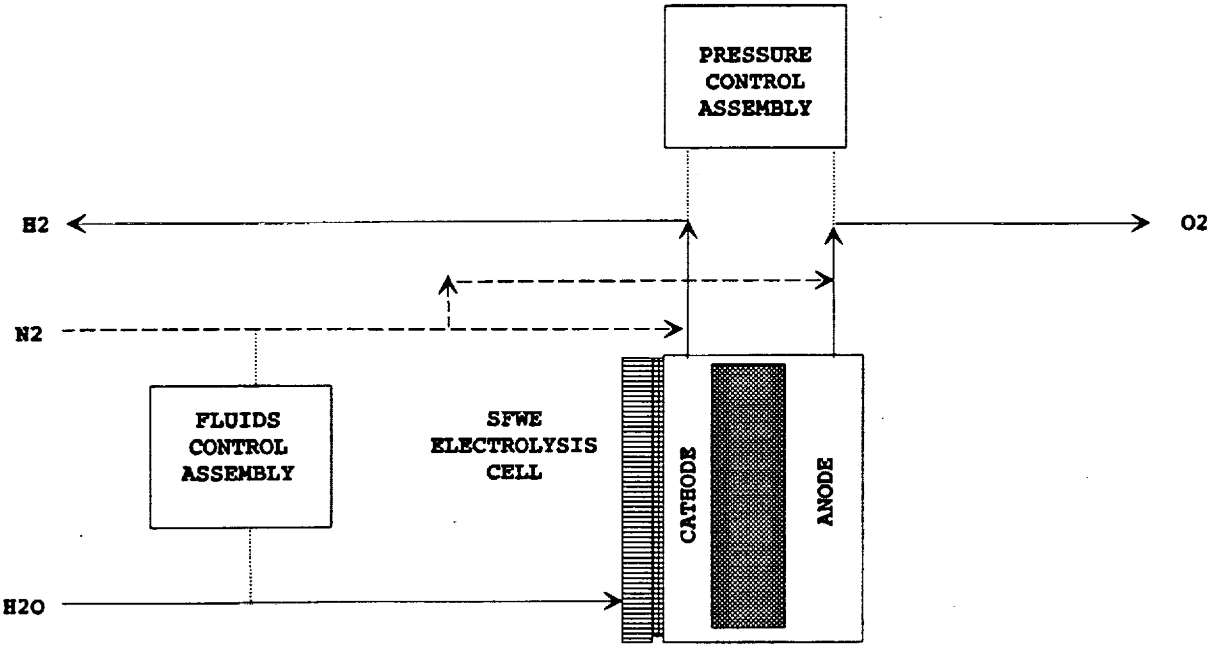
Process Flow Schematic for Advanced Carbon Reactor System

The Advanced Carbon Reactor (ACR) system consists of a Sabatier reactor, a gas/liquid separator to remove product water from methane, and a carbon formation reactor (CFR) to reduce methane to carbon and hydrogen. In the Sabatier reactor CO_2 is reacted with hydrogen in the presence of a ruthenium catalyst on a granular substrate. Operating temperatures range from 100° to 600°C, and reactor efficiency is greater than 98%. Water from the produce stream is then removed with a gas/liquid separator, and the methane is reduced to carbon and hydrogen in an expendable CFR cartridge. Two such reactors are required to maintain continuous operation and allow for cartridge replacement.



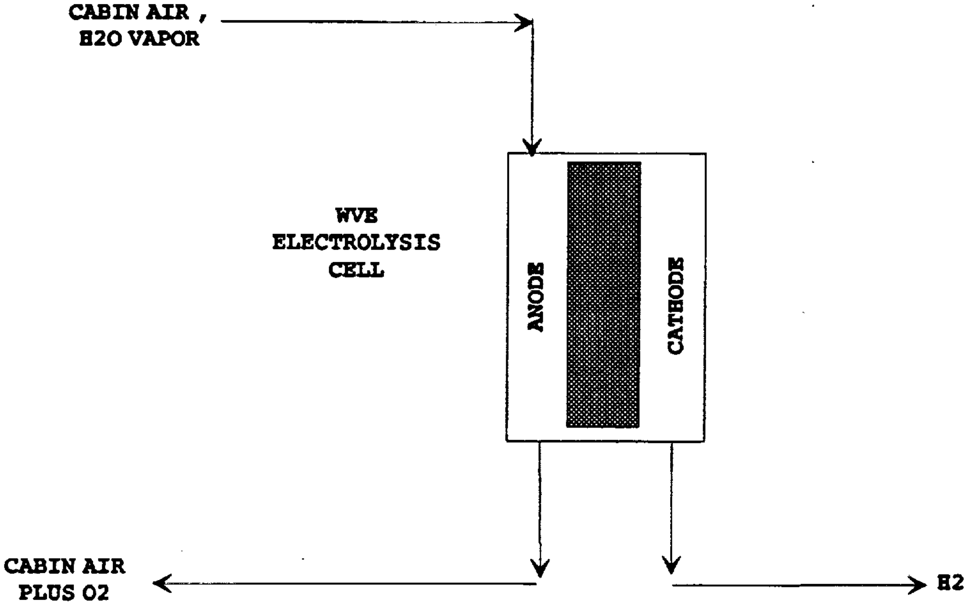
Process Flow Schematic for CO_2 Electrolysis/Boudouard

The CO_2 Electrolysis/Boudouard (CO_2EL/BD) process combines two SFE functions: CO_2 reduction and O_2 generation. CO_2 is electrolyzed using a solid oxide electrolyzer producing O_2 and CO; CO is then catalytically decomposed into solid carbon and CO_2 via the Boudouard reaction; CO_2 is recycled back to the electrolyzer. Since this process generates O_2 directly from CO_2, thereby reducing (or eliminating) the oxygen generation via water electrolysis, the need to clean condensate for water electrolysis can be reduced also.



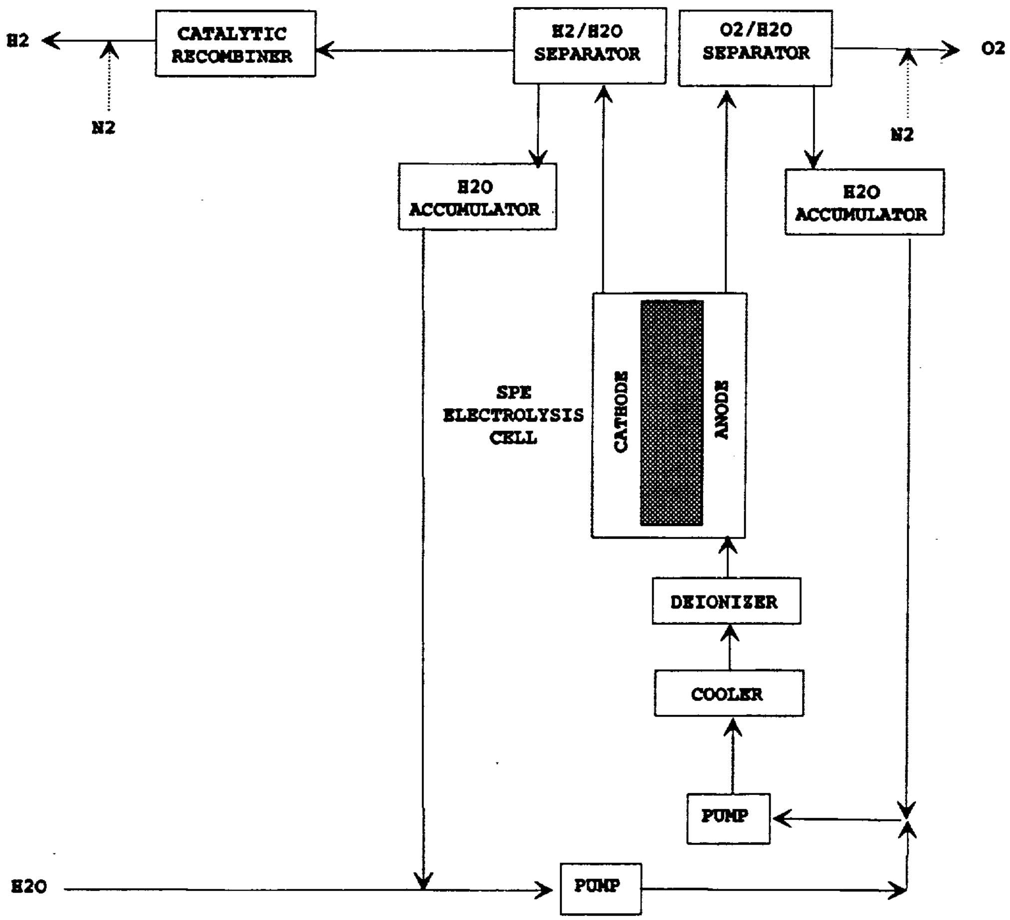
Process Flow Schematic for Static Feed Water Electrolysis

The Static Feed Water Electrolysis (SFWE) process electrolyzes water to produce H_2 and O_2. Water is fed to the feed compartment where it diffuses as a vapor through the water feed membrane and into the anode. The cell electrolyte is an aqueous KOH held on a retention matrix. H_2 and O_2 are generated in the cathode and anode, respectively. N_2 is used for purging and pressurization purposes. Normal operating conditions are 80^0C and 12 atm.



