N93-27978

ASSESSMENT OF THE STATE OF THE ART IN LIFE SUPPORT ENVIRONMENTAL CONTROL FOR SEI

Charles H. Simonds and Gary P. Noyes
Lockheed Life Support Development Laboratory

S22-54
158336
P. 14

Abstract

This paper defines the types of technology that would be used in lunar base for environmental control and life support system and how it might relate to In Situ Materials Utilization (ISMU) for the Space Exploration Initiative (SEI). There are three types of interaction between ISMU and the Environmental Control and Life Support System (ECLSS):

1. ISMU can reduce cost of water, oxygen, and possibly diluent gasses provided to ECLSS. A corollary to this fact is that the availability of indigenous resources can dramatically alter life support technology trade studies.

2. ISMU can use ECLSS waste systems as a source of reductant carbon and hydrogen, and

3. ECLSS and ISMU, as two chemical processing technologies used in spacecraft, can share technology, thereby increasing the impact of technology investments in either area.

Functions of Life Support

Sustaining life in space for long periods of time requires at a minimum (Humphries et al. 1990):

1) Maintenance of a breathable atmosphere with a partial pressure of O2 of .2-.3 bars, in a diluent gas with a total pressure of up to 1 bar. Leakage (only a few kg per day) must be replenished even on large spacecraft. A minimum of 2 kg is lost every time the crew exits an airlock.

2) Circulation of the atmosphere at velocity of ~3 m/sec to flush exhaled CO_2 away from the face. Forced circulation is required to compensate for the lack of natural convection in micro-g environments. The circulation rate for Space Station Freedom (SSF) will be about 1.36 m3/second or 142,000 kg per day.

3) Removal of the 1 kg/man-day of CO_2, and 1.8 kg of vaporized H_2O/man-day plus additional CO_2 and H_2O produced by research animals and equipment.

4) Control and removal of noxious trace constituents in the atmosphere.

5) Control of cabin temperature to 20-30 degree C and rejection of 4.4 kw-hr of heat per man-day, plus equipment loads, which generally are orders of magnitude larger.

6) A supply of potable water of about 2.6 kg per man-day.

7) Disposal of waste, including urine and fecal matter, with about 1.5 kg of moisture and 0.1 kg of solids.

8) A supply of food with a dehydrated equivalent to about 0.75 kg per man-day.

9) Disposal of packaging materials, about 0.8 kg/man-day.

10) Provision for personal hygiene and changes in clothing.

Design Solutions

System Closure and Physical Chemical Recycling

The history of spacecraft environmental control development has been one of using physical-chemical approaches to progressively increase the degree of closure and recycling of fluid constituents as mission durations became longer and longer. The availability of indigenous space resources may reverse this trend by providing an alternative to resupply of make up fluids from Earth. *Figure 1* shows the major mass flows of the life support system.

Even short duration missions like Mercury, Gemini, and Apollo recirculated the cabin atmosphere, the largest ECLSS mass flow (Diamant et al. 1990). CO_2 was removed from recirculated air by a non-regenerative LiOH cartridges and H_2O was removed by condensing heat exchangers. Skylab used a regenerative approach. Humidity control was provided by condensing heat exchangers and zeolites (molecular sieves) removed both H_2O and CO_2 using a pressure swing batch process. The gases were vented to space after the beds were modestly heated to enhance desorption. Ullage loses in such a system are quite large, since air equal in volume to the unfilled porosity in the bed is vented each cycle. Losses can be reduced by pumping air trapped between the mol sieve pellets back to cabin pressure. Even Shuttle uses the LiOH-condensing heat exchanger approach.

However, for the Extended Duration upgraded Columbia Orbiter, and amine stabilized in pellet form serves as absorbent in a pressure swing batch process.

Numerous emerging technologies can be made available for CO_2 and H_2O removal from air for the Space Exploration Initiative (SEI). Good system engineering practice as well as sound economic theory demands that the Figure of Merit on which to base technology selections for future programs is Life Cycle Cost. *Figure 2* shows a modification of the Lockheed view of Life Cycle Costs, adapted from the original form designed for unmanned Earth orbiting spacecraft. The modified diagram is appropriate to manned spaceflight with resupply sorties and possibly ISMU.

Four factors dominate considerations in life support technology selection for SEI:

1) First is the relative value of recovered gases versus the value of additional equipment required for their recovery. If there are no provisions to extract O_2 from CO_2, there is little incentive to recover CO_2. Similarly if the installation is water rich due to abundant water from H_2-O_2 fuel cells or importation of abundant H_2O in food, recovered water is of little value. If, on the other hand, photovoltaic or nuclear power is provided, water electrolysis is implemented and/or CO_2 is supplied to live plants or chemical reactors, then recovery of these gases may trade favorably on the basis of Life Cycle Cost.

2) The second factor is the relative savings from reducing heat rejection loads versus recovery of the gases. The latter is particularly significant for the small life support systems in space suits. Space suit systems must be particularly light, and heat rejection is one of the heaviest subsystems. The heat of condensation of H_2O plus the heat of CO_2 absorbent reactions represents about a third of the system heat rejection load. Relieving the heat rejection system of this 150-watt load allows radiator-based heat rejection to remove virtually all of the load in Earth orbit and a significant fraction of the load on the Moon. These radiator based approaches trade favorably on the basis of Life Cycle Cost.

