THE ENVIRONMENTAL CONTROL AND LIFE-SUPPORT SYSTEM FOR A LUNAR BASE—WHAT DRIVES ITS DESIGN

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INTRODUCTION

What is the likely design of an environmental control and life-support (ECLS) system that initially supports 4 crewmen during intermittent 10-day periods and ultimately supports 20 to 50 crewmen on a permanent basis? How much does it weigh, and what is its size (or volume)? The first question is ambiguous and unanswerable. The second is more specific but equally unanswerable until the mission ground rules are specified and until more information is given on systems other than the ECLS system and on the operational scenario of the base. Once specified, ground rules often become early absolute design drivers that negate some of the trade-offs of options, whereas details of other base systems and the base operational scenario often become design drivers that support and focus trade-offs between technology options. The purpose of this paper is to identify and briefly discuss some of the ground rules and mission scenario details that become drivers of the ECLS system design and of the logistics related to the design.

This paper is written for mission planners and non-ECLS system engineers to inform them of the details that will be important to the ECLS engineer when the design phase is reached. In addition, the examples illustrate the impact of some selected mission characteristics on the logistics associated with ECLS systems. The last section of this paper focuses on the ECLS system technology development sequence and highlights specific portions that need emphasis.

FACTORS THAT DRIVE SYSTEM SELECTION

As stated in the introduction, some ground rules become absolute design drivers that negate additional trade-offs. Since their impact is absolute, they will be discussed first.

Life-Cycle Costs vs. Initial Costs

The selection of either life-cycle costs or initial costs as a ground rule, coupled with the mission duration and crew size, becomes an absolute driver relative to the first-order design decision, i.e., to carry only expendables (nonregenerative system) or to reclaim usable products from wastes (regenerative system). The terms nonregenerative and regenerative will be used in this paper rather than open and closed, because they are more technically correct. Seldom will any ECLS system loop be totally closed.

Table 1 presents a highly simplified summary of the relationship between mission cost elements, mission duration, and the type of ECLS system. As shown in the table, the regenerative ECLS system is the only viable candidate for long-duration missions when life-cycle costs dominate. A permanently manned lunar base is certainly a long-duration mission, and it would be folly to adopt any costs other than life-cycle costs to dominate design studies. This particular discussion topic could end here, since only one option is viable for a manned lunar base; however, it appears prudent to explain the elements of Table 1 to clarify the rationale.

The terms short-, medium-, and long-duration missions are relative. Certainly the space shuttle missions of 7 to 10 days are short missions, and the ECLS system is nonregenerative. Certainly a permanent manned lunar base with years of occupancy is a long-duration mission. A medium-duration mission is difficult to define, but 30 to 90 days is reasonable.

The cost terms have been defined by *Hall et al.* (1985) relative to their use in ECLS system studies. The initial cost includes the cost to design, develop, test, and evaluate (DDT&E) the first flight model; the cost of the flight-unit spares and consumables for the initial launch; the ECLS system integration costs; and the programmatic costs. Life-cycle costs include the initial costs plus the operational costs. Operational costs include the cost of spares and consumables to operate over the mission duration; transportation costs of the spares and consumables; transportation costs of the initial flight units; and maintenance costs for the mission.

For long-duration missions, the operational costs are the drivers. Nonregenerative ECLS systems feature low DDT&E and flight unit costs, very high operational costs due to the transportation costs of the spares and consumables, and resulting very high life-cycle

TABLE 1. The applicability of nonregenerative and regenerative ECLS systems relative to initial and life-cycle costs.

	Initial Costs Dominant	Life-Cycle Costs Dominant
Short-Duration Missions	Nonregenerative	Nonregenerative
Medium-Duration Missions	Nonregenerative	Regenerative
Long-Duration Missions	Not applicable	Regenerative

costs over a lengthy mission duration. Regenerative ECLS systems feature opposite characteristics: high initial costs due primarily to expensive DDT&E costs, modest operational costs, and resulting lower life-cycle costs relative to those of nonregenerative systems.

To illustrate this discussion, a specific example has been extracted from *Hall et al.* (1985). Nonregenerative and regenerative techniques for removing CO_2 from the habitable environment and supplying O_2 to the environment of an Earth-orbiting space station were priced. The mission model included a crew of 6, a mission life of 10 yr, and a resupply period of 90 days. Table 2 presents the cost analysis. The accuracy of a cost analysis of this type depends on having access to factual flight costs and to the skill to which the ECLS system engineer can evaluate the DDT&E costs, spares required, maintenance costs, etc. It is obvious, however, from the example given in Table 2 that even if the cost analysis is not highly accurate, the difference between the operational and life-cycle costs of nonregenerative and regenerative systems is sufficiently large to mandate a regenerative approach. For missions of the type being proposed for early operational lunar bases, i.e., staffing at a level of 4 to 20 crew persons for multiple years, the technology of regenerative ECLS systems becomes an enabling technology.

TABLE 2. Cost analysis (in millions, 1984 dollars) for nonregenerative vs. regenerative CO_2 O_2 supply for a 10-year mission.

	Nonregenerative CO_2 Removal-LiOH* O_2 supply-stored	Regenerative CO_2 Removal-EDC† O_2 supply-Sabatier‡, SFWE§
Initial Cost	16.68	38.75
Operation Cost	783.83	129.35
Life-Cycle Cost	800.51	168.1

*LiOH-Lithium hydroxide.
†EDC-Electrochemical depolarized cell.
‡Sabatier-A CO_2 reduction reactor (to produce water).
§SFWE-Static feed water electrolysis (to produce oxygen).