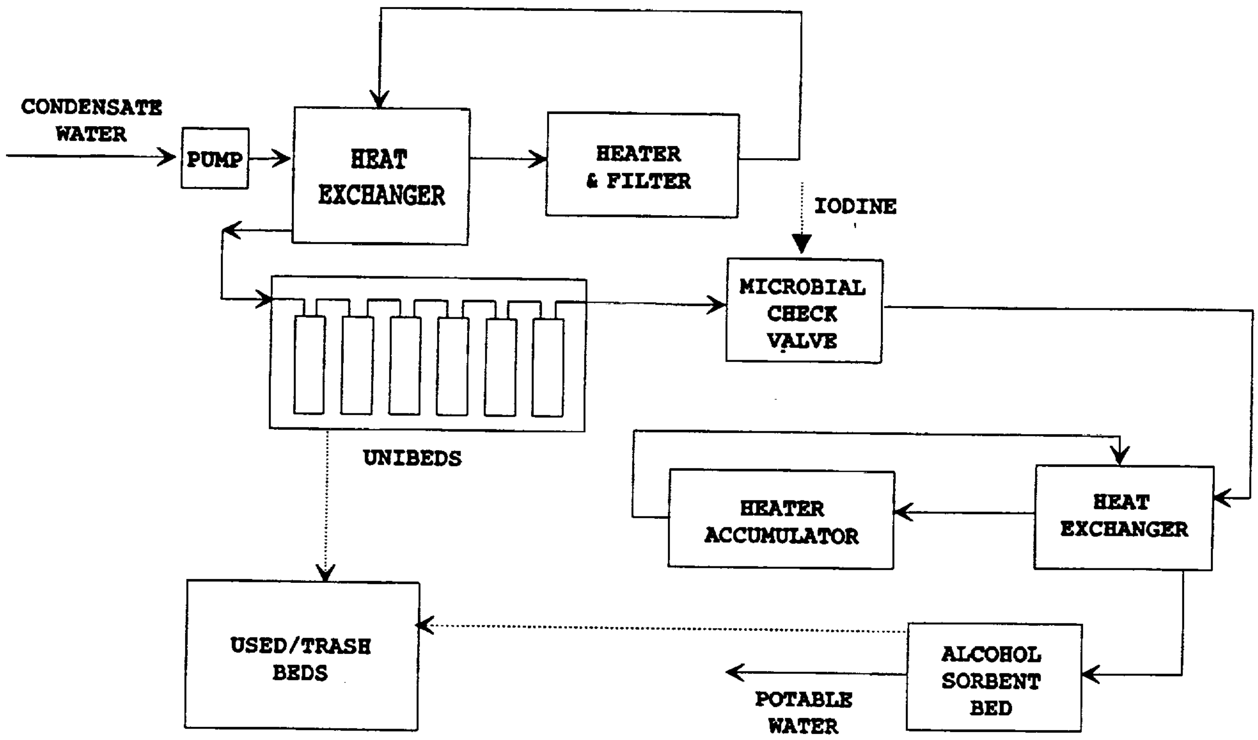
Process Flow Schematic for Water Vapor Electrolysis

The Water Vapor Electrolysis (WVE) uses a hygroscopic electrolyte (H_2SO_4) to absorb H_2O vapor from the cabin air and generate O_2, H+ions, and electrons in the anode compartment. At the cathode, H+ ions are joined with electrons to generate H_2.



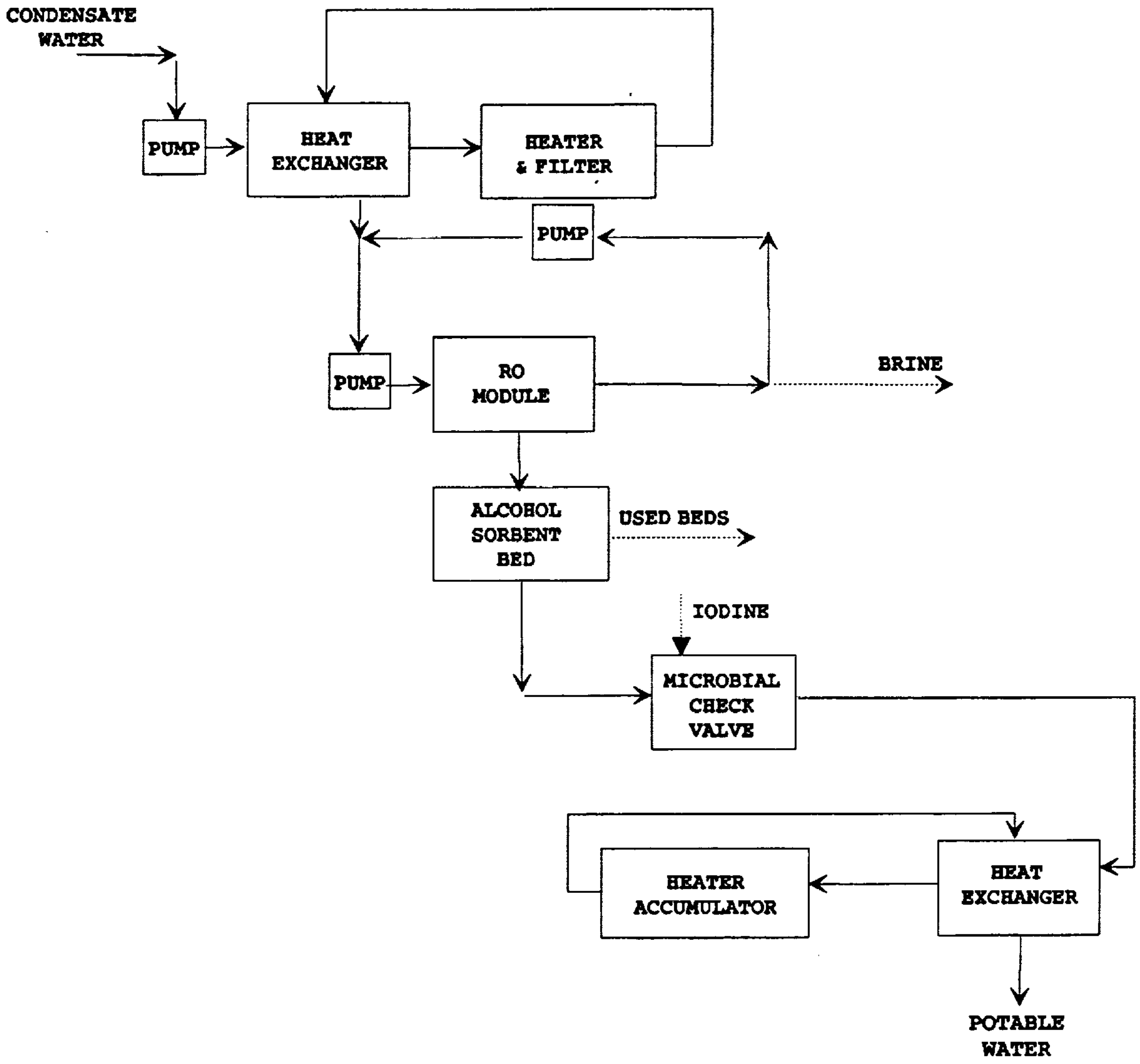
Process Flow Schematic for Solid Polymer Electrolyte

The Solid Polymer Electrolyte (SPE) uses a membrane made of sulfonated perfluoro-linear polymer (NAFION). When fully hydrated with H_2O, the membrane is an excellent conductor and functions as the electrolyte. Deionized and cooled H_2O is fed to the anode where it is decomposed to O_2, H+ ions, and electrons. The electrons travel through the external electrical circuit to the cathode, while the H+ ions migrate from anode to cathode by passing between the fixed, hydrated sulfonic acid groups. The H+ ions and electrons recombine on the cathode to evolve as H_2. Both H_2 and O_2 evolved gases contain water droplets that are separated from the gas phase. The recovered liquid H_2O is returned to the anode from H_2O accumulators. A recombiner catalytically reacts O_2 in the H_2 that may occur due to O_2 to H_2 cross-leakage. The SPE cell operates at 500°C and 14 atm on the O_2 side; the H_2 side is at a lower pressure than the O_2 side. N_2 is provided to maintain O_2 pressures above H_2 pressure and for purging purposes.