3) The third factor is the relative cost of electric power versus makeup fluids. Almost all technologies that recover and recycle fluids require electrical energy. The trade between energy intensive air revitalization and low power venting approaches is dramatically affected by the cost of the electrical power. The cost of the power is in turn affected by the generation and storage technologies selected. Nuclear power generation is smaller and cheaper on a Life Cycle Cost basis that photovoltaic power, assuming that the energy is stored in regenerative fuel cells for power through the 14 day lunar night.

4) A fourth major factor is the relative cost of ISMU produced fluids and the cost of the recovery and purification by ECLSS. If the ISMU fluids are relatively inexpensive, then venting approaches are economically favored for base as well as space suit air revitalization.

One factor that can be of significance in ECLSS trades sits outside the framework of Life Cycle Cost modeling. That factor is the negative impact of venting gases on the scientific research of the mission. Recovery of the gases, despite and increase in Life Cycle Cost, may be appropriate if the performance of scientific experiments, particularly infrared-sensitive telescopes, is jeopardized by plumes of waste gases. The negative economic impact may be minimized if only intermittent curtailing of venting is required while the experiments are actually collecting data. If the cloud of waste gas can dissipate rapidly enough it will not obscure the telescope's critical operational spectral bands.

A critical emerging technology in venting gas purification uses hollow fiber membranes. Integrating membranes with facilitated transport in CO_2 solvents is being developed by both a Lockheed-AiResearch team and Hamilton Standard for NASA space suite applications. The membrane approaches depend on the differences in solubility and diffusively of H_2O and CO_2 from N_2 and O_2 to effect a high degree of separation. The space suite membrane systems vent the CO_2 and accompanying moisture to space vacuum. The systems have the advantage that O_2 and N_2 permeation through the membranes is significantly less than ullage losses with zeolite or amine packed beds. However, in larger spacecraft the gases could be recovered with a vacuum pump for further processing.

The ECLSS developed for SSF recovers both CO_2 and H_2O, although the initial installation will use a venting batch molecular sieve until SSF has enough power to run the CO_2 recovery and electrolysis systems. *Figure 3* illustrate the three alternative CO_2 reduction technologies developed in anticipation of Space Station needs (Noyes 1988). Space Station Freedom will mature the Sabatier process for CO_2 reduction sometime after Permanently Manned Capability (Carrasquillo et al. 1991). Alternative approaches with integrated electrochemically driven separation and CO_2 decomposition have been tested at the breadboard scale.

In systems which have an excess of water and a deficiency in oxygen, water electrolysis provides a well developed set of techniques. The excess water comes from importation of moisture in food as well as H_2 and O_2 for fuel cells. Most of the moisture or respiration and perspiration by the crew finds its way into the air and eventually the condensing heat exchanger. In most spacecraft, the highest-purity source of raw recycled water comes from condensing heat exchangers in the air revitalization circuit. Water electrolysis, described in the companion paper by McElroy (1992), is the method of choice for converting high purity water to oxygen. Limited processing is required to purify condensate to the standards needs by the electrolysis units. *Figure 4* illustrates the merits of three alternative approaches to water electrolysis. Space Station Freedom baselined the low temperature, low pressure aqueous KOH process (Carrasquillo et al., 1991). However, it is not scheduled for implementation until sometime after Permanently Manned Capability.

For shorter duration lunar mission, such as the proposed First Lunar Outpost with a maximum 45 day stay time, venting approaches to air revitalization are favored in Life Cycle Cost based trades. In conducting a trade study of application of a candidate approach using hollow fiber membranes to a lunar surface EMU for a extensive multi-year program of lunar exploration, Simonds et al (1991) used quantitative decision analysis methodology. *Figure 5* presents an inference diagram for the trade. Details on the use of inference diagrams are found in Howard and Matheson, 1984. *Figure 6* shows the results of the trade in terms of histograms of the risk adjusted present value of developing the membrane technology. In conducting the study the membrane approach was contrasted with the approach which recovered and recycled all of the moisture and CO_2 produced in the space suit. A condensing heat exchanger was used to recover the water and pelletized AgO was used to recover the CO_2. The dominant factor affecting the trade is the availability of relatively low cost water and oxygen from ISMU.

Trace contaminants in recirculated air are removed by activated carbon as well as by the condensing heat exchangers. The activated carbon can be treated with phosphoric acid and catalysts to broaden the range of compounds removed from the air stream. In terrestrial practice the carbon can be regenerated by heating a mildly oxidizing environment. However, the regeneration process has yet to be matured for space applications.

The least mature ECLSS technology is waste process. Most of the preferred solutions involve oxidation of the C-H-O compounds to CO_2 and H_2O, which in turn are decomposed to C, H_2 and

O_2. In so doing, the waste is sterilized and toxic organic compounds are destroyed. For most oxidation technologies, system size is inversely correlated with operating temperature. Higher temperature systems, such as for wet oxidation at conditions slightly in excess of the critical temperature and pressure (termed Supercritical Wet Oxidation), are smaller because residence time in the reactor can be reduced to a few minutes. However, higher temperature approaches require thick-walled pressure vessels and an assortment of control, material and safety obstacles which to date have not been completely overcome. One of the most severe problems identified during testing has been the buildup of insoluble inorganic salts in the reactor and associated plumbing (Armellini et al., 1990).