Inheritance from an Earlier Program

One of the ground rules frequently used in lunar base mission studies is that systems (such as the ECLS system) to be used on the base will feature space station inheritance. This is a rational ground rule provided two assumptions are valid: an Earth-orbiting space station will precede the lunar base (highly likely), and the space station ECLS system is applicable to the lunar base (likely but not assured). If these two assumptions are valid, the ECLS system delivered to the Moon would be essentially "off-the-shelf" hardware resulting in high reliability at a modest initial cost. The second assumption, however, requires some discussion before being accepted as sacrosanct. The current space station reference configuration ECLS system features water reclamation and O_2 recovery subsystems. The water reclamation system is targeted for 95% to 97% water loop closure. If this target is met, the water reclamation system could well meet the needs of a lunar base. Tight schedules, limited funding, and any underestimate of the magnitude of the development effort required to advance the reclamation subsystem to the necessary maturity level could lead to a reduction in the water loop closure. The 95% to 97% closure requires reclamation of humidity condensate, wash and hygiene water, and urine. A decision to downgrade the reclamation subsystem to one, processing only humidity condensate by a simple filtration unit, would reduce water loop closure to the degree that it would no longer meet the needs of a lunar base. The same situation exists with the O_2 reclamation subsystem. The current space station baseline ECLS system includes an O_2 reclamation subsystem featuring a regenerable CO_2 concentrator, a CO_2 reduction reactor, and a water electrolysis unit to produce O_2. A fall-back position would be to retain the regenerable CO_2 concentrator, but drop the two units required to generate O_2. The Skylab spacecraft was flown in this configuration. Should the space station program make this decision, the lunar base ECLS system designer would need to add to the inherited baseline system. Inheriting an incomplete O_2 reclamation loop would not be as severe a problem as inheriting an incomplete water reclamation loop. The weight of O_2 needed is much less than the weight of water needed per unit of time. In addition, the quick achievement of a lunar LOX production facility (for propulsion use) would eliminate the need for an O_2 recovery loop in the ECLS system.

There is another important consideration relative to adopting a space station inheritance ground rule for the lunar base ECLS system. The inheritance ground rule would be most applicable to lunar base development scenarios that also inherit space station modules, a modular-type growth pattern, and a space station-type power system. The effect of these will be discussed in more detail in later portions of the paper.

A good way to conclude the discussion of a space station inheritance ground rule is to recommend an approach to lunar base program managers and ECLS system engineers. Space station inheritance is a good principle. It should be continually evaluated. It may result in the most reliability for the least cost; however, at this early stage in lunar base studies, it should not be accepted as a sacrosanct ground rule. It may lure the lunar base program manager into a feeling of false security, and the ECLS system may not meet the needs of the lunar base.

Self-Sufficient Base

The ground rule for a self-sufficient base is difficult to properly treat in a brief discussion. This ground rule extends beyond the ECLS system, but in this paper the discussion will be limited to its relationship to the ECLS system. Relative to the ECLS system, it is a ground rule that most likely cannot be achieved. Even the most optimistic projection of technology by *MacElroy and Klein* (1985) suggests a bioregenerative life-support system intended to recycle 97% of the mass that it contains. MacElroy and Klein state that some quantities of H_2, C, and N_2 will always be brought from Earth. The issue of N_2 logistics is discussed in detail later in this paper.

After accepting the fact that self-sufficiency within the ECLS system may not be achieveable, it is important to consider the intent of the ground rule and work toward this intent rather than the absolute definition of the term. The intent is to make the lunar base as autonomous as possible and to eliminate Earth-to-Moon logistics to the maximum possible extent. Within the ECLS system, this translates to keeping materials losses to the minimum, attempting to recover useful materials from every waste product, and increasing the closure of the food loop. The first two of these objectives are valid for all lunar base ECLS system designs, so the self-sufficient ground rule has little efffect on the design. Thus, the new factor that is introduced is the attempt to close the food loop. An attempt to close the food loop would be a major driver in the design of an ECLS system. Until the addition of food generation, lunar base ECLS systems will likely be based on physical and chemical processes. With the addition of food generation, bioregenerative processes will be added that may cause the physical and chemical processes to be modified.

Why not just include bioregenerative processes in the beginning? The technology is not ready for inclusion as a baseline. The processes are inefficient and high in energy demand. Early lunar bases may not be capable of meeting the demand. When these two limits are overcome, one more issue must be addressed. The total costs of including the "more closed food loop" must be traded off with the total costs of not including it. Total costs include many resources other than dollars: energy, space, crew time, monitoring, control equipment, etc. As long as the food that is carried from Earth is acceptable, there is no reason to attempt to generate it on the lunar base until it provides some type of payoff. When the technology for bioregenerative systems is established and mission trade-off studies conclude that it is time to integrate them into lunar base designs, it will become a major driver of the ECLS system.

FACTORS THAT DRIVE SUBSYSTEM SELECTION AND SYSTEM DESIGN

These factors are considered relative to a specific base design and development scenario. There is no priority betwen them. They each affect different elements of subsystem selection and system design.

Power Level and Type of Power System

The available power level could well be placed in the category of overpowering design drivers. Without adequate power, there can be little regeneration by the ECLS system. An overly generalized but true statement is that the more power available, the more regeneration can be accomplished and the more wastes can be processed to reduce weight, volume, and offensiveness.