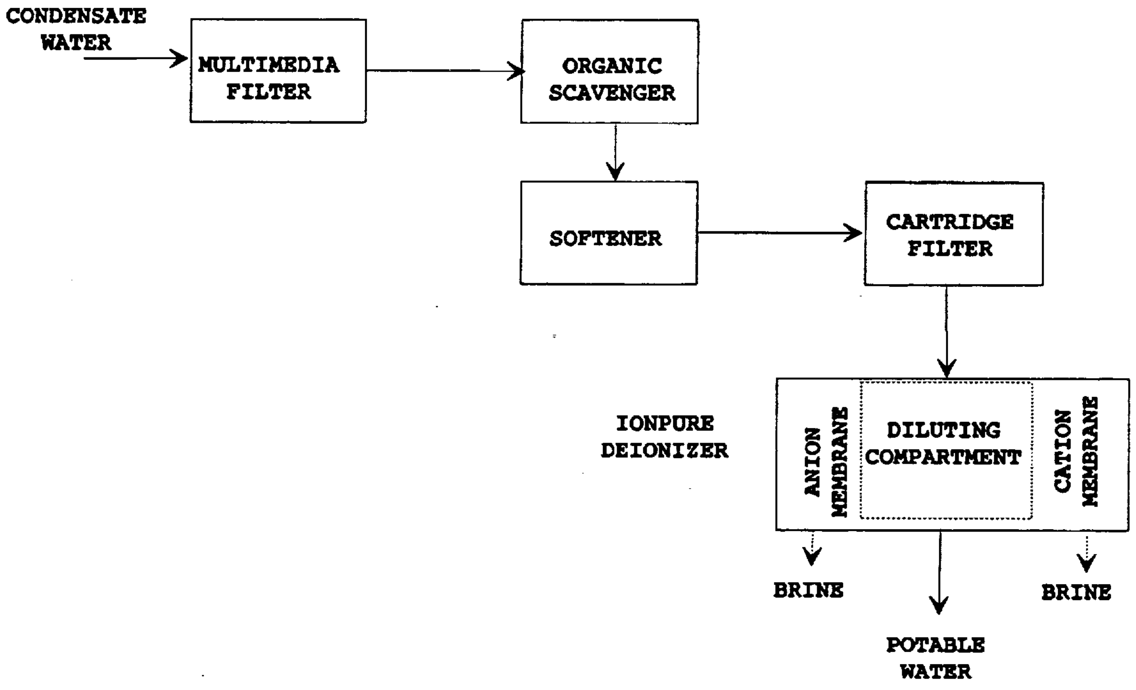
Process Flow Schematic for Multifiltration for Potable Water Processing

The Multifiltration System is designed to produce potable quality water using expendable adsorption beds to remove both dissolved and ionic impurities. Water entering the process is first heated to 125°C and sterilized for 40 minutes; it is also filtered to remove any bacteria and particulates present. Flow is then directed to a series of six unibeds composed of an adsorption bed containing activated carbon and an ionic exchange resin bed operating at 25° to 45°C; the goal is to have an effluent with a total organic carbon concentration of 500 ppb or less. Eventually, the first bed reaches storage capacity and is removed. The remaining beds are moved up to fill the gap, and a fresh bed is placed at the end of the series. Microbial growth is impeded by heating and chemically treating the processed water at similar temperatures and residence times as the first heater/filter. Downstream of the unibeds iodine is injected into the process stream . The stream is then passed through an alcohol sorbent bed for the purpose of removing low molecular weight alcohols.



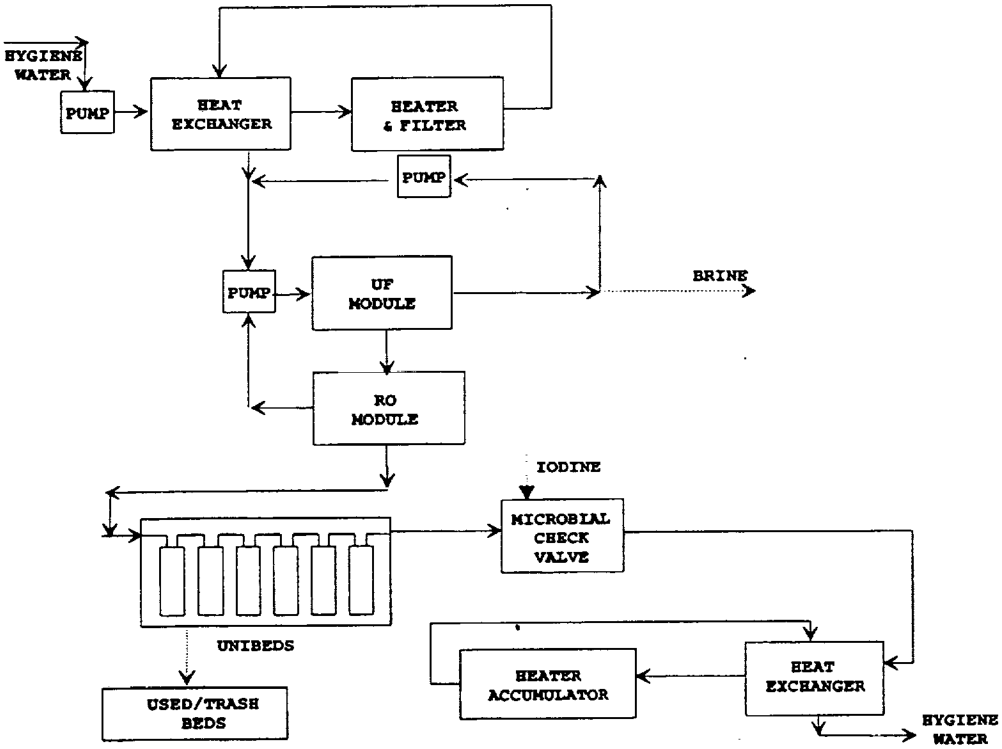
Process Flow Schematic for Reverse Osmosis for Potable Water Processing

The Reverse Osmosis (RO) process for potable water processing is designed to remove both dissolved and ionic impurities. Water entering the process is first heated to 125°C and sterilized for 40 minutes; it is also filtered to remove any bacteria and particulates present. Flow is then directed to an RO module that operates at 13 atm and 45°C. Brine is flushed from the system several times per day. The permeate is passed through an alcohol sorbent bed used to remove low molecular weight alcohols. Microbial growth is impeded by heating and chemically treating the processed water at similar temperatures and residence times as the first heater/filter.



