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SPACE SHUTTLE ENVIRONMENTAL CONTROL/LIFE SUPPORT SYSTEMS

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16. Abstract

This study analyzes and defines a baseline Environmental Control/Life Support System (EC/LSS) for a four-man, seven-day orbital shuttle. In addition, the impact of various mission parameters, crew size, mission length, etc. are examined for their influence on the selected system. Pacing technology items are identified to serve as a guide for application of effort to enhance the total system optimization.

A fail safe-fail operation philosophy has been utilized in designing the system. This has resulted in a system that requires only one daily routine operation. All other critical item malfunctions are automatically resolved by switching to redundant modes of operation.

As a result of this study, it is evident that a practical, flexible, simple and long life, EC/LSS can be designed and manufactured for the shuttle orbiter within the time phase required.

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FOREWORD

This report has been prepared by the Hamilton Standard Division of United Aircraft Corporation for the National Aeronautics and Space Administration's Langley Research Center in accordance with Contract NAS 1-10354. The report covers work accomplished between October 13, 1970 and the date of issue.

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CONTROL/LIFE SUPPORT SYSTEMS

Hamilton Standard Division of United Aircraft Corporation

INTRODUCTION AND SUMMARY

A Space Shuttle system has been identified by the NASA as a requirement for economical, rapid-turnaround transportation of equipment and personnel between the earth's surface and near-earth orbit. Missions identified include scientific experimentation, manufacturing operations, satellite deployment and retrieval, and space rescue.

To achieve these mission objectives, the Environmental Control and Life Support System (EC/LSS) for the space shuttle vehicle must be flexible, simple, reliable, low cost, require little or no in-flight maintenance and be quickly maintainable on the ground. Therefore the design of the baseline system must be optimized from a total system level approach based upon a fail operational - fail safe philosophy. To achieve this optimization, each of the subsystem functions should be optimum for use and yet be totally integratable with the EC/LSS.

This study defines: the method used to establish the evaluation criteria for the subsystems; the selection of each subsystem; and the resultant baseline 4 man - 7 day EC/LSS. Also included is a detailed description of the baseline system and the impact of varying crew size and mission length. In addition, pacing technological and development areas are identified as a guide to application of effort for total system optimization.

REPORT ORGANIZATION

This report is generally organized in accordance with the sequence of study activity. The study approach and subsystem selection philosophy, including a summary of the specification requirements and special system considerations such as design and maintainability guidelines, are presented in the Conduct of Study section. Subsequent sections describe the subsystems requirements for each function studied, together with an evaluation of the concepts investigated, and the selected subsystem concepts to be used for the initial baseline system synthesis. Included is an evaluation of the impact on the subsystem for changes in mission parameters.

The selected EC/LS System section presents system data, schematic diagrams, weight, power, and volume summaries, and discussions of the impact of mission parameters.

The Pacing Technology section identifies pacing technological and developmental areas related to the baseline conceptual designs. The discussion includes a specific identification of each area, a recommended approach to resolving the item identified and an estimate of the time and effort required to complete the task. In addition, there is a list of recommended technology areas, where advancement could further enhance shuttle operation.

MAJOR CONCLUSIONS

As a result of this study, it is evident that a practical, flexible, simple and long life, EC/LSS can be designed and manufactured for the shuttle orbiter within the time phase required. No major state-of-the-art problems exist although there are some areas which are described in the report which are recommended for immediate attention to assure completion of the shuttle mission with increased crew efficiencies.

The significant subsystem selections for the baseline mission are reflected in table 1. The number of interfaces with the vehicle system have been minimized with the result that only six basic interfaces are required with little impact on the vehicle. These are: electrical power, radiator, fuel cell water, vacuum vent, hydrogen and oxygen supply.

The use of expendables has been minimized by:

- Eliminating a wicking device in the condensing heat exchanger water separator and urine separator.

- Eliminating the need for chemicals in the main potable water supply lines.

- Making use of available fluids, water and cryogenic hydrogen, within the vehicle for heat sink purposes.

- Utilizing oxygen from the vehicle propulsion system for the primary oxygen supply.

The fail operational - fail safe philosophy has been utilized using reasonable ground-rules that insure crew safety and provide a high probability for mission success.