In a recent in-house study conducted by the Spacecraft Analysis Branch (SAB) of the NASA Langley Research Center, a baseline regenerative ECLS system supporting a Phase II lunar base (four crew persons; intermittent operation) evolving into a Phase III lunar base (eight crew persons; continuous operation) was defined. The ECLS system included both water and O_2 recovery, whole-body bathing, clothes washing, solid-waste processing, and contaminant control. Thus, the proposed ECLS system was regenerative to the maximum degree short of attempting to generate food. This is the type of ECLS system most applicable to early continuously manned lunar bases. The electrical power requirements for the Phase II and Phase III ECLS systems were 10.5 kW and 21.2 kW, respectively. The requirements are misleading, however, if used at face value, because they are peak requirements and should not occur frequently. The average values should be significantly lower.

If mission planners and ECLS system engineers develop a base operational scenario that would time phase some of the ECLS system operation, the peak and the average power-use profiles could be lowered. Mission planners and ECLS system designers need to work closely to "smooth out" the utilization of the power resource while still providing optimum service.

Another qualification of the power values can be illustrated by using the Phase II ECLS system power level of 10.5 kW as an example. It would be a mistake to conclude that the required level of 10.5 kW is due primarily to the inclusion of a regenerative ECLS system. Only 34% of the 10.5 kW can be charged directly to regenerative subsystems or to subsystems that are available because regeneration is included, i.e., whole-body shower and washable clothing.

One technique used by the ECLS system engineers to trade off the impact of regeneration on the power system and to trade off candidate subsystems within the ECLS system relative to their power-use characteristics is the use of the power penalty factor. The power penalty will be stated as a finite number, for example, 250 lb/kW. For every kilowatt of power demand by the ECLS system, the power system weight would be increased by 250 lb. Thus, the 250 lb has to be charged to the ECLS subsystem to determine its equivalent weight. The power penalty is not determined by the ECLS system; it is determined by the state of the art in the design and development of power systems.

Another power system characteristic that may have a large impact as an ECLS system design driver for advanced lunar bases is the availability of excess heat, referred to as "waste heat," from the power system. It was previously stated that regenerative ECLS systems need power. More specifically, they require energy, and it can often be in the form of heat energy rather than electrical energy. The availability of waste heat delivered to the ECLS system through a high-temperature fluid can significantly reduce the electrical energy that would have been required to provide the heat by the use of electrical resistance heaters. Hot fluid loops can be used to raise bed temperatures of solid sorbers (silica gel, molecular sieves, activated carbon, etc.) that use heat and vacuum to desorb (regenerate) the solids. Temperatures in the range of 350°-400°F are satisfactory. Waste heat can also be used to provide energy for phase-change water reclamation subsystems (air evaporation and vapor diffusion). Lower temperatures in the range of 150°-180°F are adequate for these applications. Both of these temperature ranges can easily be obtained with nuclear power systems. Before waste heat is accepted as a panacea, however, the difficult tasks of delivery, control, and maintenance of a waste heat loop containing a hot fluid in the range of 350°-400°F must be engineered. At this date, the availability of waste heat and the practicality of its use appear to coincide with the development of a mature lunar base where a nuclear power system and the ECLS system can be integrated into a "city utility" concept.

The Gravity Factor

The lunar one-sixth gravity field is a design driver that is unique to a lunar base when compared with space systems that will have preceded the lunar base. This driver will have less impact if the previously discussed ground rule of space station inheritance is applied, because the design will have previously been established. A design developed for the space station will be tailored for zero-gravity operation. It should also be functional in the one-sixth gravity field, but it may be more complex than necessary for use on the Moon. If designed specifically for lunar base use, the ECLS system design could use the gravity field to aid in waste collection and transfer, liquid/gas phase separation, transfer of fluids, and in the use of personal hygiene facilities such as the whole-body shower. If inheritance of a space station zero-gravity functional ECLS system does not occur and the ECLS system is designed specifically for the lunar base gravity field, subsystem selections will change.

Base Layout and Composition

The base layout and composition are other design drivers that are unique to the lunar base ECLS system. With previous and current spacecraft systems, the ECLS systems have been centralized compact systems within a single pressurized vehicle. Even space stations with multiple modules represent a more central core complex than possible lunar base layouts. With tight clustering, an ECLS system or subsystems supporting more than one habitat can be envisioned. As habitats spread away from each other, they will likely have to be self-contained. The mass flows of solids, liquids, and gases between the habitats and the processing subsystems are small. Lengthy plumbing lines would be incompatible with balancing the mass flows. Pumping would be an added problem. For the "city utility" ECLS system concept previously mentioned to be practical, the base must include a large crew providing a continuous large supply of wastes and using reclaimed material on a matching continuous basis. The flows need to be sufficiently large to prevent waste inputs or use of resources by a single individual habitat from significantly perturbing the flow.