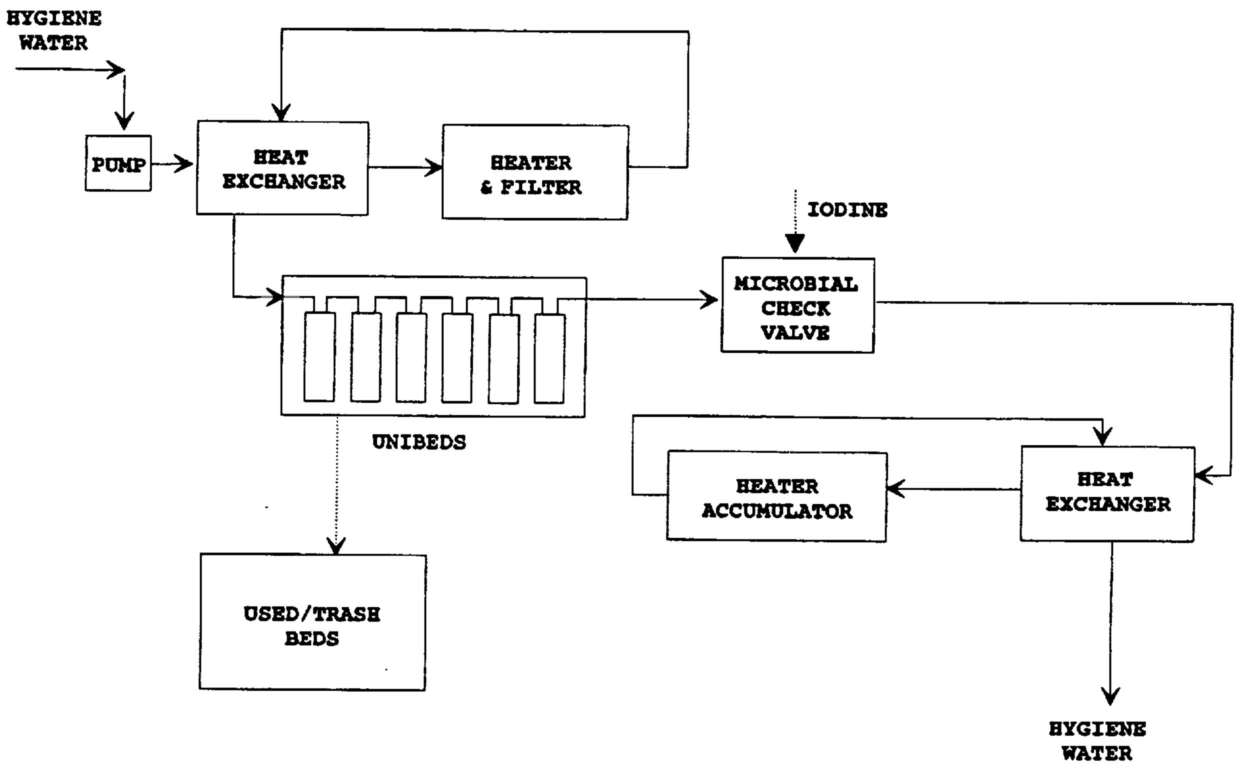
Process Flow Schematic for Electrochemical Deionization for Potable Water Processing

The Electrodeionization (ELDI) process utilizes ion exchange resins and membranes to deionize feed water. The ionpure deionizer contains ion exchange membranes that act as barriers to bulk water flow. The deionizer is divided into three adjacent compartments: a diluting compartment bordered on either side by a concentrating compartment. Feed water enters the diluting compartment (after pretreatment of the feed water by the multimedia filter, organic scavenger, and softener), which is filled with the ion exchange resins, transferring through these resins in the direction of an electrical potential gradient applied across the compartments. Due to the semipermeability properties of the ion exchange membranes and the directionality of the potential gradient, ion concentration will decrease in the diluting compartment and increase in the concentrating compartments. The system outputs brine from the concentrating compartments and purified deionized water from the diluting compartment. The ion exchange resin is continually electrically regenerated.



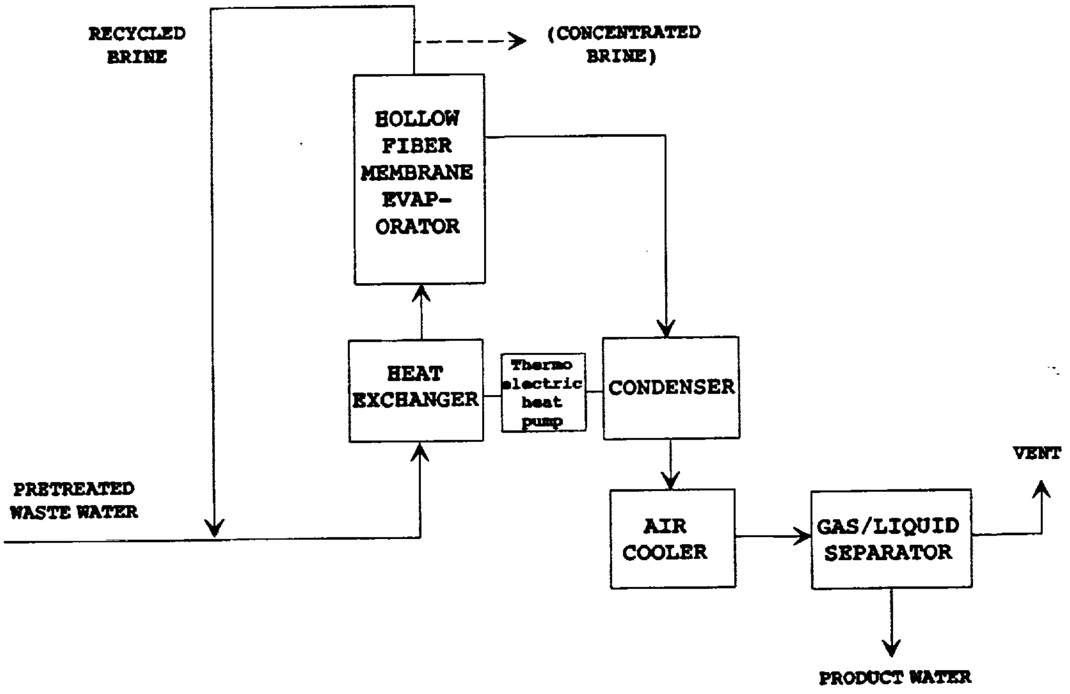
Process Flow Schematic for Reverse Osmosis for Hygiene Water Processing

The Reverse Osmosis (RO) is designed to produce hygiene quality water using a combination of an Ultrafiltration (UF) Module (to remove suspended solids, colloids, and macromolecules), a RO module (to remove salts and compounds with molecular weights >100), and expendable adsorption beds to remove both dissolved and ionic impurities from the RO permeate. The process is similar to that used for potable water processing with the exception of the lack of alcohol sorbent beds, the addition of the UF Module, and the type of material in the Unibeds. Water entering the process is first heated to 125°C and sterilized for 40 minutes; it is also filtered to remove any bacteria and particulates present. Flow is pumped to the UF Module with UF permeate entering the RO module. Brines from UF and RO are recycled and purged periodically. Flow is then directed to a series of six unibeds composed of an adsorption bed containing activated carbon and an ionic exchange resin bed operating at 25° to 45°C; the goal is to have the effluent reach a total organic carbon concentration of less than 10 ppm. Eventually, the first bed reaches storage capacity and is removed. The remaining beds are moved up to fill the gap, and a fresh bed is placed at the end of the series. Microbial growth is impeded by heating and chemically treating the processed water at similar temperatures and residence times as the first heater/filter. Downstream of the unibeds, iodine is injected into the process stream.



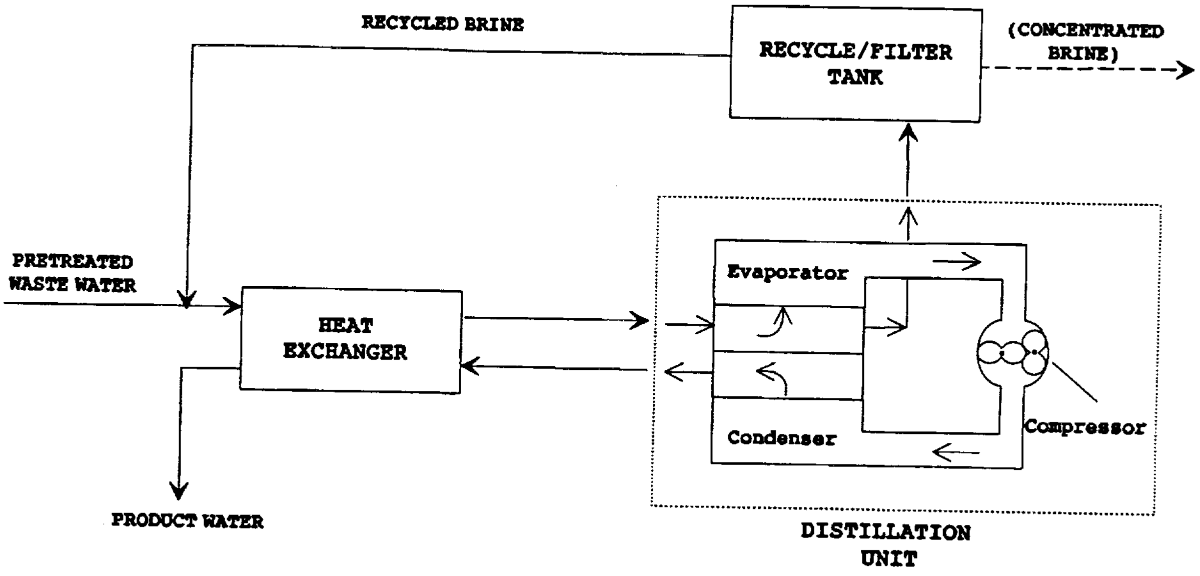
Process Flow Schematic for Multifiltration for Hygiene Water Processing

The Multifiltration System is designed to produce hygiene quality water using expendable adsorption beds to remove both dissolved and ionic impurities. The process is similar to that used for potable water processing with the exception of the lack of alcohol sorbent beds and the type of material in the unibeds. Water entering the process is first heated to 125°C and sterilized for 40 minutes; it is also filtered to remove any bacteria and particulates present. Flow is then directed to a series of six unibeds composed of an adsorption bed containing activated carbon and an ionic exchange resin bed operating at 25° to 45°C; the goal is to have the effluent reach a total organic carbon concentration of less than 10 ppm. Eventually, the first bed reaches storage capacity and is removed. The remaining beds are moved up to fill the gap, and a fresh bed is placed at the end of the series. Microbial growth is impeded by heating and chemically treating the processed water at similar temperatures and residence times as the first heater/filter. Downstream of the unibeds iodine is injected into the process stream. The stream is then passed through an alcohol sorbent bed for the purpose of removing low-molecular-weight alcohols.