No fundamental first order problems are known to stand in the way of developing physical-chemical processes for the lunar phases of an SEI program. However, much of the technology is still at a low level of maturity. The less developed items will require successful testing of preprototype and prototype hardware prior to freezing of technology selections for any lunar application. Life support equipment is generally mechanically complex due to: 1) The necessity of minimizing design margins to a fraction of those appropriate in industrial process equipment from which much of it is derived; and 2) the complex valving and control systems necessary to remain fully operational after one or more failures. The final design, fabrication, and assembly of approved designs for flight hardware has proved slower than many other major spacecraft systems. For example, the life support equipment has been a pacing item in assembly of Shuttle Orbiter 105.

Sources of Technology

NASA's ECLSS R&D has emphasized development and packaging of ECLSS equipment,rather than starting with conceptual or immature technologies. The practice is quite appropriate, because there are well-supported programs to develop fundamentally new separation or transformation techniques in the chemical process, mineral processing, and synthetic fiber/membrane industries. These industries are dynamic and well funded because of the large market for municipal and industrial waste treatment and pollution control equipment.

There are numerous non-NASA government-sponsored programs that use physical chemical ECLSS devices. One of the major sources is the Navy's nuclear submarine life support development program. The submarine program has supported the development of water electrolysis such as the units described in the companion paper by McElroy. The submarine programs also have developed a range of CO_2 scrubbing and trace contaminant detection and removal technologies. Both the space and submarine applications require very high reliability hardware which can run for long periods of time with little maintenance or servicing. The principal difference between the requirements of a spacecraft and submarine is that spacecraft have much more restricted allocations of weight, electrical power, and heat rejection than nuclear submarines. Aircraft Environmental Control has been a major proving ground for fans, motors and regulators that can be used on spacecraft. However, because jet aircraft simply compress atmosphere as their source of breathing air and bleed air from the engine's compressors to run air cycle cooling, most of the major components have little commonality between aircraft and spacecraft. Armored ground vehicle environmental control also has been a source of contamination removal technology.

In addition to development of new unit processes, a vast improvements seem possible in reducing weight by material replacement. Many of the most significant reductions in spacecraft weight have been the result of improvements in advanced materials and fabrication techniques. As in the case of the development of fundamentally new life support processes, NASA programs can piggyback on well-funded programs of the synthetic fiber/membrane industry, fiber reinforced composite industry, metals industry, and the high technology ceramics manufacturers. Particular interest exist in use of lightweight composites in reducing the mass of fluid handling components, tubing and valves.

Bioregenerative Recycling

Bioregenerative systems would use plants, generally higher plants such as agricultural crops, (e.g. wheat, rice, lettuce, tomatoes) to remove the carbon dioxide from air and decomposition of wastes to make oxygen. Considerable detail in this area is presented in the preceding paper on Closed Ecological Life Support System (CELSS) development. CELSS technology is considerably less mature than the competing physical-chemistry approaches that have been studied for many years and have been implemented in a variety of test facilities. Man-rated CELSS test facilities are in development. The bioregenerative life support technology development process, like the physical-chemical processes, piggybacks on development funded elsewhere.

Role of Indigenous Space Materials Utilization

Many of the processes proposed for extraction of O_2 from lunar materials as well as gases adsorbed on lunar soil (H_2, He, N_2, C) lend themselves to integration with life support. The most obvious applications are as a source of gases to make up for leakage, ullage losses in devices like pressure swing molecular sieves, and losses during the reduction of H_2O and CO_2. A potentially more significant integration of resource extraction and life support is to utilize the 0.8 kg of trash and 0.1 kg of solids in urine and feces to provide a significant source of reducing agents that can be used in an ilmenite reducing process. These materials provide each day about 1.4 kg of carbon and 0.3 kg of H that can yield about 70 kg of oxygen before the reactants are lost to space as ulllage with the spent soil. *Figure 7* illustrates such a concept.

Conclusions

1) Indigenous space resources can be integrated with life support to reduce life cycles costs.

2) Both ISMU and ECLSS are chemical processing in space. They can share technology.

3) ISMU can offset the resupply penalties of venting life support. Venting life support systems are typically lighter and less power intensive that non-venting systems. Thus ISMU can reduce the Life Cycle Cost of the providing life support to future space exploration missions.

References

Armellini, F. J. Tester, J. W. 1990, Salt Separation during Supercritical Water Oxidation of Human Metabolic Waste: Fundamental Studies of Salt Nucleation and Growth, SAE Paper 901313, 20th International Conference on Environmental Systems, Williamsburg, Virginia, July, 1990

Carrasquillo, R. L., Carter, D. L. Holder, D. W. McGriff, C.F. and Ogle, K.Y., ECLSS Regenerative Systems Comparison and Subsystem Selection, SAE Paper 911415, 21st International Conference on Environmental Systems, San Francisco, California, July, 1991

Diamant, B.L. and Humphries, W. R. Past and Present Environmental Control and Life Support Systems on Manned Spacecraft, SAE Paper 901210, 20th International Conference on Environmental Systems, Williamsburg, Virginia, July, 1990

Howard, R. A. and Matheson, J. E. eds. *Readings on the Principles and Applications of Decision*

Analysis, 2 volumes, Strategic Decisions Group Menlo Park, CA, 1984

Humphries, W. R., Reuter, J. L., and Schunk, R. G., Space Station Freedom Environmental Control and Life Support System Design, SAE Paper 901211, 20th International Conference on Environmental Systems, Williamsburg, Virginia, July, 1990

McElroy, J.F. SPE Water Electrolyzers in Support of the Lunar Outpost, paper delivered at the University of Arizona/NASA Space Engineering Research Center and Indigenous Space Materials Utilization Advisory Panel Lunar Materials Technology Symposium. Tucson, AZ, February 1992.