TABLE 1

EC/LS SELECTED SYSTEM

Subsystem	Description
Atmospheric Storage	Oxygen from vehicle propulsion system. Nitrogen stored in composite material tank at 3000 psia. Emergency Oxygen stored in composite material tank at 3000 psia.
Pressure and Composition Control	Pressure regulated, 2-gas control provided by cabin total pressure and oxygen partial pressure sensors.
CO_2, Humidity and Temperature Control	LiOH Bed for CO_2 control, humidity control utilizes condensing heat exchanger followed by an elbow type water separator connected to the waste management subsystem. Temperature control is obtained by bypassing air flow around the condensing heat exchanger.
Atmospheric Contaminant Control	Charcoal bed for odor and trace contaminant control. Copper sulphated sorbeads for ammonia control. Particulate filter for debris control. Bacteria filters for bacteria control.
Heat Rejection	Space Radiator for main heat sink. Water evaporator for on-orbit peak loads. Cryogenic Hydrogen heat exchanger for reentry and ferry mission cooling.
Water Management	Utilize fuel cell water for all crew water uses and as an evaporant. Heated 160°F zero gravity storage tanks. Hot and cold water lines automatically cycled every 24 hours for bacteria control.
Waste Management	Wall type urinal, male use. Conventional "earth like" split-commode for male and female use. Heated overboard dump nozzles for urine and waste water dump. Combination fan centrifugal separator for water transport and phase separation.
Crew Provisions	Combination frozen and freeze-dried foods. Reuseable wettable wipes and soap for body washing. Reuseable clothes for crew wear.

The requirement for in-flight maintenance has been minimized by having only one daily routine operation, that is, to replace the LiOH cartridge. All other critical item malfunctions are automatically resolved by switching to redundant modes of operation. Ground maintenance has been minimized by requiring only relatively simple operations. Two factors that have helped in this regard are the elimination of all valving from the cabin coolant loop line and the use of an installed Ground Support Equipment (GSE) heat exchanger in the heat rejection loop to maintain the integrity of the coolant loop. This approach eliminates the need to service the coolant loop unless an actual malfunction within the loop occurs. Sufficient instrumentation has been supplied to provide for fault detection, control, and to facilitate ground maintenance.

Crew comfort and convenience have been implemented by using an earth-like wall mounted urinal for male use and a split-commode which is equally satisfactory for both male and female use. Crew safety is enhanced by using water inside the cabin cooling loop and by providing on-line pasteurization of both the hot and cold water lines. Pasteurization is achieved at minimum power by utilizing the hot water delivery from the fuel cell and by providing sufficient insulation on the water storage tank and delivery lines to reduce the quantity of electrical heat required. A 48-hour reserve capacity has been provided for all critical functions and supplies in the event of a vehicle malfunction.

The total EC/LS system, less food supplies, consists of 215 components and weighs 1,821 pounds including expendable and requires 750 watts of power for the high cross range vehicle. It provides the means for cooling for all of the specified cabin and radiator heat loop loads. The EC/LSS hardware weight amount to approximately 0.2% of the estimated orbital vehicle total weight.

CONDUCT OF STUDY

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CONDUCT OF STUDY

This section presents the pertinent factors regarding the conduct of this Space Shuttle Environmental Control/Life Support Systems (EC/LSS) study. Discussed are the study approach, selection philosophy, study flow, and study method. In addition, general discussions of special system considerations including reliability, maintainability, modularity, commonality, fire safety, and microbiology are presented.

OBJECTIVES

The objectives of this study are to:

- provide an objective evaluation of the EC/LSS requirements for the orbiting vehicle portion of a multi-purpose Space Shuttle System,
- determine baseline conceptual EC/LSS designs for the Space Shuttle Orbiter which can serve as focal points for advanced research and development, and
- identify the pacing EC/LSS technological problems which will require resolution to assure successful development of the Space Shuttle System.

STUDY APPROACH

In order to obtain a system overview as early as possible in this study, use was made of prior system studies, current NASA and prime contractor guidelines, the contract statement of work, and discussions with the technical monitors to prepare and release a set of Requirements/Guidelines (appendix A) early in the performance period. In addition, a set of evaluation criteria was established for the conduct of the subsystem trade studies. Using the Requirements/Guidelines as a guide to system requirements, tentative subsystem trades were completed. These tentative subsystem selections were integrated into a baseline system concept presented herein. Recycling of this sequence was accomplished as required to achieve the final integrated shuttle orbiter EC/LSS concept.

The baseline system described in this report is for a seven (7) day space shuttle orbiter with a four (4) man crew. Also included is an allowance for a 48-hour emergency provision.

SELECTION PHILOSOPHY

The selection criteria used in the Space Shuttle EC/LSS trade studies, are presented in table 2. The choice of selection criteria is based on a recognition that some requirements are absolute, others are quantitative and still others are qualitative. The criteria are applied sequentially in the groups shown to eliminate concepts that fail on either an absolute or comparative basis and to provide the basis for selection between surviving candidates.