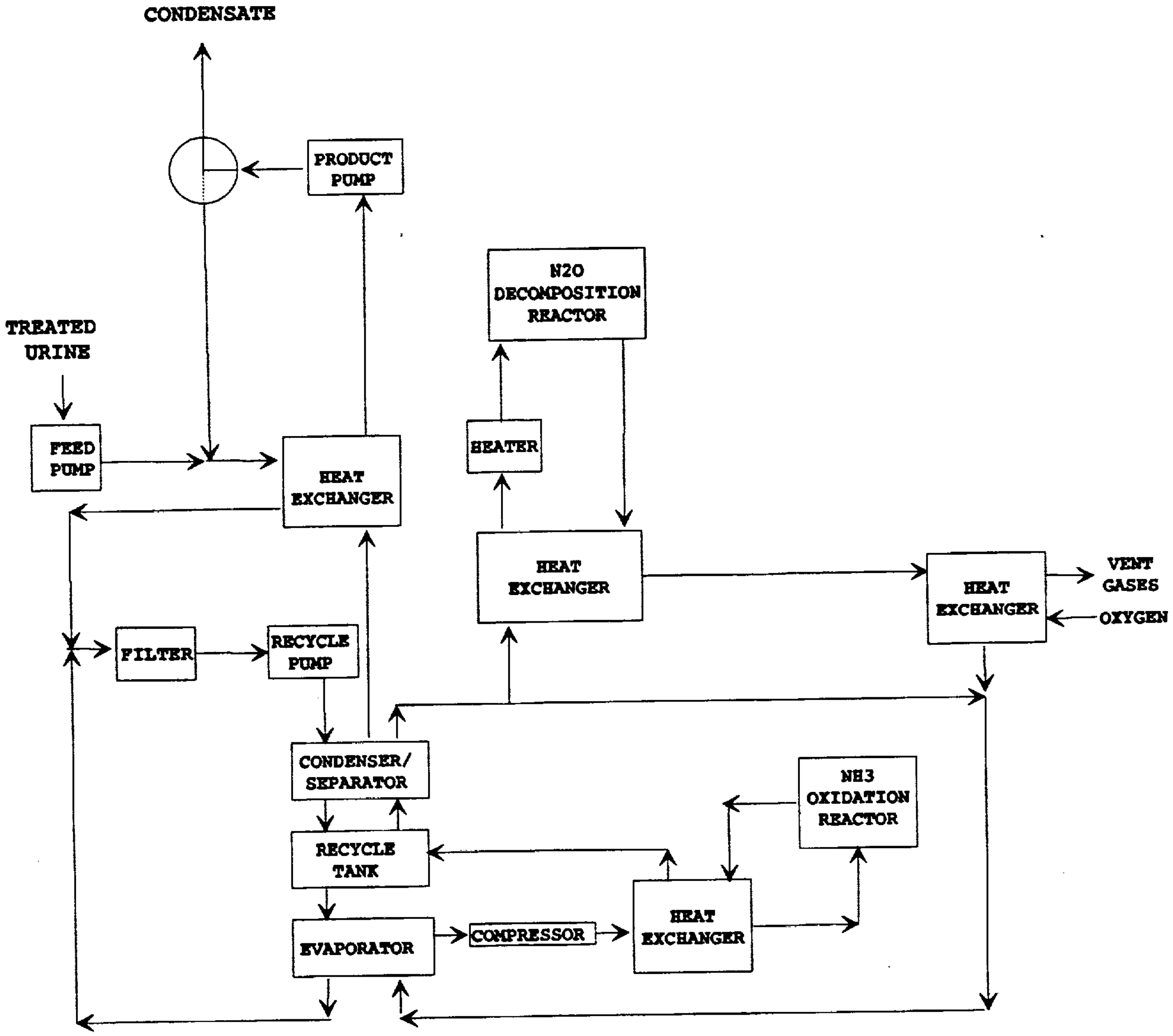
Process Flow Schematic for Thermoelectric Integrated Membrane Evaporation Subsystem

The Thermoelectric Integrated Membrane Evaporation Subsystem (TIMES) is designed to produce hygiene quality water from urine waste water attaining a 95% water recovery efficiency. Before entering TIMES, urine is chemically pretreated to fix free ammonia. After pretreatment, the waste water stream is first heated and then passed through hollow fiber membranes for evaporation at low temperatures. The evaporator consists of six bundles of 100 Nafion tubes each. Steam evaporates from the outer surface of the membranes and is partially condensed before flowing to an air cooled heat exchanger. Noncondensible gases entrained in the condensate stream are removed by a pump which functions as a gas/liquid separator. Unevaporated waste water is recycled until solid concentrations reach a predetermined level, at which time the concentrated brine is removed for disposal. Using thermoelectric devices, the latent heat of condensation is recovered and reused in the evaporation process.



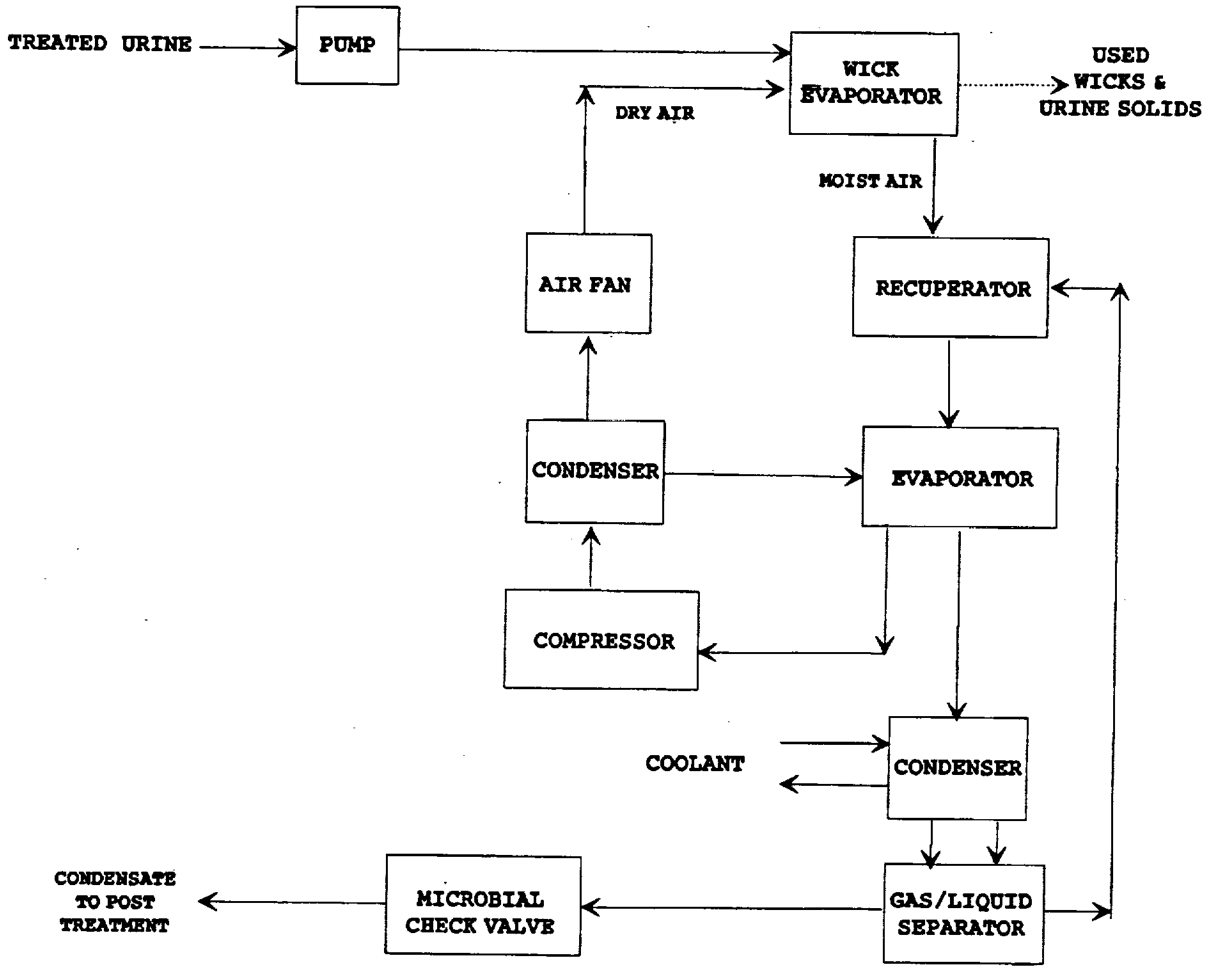
Process Flow Schematic for Vapor Compression Distillation