Noyes, G. P. Carbon Dioxide Reduction Processes for Spacecraft ECLSS: A Comprehensive Review, SAE Paper 881042, 21st International Conference on Environmental Systems, San Francisco, California, July 1988

Figure Captions

Figure 1
The major fluid and material flow streams in supporting life on a spacecraft. These flows are sized for a Space Station Freedom size spacecraft with a crew of four. The immense flow of air is required to flush exhaled gases away from the crews face in zero-g. However similar flows are typical of office space in modern buildings. A large fraction of the hygiene water flow is for bathing and cloths washing.

Figure 2
Life Cycle cost terminology modified for Life Support System trade studies for NASA Manned Spaceflight programs with possible resupply and possible ISMU.

Figure 3
Three alternative CO_2 reduction approaches evaluated for Space Station Freedom.

Figure 4
Alternative approaches to water electrolysis.

Figure 5
Inference Diagram for the decision to develop membrane based EVA Life Support Technology. Rectangular boxes represent decisions. Ovals represent chance events or events determined by forces outside the control of the decision makers. The octagon represents the decision criteria, rick adjusted net present value in this case.

Figure 6
Results of decision analysis calculations (Simonds et al. 1990) comparing development of hollow fiber membrane approaches with non-venting approaches to revitalizing space suit air. In the recover/recycle approach a condensing heat exchanger recovered moisture. Carbon dioxide is removed by reaction with AgO to form $AgHCO_3$. The venting approach reduces the size of space suit by reducing heat rejection loads. The venting approach also eliminated the need for complex servicing equipment to desorb the AgO canisters and drain and clean the condensate tanks.

Figure 7
Flow streams associated with integrating life support waste streams into resource extraction.