The composition of the lunar base will also be an ECLS system design driver. Simultaneous operation of a continuously manned habitat area (with or without attached laboratories), a LOX production plant, a detached and remote observatory, a storage and maintenance shed, remote stations, etc., will undoubtedly impact ECLS system design. Separate ECLS systems of different types would probably be needed. For example, a continuously manned habitat cluster will require a more complex ECLS system (probably regenerative) than an observatory that is manned periodically (probably nonregenerative and containing fewer functions). Perhaps the most important part of this issue is yet to be resolved. What kind of internal environment do these "nonhabitat" facilities have to provide? Are they pressurized? Are we providing an environment for shirt-sleeve operation, or are we going to mantend these facilities with astronauts in pressure suits? What are the thermal control requirements for both the crew and the equipment? The answers to these questions may not be design drivers for the initial lunar base with a small crew and a tightly clustered habitat area; however, as the base expands into a complex habitat with lunar production and a scientific complex, base layout and composition will become major design drivers.

Use of the Lunar Environment

A decision that the lunar environment can or cannot be used in the operation of the ECLS system is a significant design driver, specifically in the selection of processes and subsystems to provide specific functions. The lunar environment offers unlimited hard vacuum, high and low temperatures, and potential waste disposal areas. Two of these, vacuum and high temperature, are commonplace in an ECLS system and are normally acquired at the cost of electrical power and additional hardware elements (vacuum pumps, heaters, blowers, etc.) If the lunar environment can be utilized, considerable savings in ECLS system weight, volume, and power could be realized. Two examples can be used to illustrate how the environment can be used. In an ECLS system that does not reclaim O_2 from CO_2, the CO_2 still must be removed from the habitable atmosphere. A leading candidate for this function is to use molecular sieves to selectively adsorb CO_2 from a cabin airstream. After the bed of molecular sieves is saturated with CO_2, it must be desorbed. This could easily be accomplished by venting the bed to the lunar vacuum. Another example is to use the lunar cold and vacuum to vacuum/freeze-dry wastes including human feces and miscellaneous garbage. The environment would then provide an ideal sterile storage for the processed waste material. A variation of this approach is to process the waste material in the habitat or other enclosed structure and expose the material to the lunar environment (disposal) only after it has been sterilized. Several possible approaches are available depending on how the lunar environment conditions are worked into the processing and storage scheme.

The opposite approach to the above is often suggested, i.e., no venting of gases to the environment or storage of wastes on or under the lunar surface. An absolute adherence to this position would be a significant ECLS system design driver. It would eliminate the use of all ECLS system processes that require venting to operate. It would add additional components to the molecular sieve CO_2 removal unit to store the desorbed CO_2 for return to Earth. It would also restrict the use of the Sabatier CO_2 reduction unit (which produces water) because it could no longer vent methane to the outside environment. As any one unit is eliminated, the effect may cascade throughout the subsystem because some of the units are practical only when integrated with other specific units *Quattrone* (1981). There are valid reasons for the approach of isolation between the lunar environment and the ECLS system; however, total isolation between the two will be technically difficult and practically impossible. Regardless of the ultimate decision on how the lunar environment can be used, the decision will become a design driver.

Intermittent or Continuous Occupancy

This mission operational feature may ultimately become one of the major design drivers. There are at least two entirely different types of impact that it may have on the ECLS system design. The first impact is to again raise the issue of nonregenerative vs. regenerative systems. For an intermittently occupied base, a likely scenario would be to include an air revitalization subsystem with a regenerable CO_2 removal unit, but without units for subsequent O_2 recovery. The ECLS system could also include a simple filtration-type water recovery unit for processing humidity condensate, but not include the more complex water recovery unit for processing wash water and urine.

The second type of impact relates to operation of the ECLS system. There are four problems with an intermittent operation scenario: complexity of startup and shutdown procedures, protection of the ECLS system during the down periods, matching of process flows with use rates, and maintenance of sterility of the process loops. The first three problem elements are readily apparent, but the fourth one needs some explanation. Testing experience to date with water recovery subsystems has repeatedly demonstrated that maintaining acceptable microbiological conditions throughout the entire water management subsystem (process unit, plumbing, storage tanks, etc.) is difficult. It is especially difficult during shutdown periods between operations. At many locations throughout the subsystem, there will be sufficient moisture and temperature to support microbial growth. The addition of waste waters with their inherent supply of nutrients then completes setting up the environment in which microbial growth can flourish. As was necessary during ground testing, each operational period may need to be initiated by a complete water management subsystem sterilization. The only completely satisfactory way to accomplish this during testing has been steam sterilization. Steam sterilization requires water, power, and subsystem components that are not damaged by steam. It also requires a subsystem design that accommodates the injection and passage of steam. The microbial problem associated with intermittent operation of water management subsystems will be a design driver in the selection of subsystems and in the operational scenarios. The problem may even preclude the use of complex, regenerative water reclamation subsystems until the base is continuously manned and the water reclamation subsystem can be operated continuously in a mode that maintains an acceptable microbial profile.

Safety and Convenience of Operation and Maintenance

Up to this point in the discussion of factors that drive subsystem selection and system design, the factors discussed were those more associated with characteristics of the overall mission and systems other than the ECLS system. There are some important factors that are inherent within the candidate ECLS system processes and hardware configurations and have little to do with the overall mission characteristics. These factors could be discussed under numerous titles, but safety and convenience are certainly appropriate. No one takes exception to the statement that the ECLS system must be safe to operate and maintain. The difficulty is to define "safe" or its corollary, "unsafe." Many of the candidate processes involve producing and handling gases such as H_2, O_2, CH_4, CO_2, and NH_3. High-temperature fluids, including the previously mentioned steam and waste-heat fluid loops, may be present. High pressures are also possible. One advanced concept discussed by *Sedej* (1985) for combining functions of water reclamation and waste processing operates at a pressure of 250 atm and temperature of 670°F. This concept has great potential when the lunar base ECLS system advances to the "city utility" type of operation, but it is not likely to be factored into a habitat based on space station-type modules where the crew lives alongside the ECLS system. Safety considerations extend beyond normal operations into planned and unplanned maintenance. The hazard of "breaking into" or "opening" a process for maintenance can be a problem. Once beyond the safety issue, the next consideration is one of convenience and time. Crew time is a valuable commodity, and demand on crew time is certainly a driver in the selection and design of the ECLS system.