Trade Study Data Presentation

The format used for the presentation of most subsystem discussions follows the order of selection criteria (Performance, Safety, Reliability, Availability, Weight, etc.). Candidate descriptions are provided, with emphasis placed on operational considerations rather than on the theoretical aspects of design. Background information on the theoretical aspects may be found in other literature.

Data sheets and schematics are included to summarize the information presented for the concepts that were evaluated. Each concept is identified by its generic name and within its subsystem area.

Absolute Criteria

Absolute criteria define the minimum acceptable requirements for a concept. If a concept does not meet or cannot be modified or augmented to meet all of the absolute criteria, no further consideration is given in the trade study. If a concept does meet all of the absolute criteria, a relative rating is assigned to aid in evaluating the concept should the quantitative and qualitative criteria fail to establish a clear-cut selection. This relative degree of acceptability is given a Poor to Very Good ranking. A Poor rating rejects the concept from further consideration. The criteria against which this absolute assessment is made are discussed below:

Performance.- To be considered as candidates, all concepts must be capable of fully meeting all pertinent subsystem performance requirements during the mission, as applicable.

Safety.- All candidate concepts are examined with respect to fire hazard, atmosphere contamination, explosion hazard, bacteriological problems, hot spots, and other crew hazards to determine if any of these problems are present. If a problem could not be eliminated by careful design, the concept was eliminated.

TABLE 2
SELECTION CRITERIA

Absolute Criteria
Performance
Safety
Reliability
Availability
Quantitative Criteria
Total Equivalent Weight
Cost
Volume
Qualitative Criteria
Complexity
Flexibility
Durability (Life)
Refurbishment
Checkout Capability
Maintainability

Reliability. - All candidates must meet a minimum reliability requirement. Sufficient redundancy may be added to meet this requirement. Also considered under this criterion is the inherent reliability of the basic concept and other factors relating to limited-life items and the complexity of the resultant subsystem.

Availability. - All candidates must be available for flight by 1977. The availability of the candidates is the date that the concept, considering its present status, could be qualified for flight assuming that a well defined program with adequate funding is initiated in early 1972. In determining this projection, the present hardware status, the known problem areas, the probable development areas, the long lead time items required, as well as the normal development and qualification time are considered. The mission phase applicability of each concept is also noted.

Quantitative Criteria

The first-order or quantitative criteria are the principal criteria for all concepts that pass the absolute requirements listed above. The ratings applied to a candidate-Very Good, Good, Fair or Poor -- are dependent upon the characteristics of the candidate relative to other candidates. A Poor rating rejects the concept from further consideration. A candidate concept is selected if its overall rating is clearly the best of the competing concepts. If two or more concepts are rated essentially equal, the absolute criteria ratings are re-considered and a selection is made. If no clear choice is evident, the competing candidates are reviewed against the qualitative criteria to determine the best candidate. The quantitative criteria are:

Total equivalent weight. - This criterion consists of three factors: fixed weight, power equivalent weight, and expendables. An estimate of these factors is made on a permission basis. Installed weight refers to the parts of the candidate concept that are installed to actually perform the function or for standby use. Power equivalent weight is the weight of the fuel cell and expendables (H_2 and O_2) required to produce the power (watts) for the mission length. It is determined by using the following equation as defined in appendix A.

$$\text{Power equivalent weight} = 0.16\ \text{lb/watt} + 0.00133\ \text{lb/watt-hr.}$$

Expendables refers to the weight of the expendables, required to attain the desired performance for mission completion.

The data presented on the concept data sheet assumes that the crew is located within one compartment. The data sheet format is shown in figure 1. To determine the approximate total subsystem weight for separate compartments, obtain weight values for the selected crew size from the weight versus crew size data curves and add them together.

SUBSYSTEM:

CONCEPT:

FLIGHT AVAILABILITY:

Mission Phase Application

Launch ____ Orbit ____ Reentry ____ Cruise ____

RELIABILITY: MTBF:

4 Men - 7 Days Plus 48 Hours Contingency

	Total Equivalent Wt. (lb)	Volume (ft^3)	Power (watts)
Installed Unit			
Expendables			--
Power Equiv. Wt.			--
Totals			

Cost Factor

Recurring -

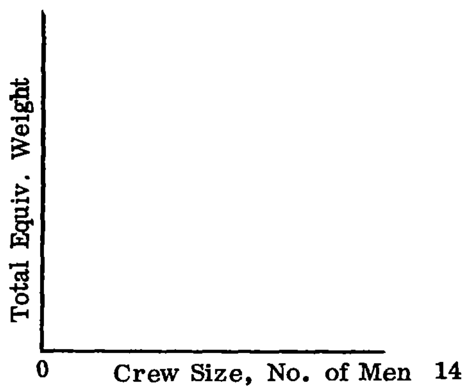
Nonrecurring -

Total -

Crew Time (hrs)