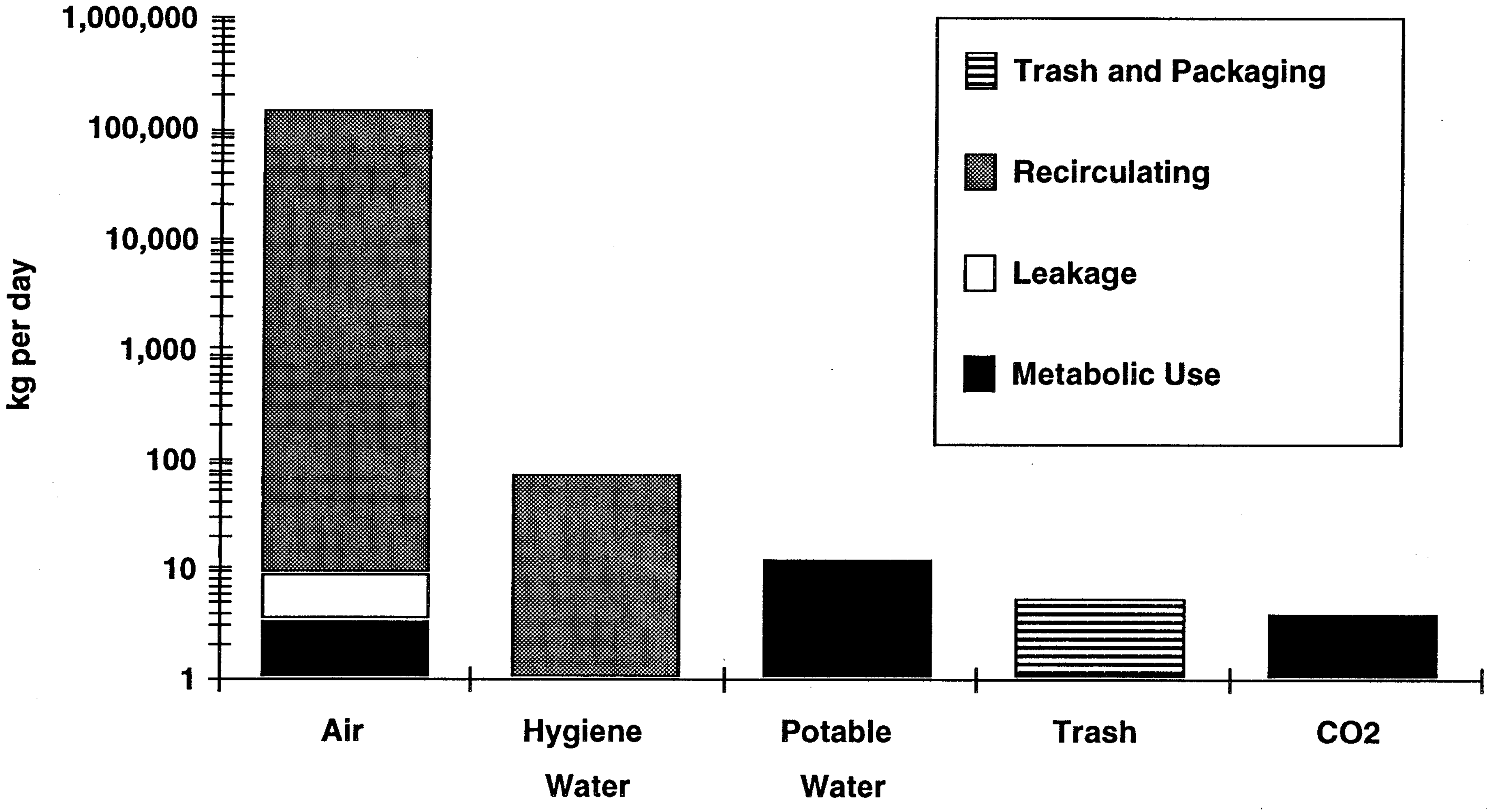
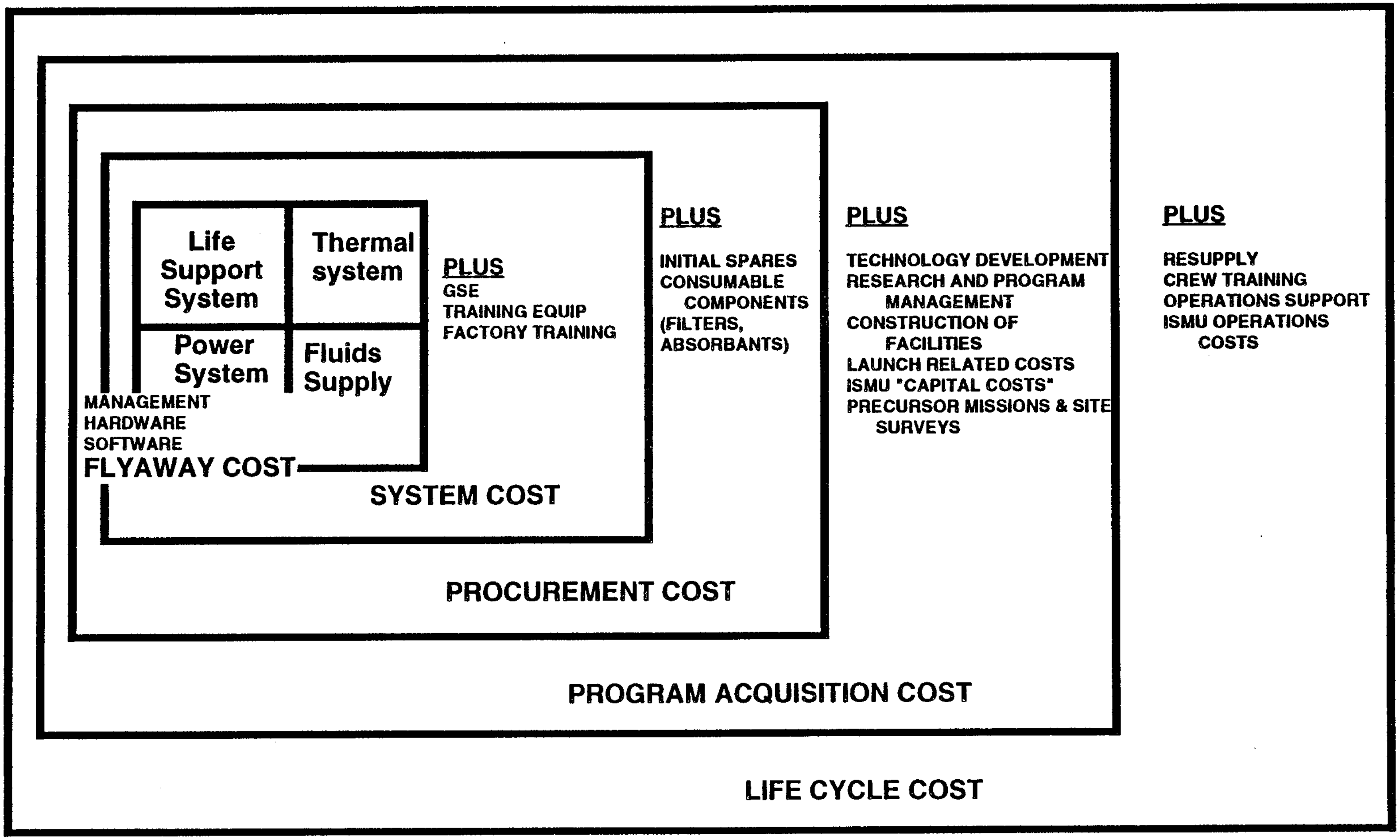

1,000,000
100,000
10,000
1,000
100
10
1
kg per day
Air
Hygiene Water
Potable Water
Trash
CO2
▤ Trash and Packaging
▨ Recirculating
☐ Leakage
■ Metabolic Use

FIGURE 1

LIFE CYCLE COST DEFINITIONS AND TERMINOLOGY



Life Support System

Thermal system

Power System

Fluids Supply

MANAGEMENT
HARDWARE
SOFTWARE

FLYAWAY COST

PLUS
GSE
TRAINING EQUIP
FACTORY TRAINING

SYSTEM COST

PLUS

INITIAL SPARES
CONSUMABLE COMPONENTS
(FILTERS, ABSORBANTS)

PROCUREMENT COST

PLUS

TECHNOLOGY DEVELOPMENT
RESEARCH AND PROGRAM MANAGEMENT
CONSTRUCTION OF FACILITIES
LAUNCH RELATED COSTS
ISMU "CAPITAL COSTS"
PRECURSOR MISSIONS & SITE SURVEYS