The Vapor Compression Distillation (VCD) system maintains a vapor/liquid interface using centrifugal force created by a rotating drum. Waste water is discharged to the inner surface of a centrifugal evaporator drum inside the distillation unit. Water vapor is removed from the evaporator, compressed to raise its saturation temperature, and then forced against the outer surface of the rotating drum where it condenses. The latent heat of condensation is transferred through the drum wall and reused in the evaporation process. Unevaporated waste water is recirculated until solid concentrations reach a predetermined level, at which time the concentrated brine is removed for disposal.



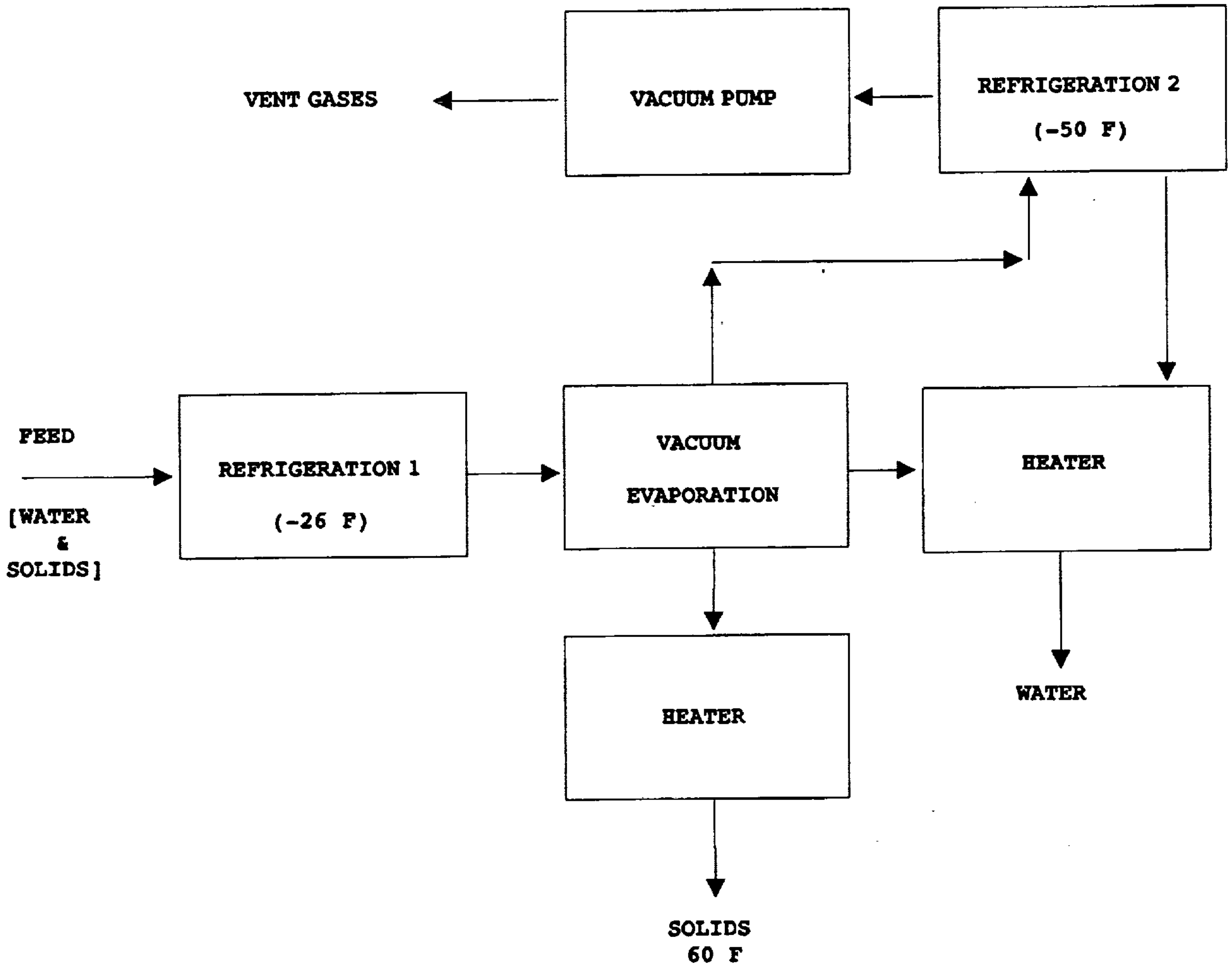
Process Flow Schematic for Vapor Phase Catalytic Ammonia Reduction for Urine Processing

The Vapor Phase Catalytic Ammonia Removal (VPCAR) Process utilizes catalytic reactors to react vaporized impurities in the feed water to innocuous gases. Urine is vaporized at 100°C in an evaporator. The process employs two catalytic reactors. The NH_3 oxidation reactor uses a Pt catalyst to oxidize NH_3 to a mixture of N_2 and N_2O and volatile organic hydrocarbons are oxidized to CO_2 and water vapor at 250°C. The N_2O decomposition reactor uses a Ru catalyst at 400°C to N_2 and O_2. The recovered H_2O has little NH_3, few hydrocarbons, low conductivity, and only requires pH adjustment to be a candidate for potable water.



Process Flow Schematic for Air Evaporation for Urine Processing

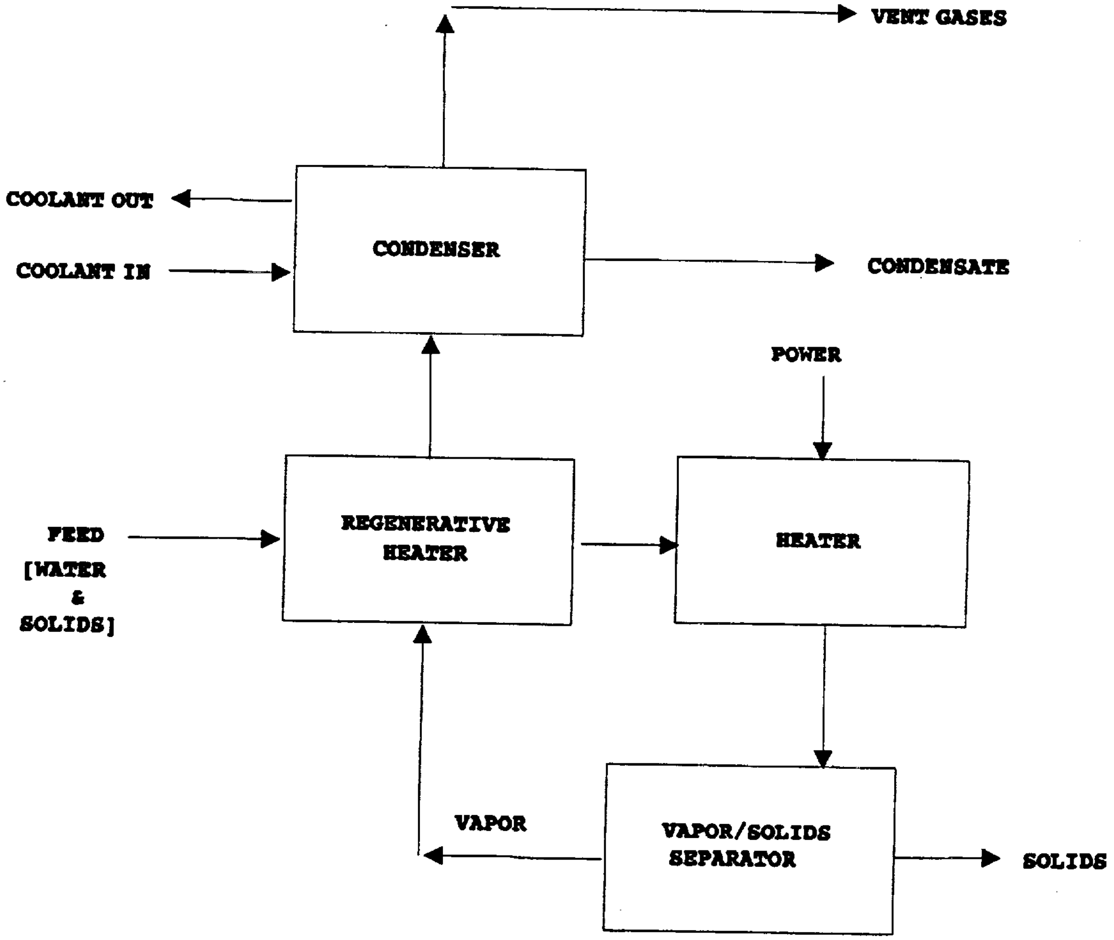
In the Air Evaporation (AIRE) process, treated urine is pumped to a wick package along with a dry air stream. The circulating heated air evaporates water from the urine leaving solids in the wicks. When sufficient solids accumulate in the wicks, the feed is stopped and the loaded wicks are dried down and replaced. Humid air leaving the wick evaporator passes through a heat recuperator and a condensing heat exchanger. A water separator downstream of the condenser removes water from the air and pumps it out as condensate. Iodine is added to the water before it is sent to post treatment before it can be used as hygiene water.