It was not intended in this paper to discuss all the trade-offs that occur within the ECLS discipline while arriving at a proposed design. The primary reasons for including this short discussion on safety and convenience are twofold. First, safety and convenience are important, and second, it is only fair to acknowledge that many of the design drivers are still under control of the ECLS system engineer rather than in the hands of the mission planner. The ECLS system engineer still has to advance process and hardware technology to the extent that advantageous concepts resulting in the most efficient mission scenarios can be incorporated into the designs in an operational mode that is within limits of safety and operational convenience.

FACTORS THAT IMPACT INITIAL LAUNCH AND RESUPPLY LOGISTICS

There is a group of factors that have little effect on ECLS system design and subsystem selection (once the decision to regenerate is made). They do, however, have a large effect on the final weight and volume totals for the initial launch and resupply logistics. They will be discussed separately, but in reality, their effects are interlocked.

Crew Size

The ECLS systems design engineers routinely work with crew needs and effluents in units of pounds per man-day. A typical needs/effluents mass balance is shown in Fig. 1. Each crewman

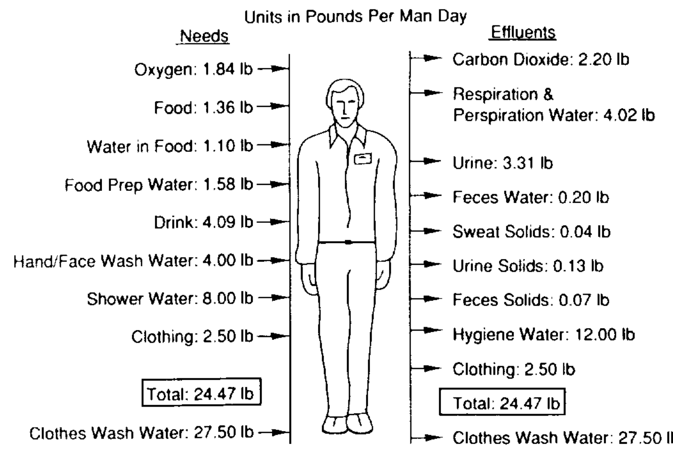

Fig. 1. Typical needs/effluents mass balance.

has to be supplied with 24.47 lb of supplies per day, and if clothing is washed, the number climbs to 51.97 lb of supplies per day. Current ECLS system technology and technology projected into the near future cannot close all the loops recycling useful materials from the effluents side of Fig. 1 back to the needs side. The O_2 requirement can be recovered from CO_2, although make-up O_2 will be required for leakage, air-lock losses, and emergency repressurizations. A large percentage of the total water needs (90% is a reasonable estimate) can be recovered. The food and food water will need to be transported from Earth. In addition to these expendables (total needs minus total regenerated), other expendables are present in food preparation items, waste handling packages, etc. The total weight and volume of the expendables that need to be launched and resupplied are then directly proportional to crew size and to the resupply interval.

There is another more subtle effect of crew size on ECLS system design. Subsystem developments during the past 25 years have evolved to a crew size of 4 as the target for full-scale models. A crew size of four is consistent with early space station crew size concepts and with individual modules of later, more advanced space station concepts. There is another reason, however, why the four-man-sized subsystem has persisted. It has proven to be a practical, convenient-sized unit to develop, test, and "handle." Process rates associated with four-man subsystems are in the general range of those "most easily controlled." Four-man-sized subsystems are also of the size to rack up efficiently in a habitat module. The four-man-sized subsystem may not remain the target size for development, but, if it does change, it is likely to remain within a three- to six-man range. At some point in the development of advanced lunar bases when crew sizes reach above approximately 15 to 20 (an estimate), individual four-man-sized subsystems may no longer be efficient.

Advantages may be gained by upscaling the subsystems. A reasonable estimate of the time in the base development at which the optimum subsystem size will change is the point at which the base is supported by a "city utility" type system as opposed to individual ECLS systems for each habitat unit.

Resupply Interval

This factor is tightly coupled with crew size relative to its impact on launch and resupply logistics. Once the quantity of expendables per man-day has been determined, a simple multiplication with crew size and resupply interval quickly establishes the resupply weight and volume logistics. The ECLS system expendables will probably not be the prime factor in establishing the resupply interval. The interval will most likely be determined by crew rotation needs, base assembly schedules, or possibly by the need to supply replacement units and maintenance items for the various lunar base systems, including the ECLS system.

Redundancy and Fail-Operational/Fail-Safe Ground Rules

A discussion of the rationale supporting redundancy and fail-operational/fail-safe ground rules is beyond the scope of this paper. There will be many disciplines involved in setting the ground rules, and the ECLS discipline is one of them. Certainly the reliability of the ECLS system and the time-related impact of subsystem failures within the ECLS system will be a key issue in setting the ground rules; however, this paper is addressing only the impact of the ground rules on launch and resupply logistics.