PROGRAM ACQUISITION COST

PLUS

RESUPPLY
CREW TRAINING
OPERATIONS SUPPORT
ISMU OPERATIONS COSTS

LIFE CYCLE COST

FIGURE 2

CARBON DIOXIDE REDUCTION SYSTEM FUNCTIONAL BLOCK DIAGRAMS

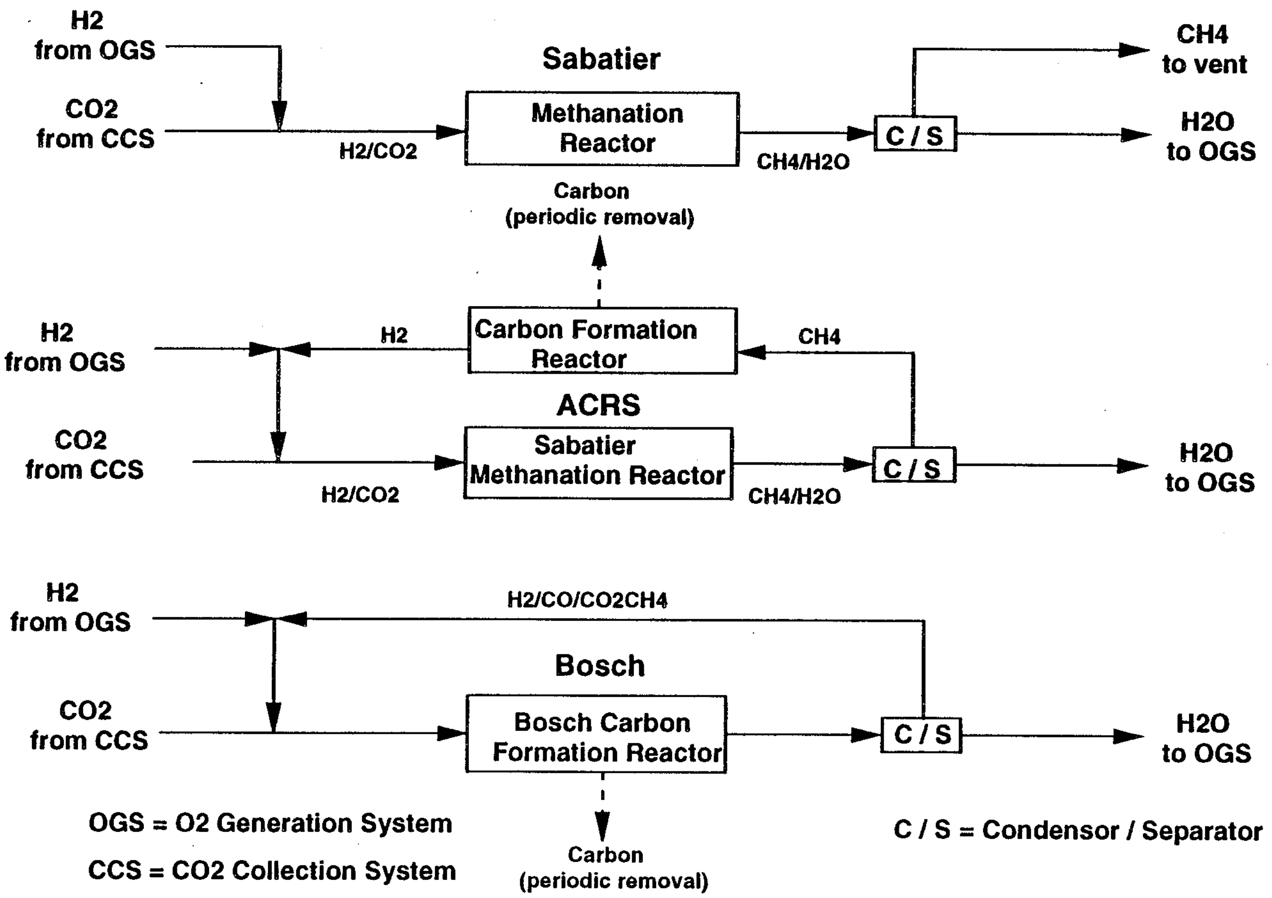


FIGURE 3

WATER ELECTROLYSIS FOR ECLS/ISRU INTEGRATION ISSUES

OPERATING MODE	LOW PRESSURE LOW TEMPERATURE	HIGH PRESSURE LOW TEMPERATURE	LOW PRESSURE HIGH TEMPERATURE	HIGH PRESSURE HIGH TEMPERATURE
ELECTROLYTE	KOH or SPE	SPE	CERAMIC	CERAMIC
ADVANTAGES	CURRENT TECHNOLOGY VERY SAFE	CURRENT TECHNOLOGY O2 DELIVERED AT HIGH PRESSURE	IDEAL FOR INTEGRATION WITH REGOLITH REDUCTION AND THERMIONIC POWER MOST EFFICIENT REDUCES CO2	POTENTIALLY SMALLEST, LIGHTEST APPROACH O2 DELIVERED AT HIGH PRESSURE REDUCES CO2
DISADVANTAGES	LARGE VOLUME AND WEIGHT REQUIRES COMPRESSOR FOR HIGH PRESSURE O2 USE	LEAST EFFICIENT PRESSURE SAFETY ISSUE	DEVELOPING TECHNOLOGY REQUIRES COMPRESSOR FOR HIGH PRESSURE O2 USE	NOT DEMONSTRATED TO DATE SERIOUS SAFETY ISSUES