Process Flow Schematic for Freeze Drying

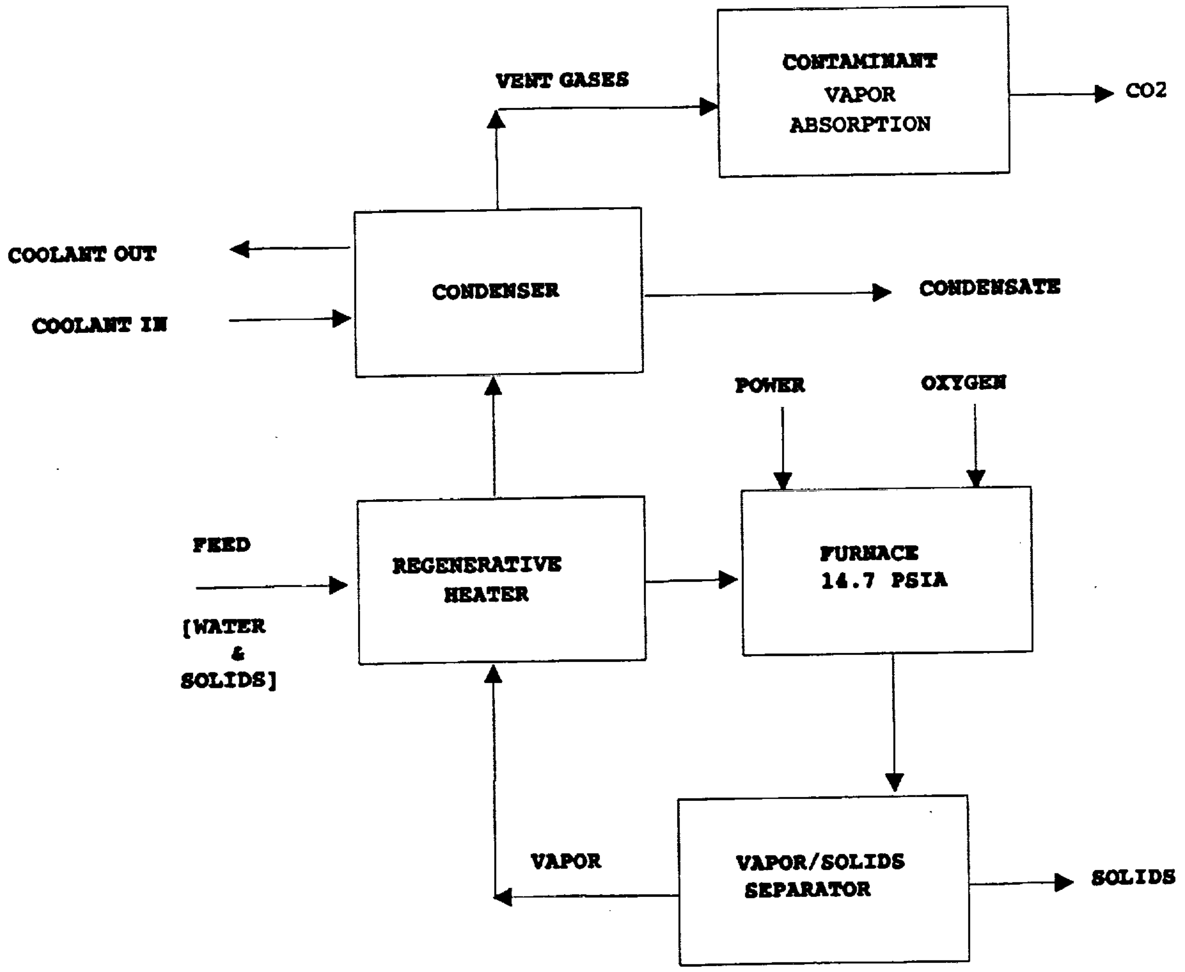
The freeze drying (FRZ) process consists of four major steps as illustrated above:

(1) pre-freezing at -3°C to freeze dissolved and suspended materials along with water;
(2) vacuum evaporation or sublimation of the frozen ice at <0.0001 atm;
(3) re-freezing water vapor at -15°C and
(4) melting of the frozen ice at 16°C.



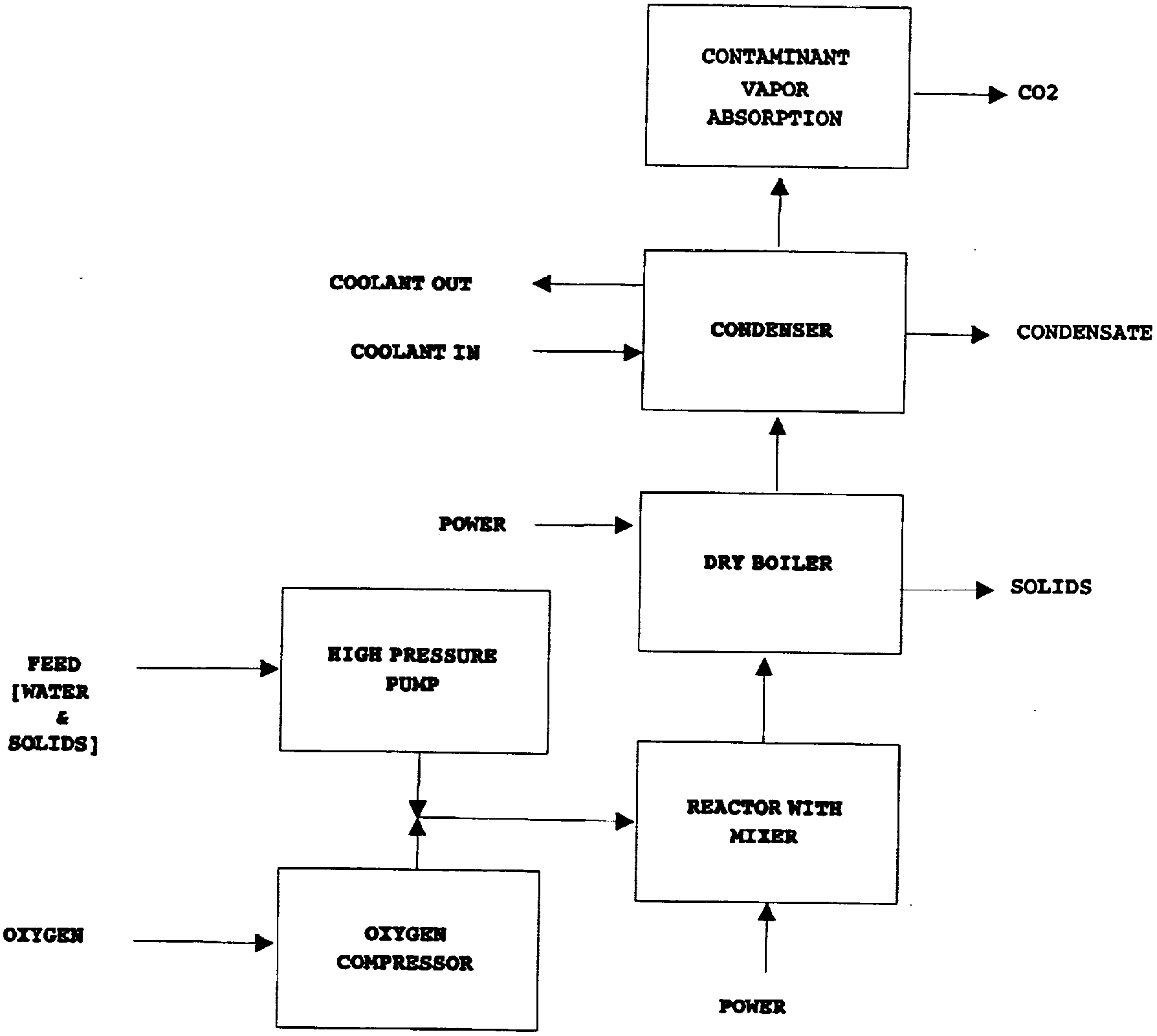
Process Flow Schematic for Thermal Drying

The Thermal (or hot) Drying (HD)process uses power to dry the feed at temperatures exceeding 150°C. Regenerative heaters are provided to increase the thermal efficiency. Potential waste heat sources, rather than electrical power, could be process waste heat from other physical/chemical processing steps, such as CO_2 reduction.