A very conservative and oversimplified ground rule would be that, because the ECLS system is so vital to a lunar base, the entire system has to be redundant. That would double the launch weight and volume and result in penalties that are not acceptable. There is no reason, for example, for including two sets of stored food, two galleys, and two sets of duct work for air distribution. The ECLS system engeineer would need to examine the total system on a subsystem-by-subsystem (probably component-by-component) basis relative to the ground rule. Then the impact of redundancy on logistics could be assessed. In the SAB study of ECLS systems for a lunar base, an assumption was made that only the air revitalization subsystem of the proposed ECLS system for a habitability module needed to be redundant. The assumption is valid only for that specific study. Adding the redundant air revitalization subsystem increased the launch weight by 872 lb and the launch volume by 69.1 ft^3. If a redundant water reclamation subsystem had been included, an additional 392 lb of launch weight and 38.5 ft^3 of launch volume would have been added. These values are for redundant reclamation units only. They do not include additional tankage and plumbing. Obviously redundancy adds significant increases in weight and volume. It also drives up the initial and total mission costs. Mission planners and project managers should work closely with the ECLS system engineer to develop a sensible rationale for redundancy so that mission safety and success can be achieved with minimum impact on the logistics.

Degree of Water Loop Closure

By examining the needs and effluents values on Fig. 1, one can initially conclude that the water loop can be closed. Water needs (water that must be supplied as free water) total 45.17 lb per man-day (1.58 + 4.09 + 4.00 + 8.00 + 27.50). Water that is available for recovery totals 46.83 lb (3.31 + 4.02 + 12.00 + 27.50). The additional water was gained from the water in the food and in water produced by metabolism. Then, if one assumes 100% recovery, the loop should show a net daily gain. Most engineers realize 100% recovery is not feasible, but 97% recovery has been suggested in numerous space station planning documents. At 97% recovery, the water balance still shows a slight net gain, 0.25 lb per man-day. Past experience with development testing, however, indicates that the 97% recovery is not realistic.

There are many ways in which useful reclaimed water can be lost. Two of the leading waste-water processing techniques end with a brine (residual water with a high concentration of salts and solids) that will likely be dumped, or stored and returned to Earth. There may be batches of reclaimed water that will not meet water quality standards, and reintroducing them into the recovery subsystem is not desirable. Leaks and spills will occur. The net result is that 90% recovery is more realistic, although, in fact, it still may be an optimistic estimate. Assuming 90% recovery to be achievable, the water balance now shows a net daily loss of 3.02 lb per man-day. This loss translates to 12.08 lb per man-day for a crew of four and 10-87 lb per crew for a 90-day resupply period. Based on shuttle tankage data, typical water tanks carry 162 lb (165 lb - 3 lb ullage) of available water and weigh 50 lb. Thus, approximately seven tanks with a total weight of 350 lb are needed. The total weight at the 90% recovery level is now 1437 lb per 90-day period. Any variation from the 90% recovery causes a proportional change in total weight. The primary message in the above discussion is that a closed water loop cannot be assumed, and the recovery percentage that is achieved will significantly impact launch and resupply logistics.

Volume of Pressurized Structures

Supplying the gases for pressurizing structures on a lunar base will always significantly impact launch and resupply logistics. In the SAB lunar base study previously mentioned, calculations determined that 554 lb of O_2 and tankage and 1573 lb of N_2 and tankage were required to pressurize and support the habitat area for the first 90 days. The pressurized volume was 9383 ft^3 (1 module and 2 nodes) at a pressure of 14.7 psia. A two-gas atmosphere was assumed, and an O_2 recovery subsystem was included. After the first 90-day period, each 90-day resupply must include 384 lb of O_2 and tankage and 742 lb of N_2 and tankage. Note that even though the ECLS system recovers metabolic O_2 from CO_2, O_2 make-up is required for emergency repressurization, leakage, and airlock losses. Transporting these gasses cannot be avoided, since the habitat area will always be pressurized and losses will always occur. The O_2 resupply may be eliminated, however, when the LOX production facility becomes operational. The key gas is the diluent, most likely N_2. It is 79% of the total by volume, and there appears to be no source for producing sufficient quantities of it on the Moon. The supply of N_2 will always be a high-cost logistics item.

Pressurizing structures other than those of the habitable area greatly expands the problem of gas logistics. The surface structures that have been proposed for storage and maintenance shed, LOX production plants, observatories, etc., are all large in volume. Most likely some of these structures do not need to be pressurized, but if they do, the supporting logistics costs will be high. Once the decision is made to pressurize a structure, the costs in terms of weight, volume, and the power extend well beyond just the costs of the gases and tankage. If a structure is to be pressurized, a pressure control subsystem has to be added. If crewmen enter and exit the pressurized structure, airlocks need to be added. If airlocks are added, pump back units have to be added, because a complete loss of gases in the airlock during each operation cannot be tolerated.