FIGURE 4

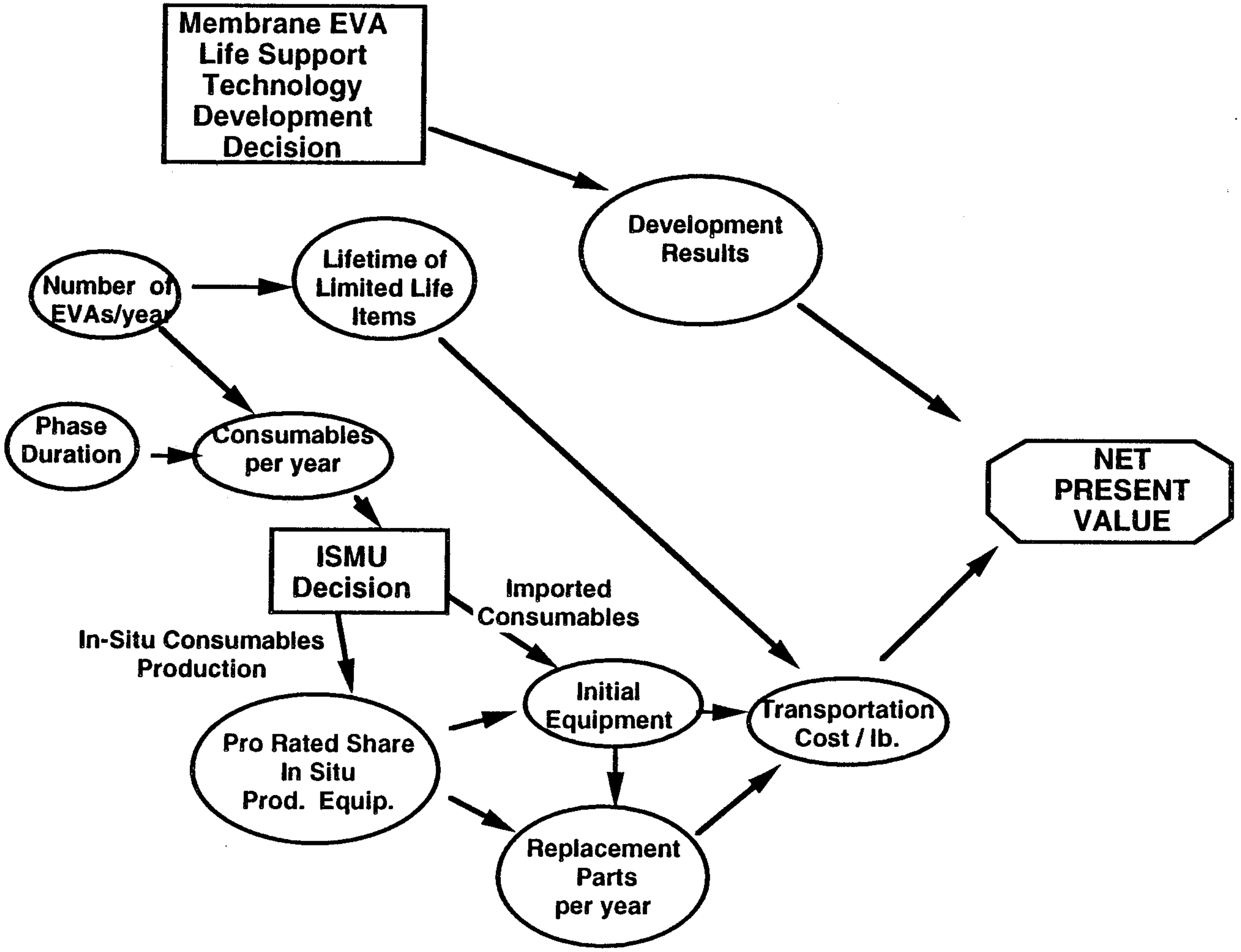

Membrane EVA Life Support Technology Development Decision
Development Results
Number of EVAs/year
Lifetime of Limited Life Items
Phase Duration
Consumables per year
ISMU Decision
Imported Consumables
In-Situ Consumables Production
Initial Equipment
Transportation Cost / lb.
Pro Rated Share In Situ Prod. Equip.
Replacement Parts per year
NET PRESENT VALUE

FIGURE 5

Histograms of Life Cycle Cost Reduction With Venting Membrane EMU Air Purification