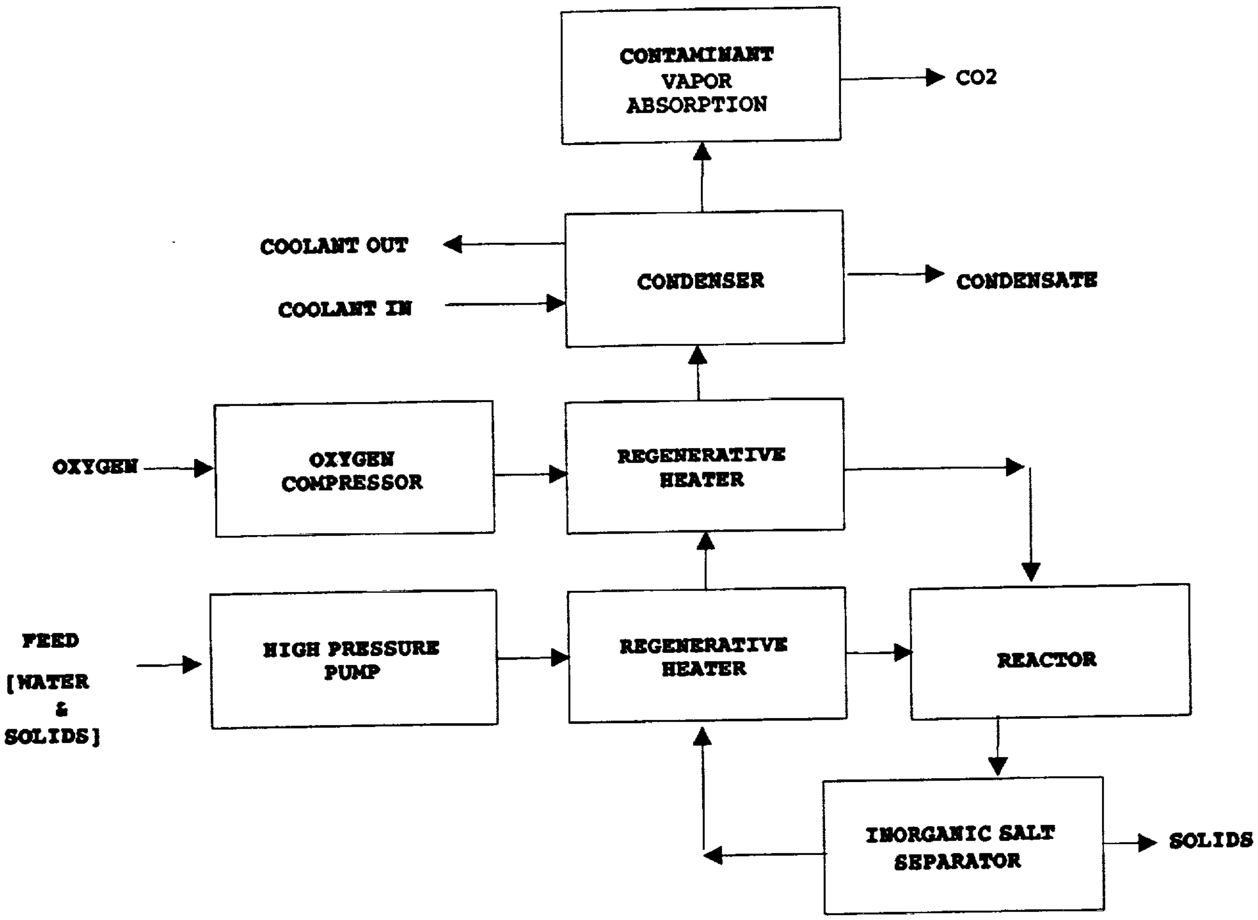
Process Flow Schematic for Combustion Oxidation

The Combustion (COMB) Oxidation process uses pure oxygen to incinerate the organics in the feed. Power is also required as the stream has a low heating value. An ambient pressure furnace is used; ash solids residue is separated after incineration. After recovery of some of the waste heat in a regenerative heater, the water condensate formed from the original water and the oxidized organics is condensed. Unreacted or partially oxidized organics and other contaminant vapors are absorbed. CO_2 formed from oxidizing the organics is recycled to the air revitalization subsystem to reduce the CO_2 to carbon and oxygen.



Process Flow Schematic for Wet Oxidation

The wet oxidation (WOX) process uses pure oxygen to oxidize the organics in the feed in a reactor maintained at 290°C atm and 150 atm. Power is also required as the stream has a low heating value; in addition, power is required to pump the feed waste stream and compress the oxygen. Ash solids residue is separated after the reactor in a dry boiler, operated at low pressure and over 230°C. The water condensate formed from the original water and the oxidized organics is condensed. Unreacted or partially oxidized organics and other contaminant vapors are absorbed. CO_2 formed from oxidizing the organics is recycled to the air revitalization subsystem to reduce the CO_2 to carbon and water.



Process Flow Schematic for Supercritical Water Oxidation

The supercritical water oxidation process uses pure oxygen to oxidize the organics in the feed in a reactor maintained at supercritical conditions for water: over 250 atm and 600°C. Power is also required as the stream has a low heating value; in addition, power is required to pump the feed waste stream and compress the oxygen. Ash solids residue consisting primarily of inorganics, can be separated by an inorganic cyclone salt separator, as inorganics are insoluble and can be precipitated at reactor conditions. Regenerative heaters are used to recover some of the reactor heat; the water condensate formed from the original water and the oxidized organics is condensed. Organics are estimated to be almost completely oxidized due to the high conversion rate. Unreacted or partially oxidized organics and other contaminant vapors are absorbed. CO_2 formed from oxidizing the organics is recycled to the air revitalization subsystem to reduce the CO_2 to carbon and water.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** October, 1993	**3. REPORT TYPE AND DATES COVERED** Technical Memorandum

4. TITLE AND SUBTITLE

Life Support Systems Analysis and Technology Trades
For a Lunar Outpost

5. FUNDING NUMBERS

6. AUTHOR(S)

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8. PERFORMING ORGANIZATION REPORT NUMBER

NASA TM 109927

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

TM 109927

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified

12b. DISTRIBUTION CODE

Unlimited / Unclassified

13. ABSTRACT *(Maximum 200 words)*

The NASA/JPL life support systems analysis (LiSSA) software tool was used to perform life support system analysis and technology trades for a Lunar Outpost. The life support system was modeled using a chemical process simulation program on a steady-state, one-person, daily basis. Inputs to the LiSSA model include metabolic balance load data, hygiene load data, technology selection, process operational assumptions and mission parameter assumptions. A baseline set of technologies has been used against which comparisons have been made by running twenty-two cases with technology substitutions. System, subsystem, and technology weights and powers are compared for a crew of 4 and missions of 90 an 600 days. By assigning a weight value to power, equivalent system weights are compared. Several less-developed technologies show potential advantages over the baseline. Solid waste treatment technologies show weight and power disadvantages but one could have benefits associated with the reduction of hazardous wastes and very long missions. Technology development towards reducing the weight of resupplies and lighter materials of construction was recommended. It was also recommended that as technologies are funded for development, contractors should be required to generate and report data useful for quantitative technology comparisons.

14. SUBJECT TERMS

Life support; Lunar outpost; systems analysis

15. NUMBER OF PAGES

112

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** Unlimited

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std Z39-18
298-102