During the lunar base study previously mentioned, three structures other than the habitat area were proposed. They included a pilot LOX production plant with a volume of 4000 ft^3, an observatory with a volume of 4000 ft^3, and a storage and

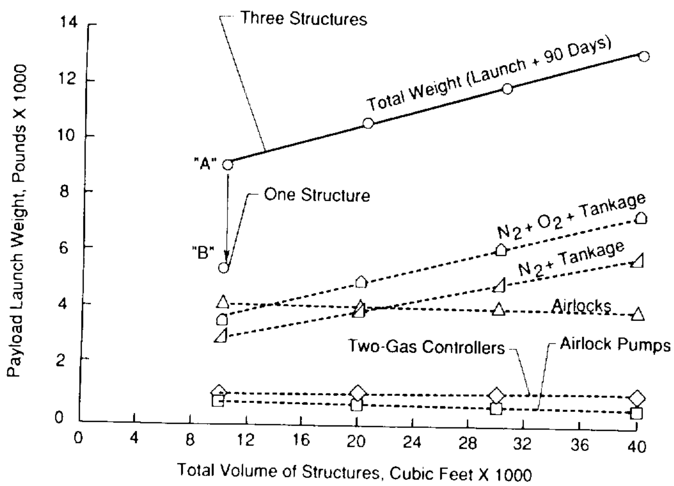

Fig. 2. Weights incurred to pressurize large facilities (structure volume is a total of three structures).

maintenance shed with a volume of 3500 ft^3. During the basic study, the entire 11,500 ft^3 was assumed to be unpressurized, but in order to scope the problem should the facilities need to be pressurized, the payload launch weight was calculated and plotted (Fig. 2). The structure volume given on the abscissa assumes the volume is a total of three structures. Thus, in addition to the gases, six airlocks (two per structure), three airlock pumps, and three two-gas controllers are needed. The resultant total weight for initial launch and the first 90 days of use can be extracted from the "total weight" plot. To pressurize the three structures totaling 11,500 ft^3 requires 9490 lb of gases and equipment in addition to the actual structure weight. The study assumed the use of cryogenic O_2 and N_2 transported from Earth. The equivalent weights for other structure volumes (combined volume of three structures) can be determined from the plot. Another interesting observation shown on the figure is the relationship between obtaining the volume in one structure (new design) that is equivalent to the combined volume of three space station modules. The 10,000 ft^3, three-structure total weight anchor point "A" is displaced downward to point "B." The total weight is reduced 41% from 9173 lb to 5425 lb. The large reduction is the result of elimination of four airlocks, two pumps, and two gas controllers.

These calculations were based on certain assumptions and a limited database, but the absolute values are not important at this time. The relative values do, however, support an important conclusion. The total system costs (weight, volume, and power) of pressurizing large structures will be high. Lunar base planners must continually be aware of the impact of adding large, pressurized structures. Remember that the majority of the pressuring gas will be N_2, some of it will be lost, and it is not likely that N_2 can be obtained in the quantity needed from a lunar resource.

AIRLOCK OPERATIONS

Airlock operations are tightly coupled to the subject of pressurized structures. The presence of a pressurized structure implies crew ingress and egress, and with each operation of an airlock, pressurization gases are lost. Examples from the SAB lunar base study illustrate the impact of airlock operations on logistics. The study assumed airlocks with a volume of 100 ft^3 supporting passage of one crewman. If the entire airlock volume, beginning at a pressure of 14.7 psia, were dumped with each airlock operation, 8.04 lb of pressurization gas would be lost. The operational scenario for the base resulted in 10 airlock operations per day (24 hr). With a 90-day resupply, 7236 lb of gases would be lost each resupply period. That magnitude of loss could not be tolerated, so a system (pumps, valves, and controller) was added to pump back 90% of the airlock gases with each operation. Thus, only 723.6 lb of gas were lost, but that remains a sizeable loss that must be replenished with each resupply. Of course, tankage weight has to be added to arrive at the true logistics cost. The 90% pump-back level was determined to be practical after trading off size relationships between airlock and module or node, pumping time, pump efficiency, and pump size and power requirements. To recover more than 90% requires an unreasonable pumping time or a much larger pump. A calculation was also made relative to a base in which the three operational facilities (LOX plant, observatory, and storage and maintenance shed) were pressurized and needed airlocks. The airlocks were chosen to support simultaneous passage of two crewmen. The airlock volume was 226 ft^3. Again, if 10% of the atmospheres were lost each time, 1635 lb of gas would be lost each 90 days. The airlock operations scenario, the airlock volume, and the amount of gas lost during each operation would combine to have a significant impact on the launch and resupply logistics.

ADDITIONAL FACTORS THAT MAY BECOME DRIVERS

Up to this point in the paper, the discussions have focused on mission ground rules, mission characteristics, and systems other than the ECLS system that are design drivers inherited by the ECLS system engineer. The implication is that given all the details of these, the ECLS system engineer will produce an optimum system for the lunar base. This assumption is overly optimistic. In order to assure that the technology of regenerative systems is ready when needed, more emphasis has to be placed on specific portions of the development cycle. Figure 3 can be used to illustrate the needed emphasis. The candidate technology readiness level column on the left side shows the sequence through which processes and related hardware components (a candidate subsystem) evolve from concept to operational flight hardware. The eight levels of technical readiness have been accepted by the ECLS system community as a proper scale for rating the readiness levels. The hardware sequence bar chart on the right of the figure was added by the authors to relate the type of hardware required to move the candidates through the readiness level.

One problem with the figure is that all the steps and substeps on the left and all the hardware-type bars on the right give a visual appearance of all being about equal in scope. That is entirely misleading. Advancing from level 1.0 through 3.0 using laboratory and breadboard models is easy. The time element is short, the costs are relatively low, and progress can quickly be shown by proving the "technical feasibility" of a process. At that point, however, the scope of the job changes. Levels 4.0 and 5.0, sometimes level 6.0 also, are much more lengthy, require many more resources in dollars and manpower, and are not scientifically or technically exciting. For these reasons they have been more difficult to sell to sponsoring agencies.