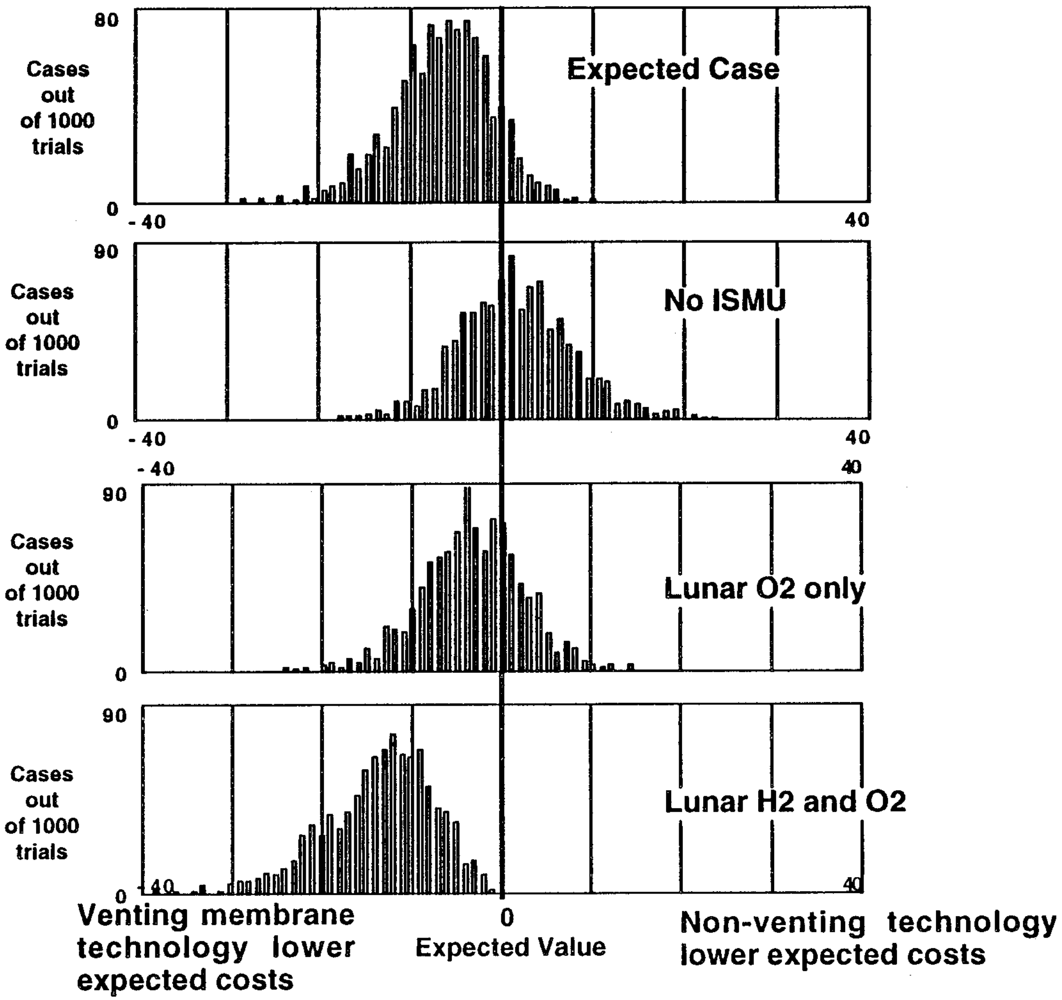


FIGURE 6

INTEGRATION OF LIFE SUPPORT WASTE STREAMS INTO ISMU

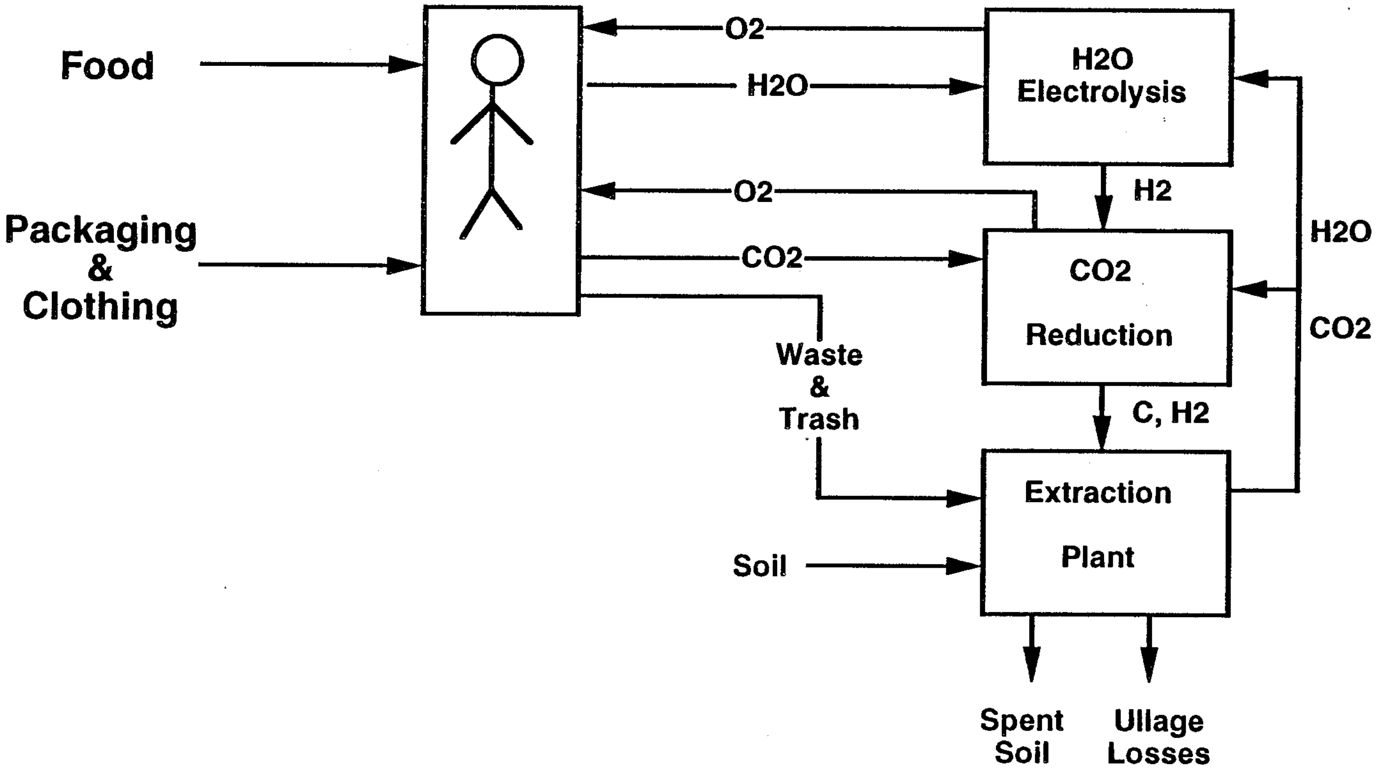


FIGURE 7