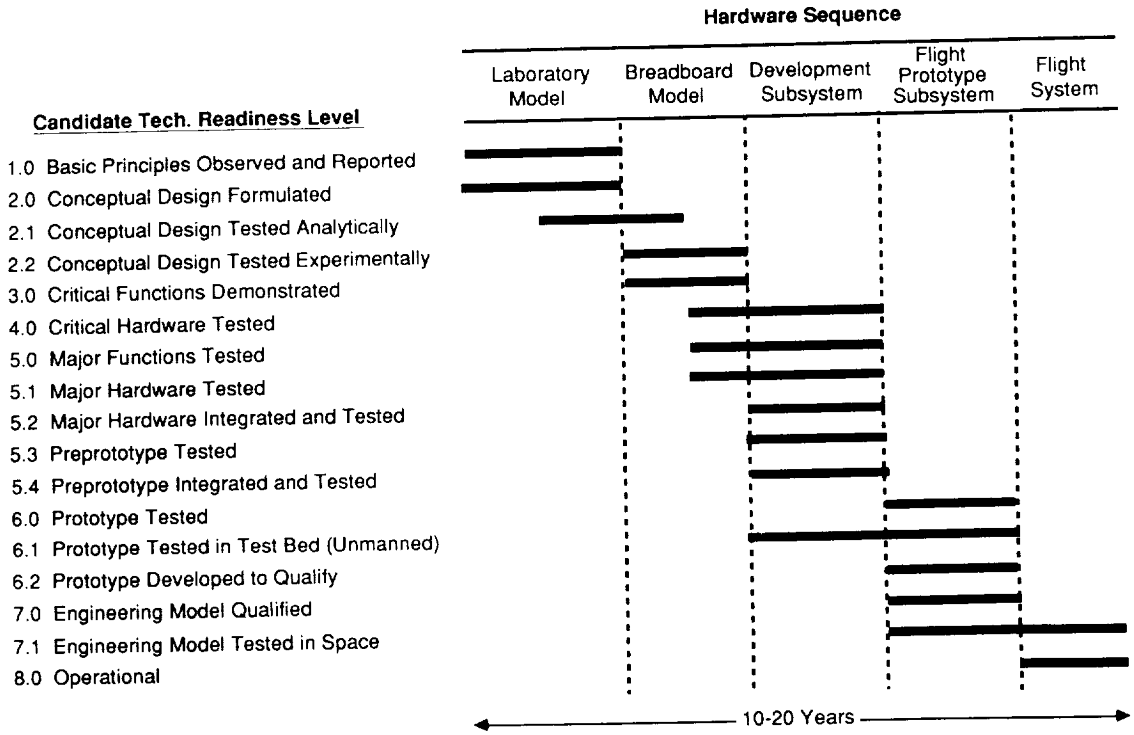

Fig. 3. The ECLS system technology development sequence.

The dichotomy present, however, is that it is steps (levels) 4.0 through 6.0 that advance the technology to a usable level. Real long-term use problems of materials selection, materials degradation, long-term component reliability, integration, maintenance of mass balance, process control (a pacing technology for integrated systems), microbiological control, automation, and fault detection and isolation are encountered and must be solved in order to reach levels 7.0 and 8.0. Noticeable efforts have been made in the past on these important steps by several NASA centers. The Langley Research Center made the early progress in integrated ECLS systems during the late 1960s and early 1970s. The Ames and Johnson Space Centers made significant progress in long-life testing of components and subsystems in the 1970s and early 1980s. The Marshall Space Flight Center is now engaged in an integrated ECLS system development and testing program focused on the early space station. These types of efforts must be expanded and given more emphasis because the job is more difficult than it may appear. It is also apparent on the "bottom line" that a typical 10-20 yr development period experienced in the past cannot be tolerated. Fortunately ECLS system engineers are not faced with beginning at level 1.0. Many of the proposed techniques are now in levels 4.0 and 5.0. They must be pursued vigorously, however, or else the lack of technology readiness may be the most overpowering design driver of all.

CONCLUDING REMARKS

Early mission planning must include parallel consideration of all technical disciplines that contribute to the total lunar base infrastructure. Ground rules derived unilaterally by mission planners may impose unnecessary penalties on the ECLS system design. Conversely, system designs developed unilaterally by the ECLS system engineer may limit the operational flexibility of the base or may violate some ground rule considered important by the scientific community.

There is no single ECLS system that is most applicable to a mission of "x" days with a crew of "y." All the mission parameters and details of the other systems must be factored into the ECLS system design.

Mission planners and systems engineers, including the ECLS system engineer, should refrain from using the term "closed loops." Even with the best regenerative processes, some expendable material that must be resupplied is included. The resupply logistics required to support the lunar base ECLS system, even if regenerative, is significant.

Perhaps the most important ECLS system design driver of all those discussed is the technology status of candidate processes and subsystems. The development cycle of regenerative ECLS system techologies is lengthy, laborious, and expensive. It will require great diligence on the part of the ECLS system engineers and their sponsors to assure that when the time arrives to design a lunar base, it is the mission parameters that drive the ECLS system design rather than the lack of an adequate technology baseline.

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