Scheduled

Ground Refurbishment



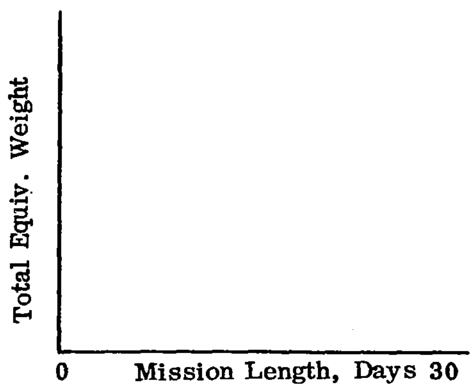


FIGURE 1. CONCEPT DATA SHEET

Cost.- This criterion considers the rough order of magnitude (ROM) cost for two cost elements. The non-recurring cost is the cost of hardware design, development, qualification and tooling and manufacture of one ship set of flight hardware and expendables for one mission. The recurring cost is for the entire program assuming five flight vehicles and the spares to maintain them for ten years. It is assumed that the spares required over this period is equivalent to one ship set per vehicle. Also included in the recurring costs is the cost of expendables for 500(seven-day, four-man) missions. Emphasis will be placed on the near-term or non-recurring costs as a dominant portion of this criterion. The costs are expressed as a cost factor which is a normalized rating of the competing candidates concepts for a particular subsystem.

Volume.- This criterion considers the volume occupied by the candidate concept as well as the volume for the expendables required for one complete mission.

Qualitative Criteria

The qualitative criteria represents a step in the depth of the competitive evaluation of the leading concept contenders that is taken if no clear cut selection is available. They also represent a systematic review of the overall acceptability of selected concepts. Candidate concepts are rated Poor to Very Good. At this level of evaluation, however, a Poor rating does not necessarily disqualify a concept form further consideration. The qualitative criteria are:

Complexity.- This criterion is a measure of the quantity of hardware, number of controls, different modes of operation and number of interfaces with other subsystems that are necessary to perform the desired function.

Flexibility.- This criterion is a measure of the candidate's adaptability to extended mission durations and increased crew size. Also included is the ability of the candidates to operate in degraded modes.

Durability.- This criterion considers the operational life of each candidate. Candidates are investigated for potential limited life components which must be serviced frequently.

Refurbishment.- This criterion is a measure of the servicing or refurbishment time required for each concept as well as the quantity and complexity of ground support equipment required to service each candidate between flights. Estimates for ground refurbishment maintenance are based on the predicted probable failure rates and average times for repair of those parts most likely to fail.

Checkout capability. - This criterion measures the complexity crew stress, and crew time required for checkout of the candidate approaches.

Maintainability.- This criterion measures the ease with which a failed subsystem or component can be replaced. The scheduled maintenance time estimations are the average times in hours expected to be expended on a particular concept for the entire mission, assuming the hardware is flight qualified.

Impact of Mission Parameters

Included in each subsystem concept discussion, as applicable, is consideration of the impact of varying mission parameters. This information is supplied to show the impact on candidate concepts as a mission parameter changes. The information is significant because the vehicle design and/or mission is still subject to change. Some of these changes have more impact on some candidates concepts than others and this is a factor in selecting a subsystem concept as well as providing a broader study data base. These parameters are discussed below.

Mission length. - The impact, if any, of a mission longer or shorter than the baseline seven (7) days is shown as it affects the design point of a given concept. The impact is normally noted as a function of total equivalent weight. The impact of off design conditions is also discussed. Typical mission profile time periods are shown in table 3.

Crew size. - The impact of crew size is shown as it affects the design point of a given concept as a function of total equivalent weight. Figure 2 defines the crew size considered as a function of the defined mission length. Also shown is the parametric data range of this study report.

Coolant temperature. - The effect of varying coolant temperature to determine the radiator coolant outlet temperature as a function of total equivalent weight for various concepts is examined.

Coolant flow. - The effect of varying coolant flow to determine the minimum total equivalent weight of a concept is also examined.

TABLE 3
MISSION PROFILE

PHASE	TIME
Prelaunch	2 hours
Boost	6 minutes
Orbit	0-717 hours
Reentry	18 minutes
Atmospheric Flight	30 minutes
Ferry	4 hours
Emergency with Radiator	48 hours
Emergency without Radiator	12 hours

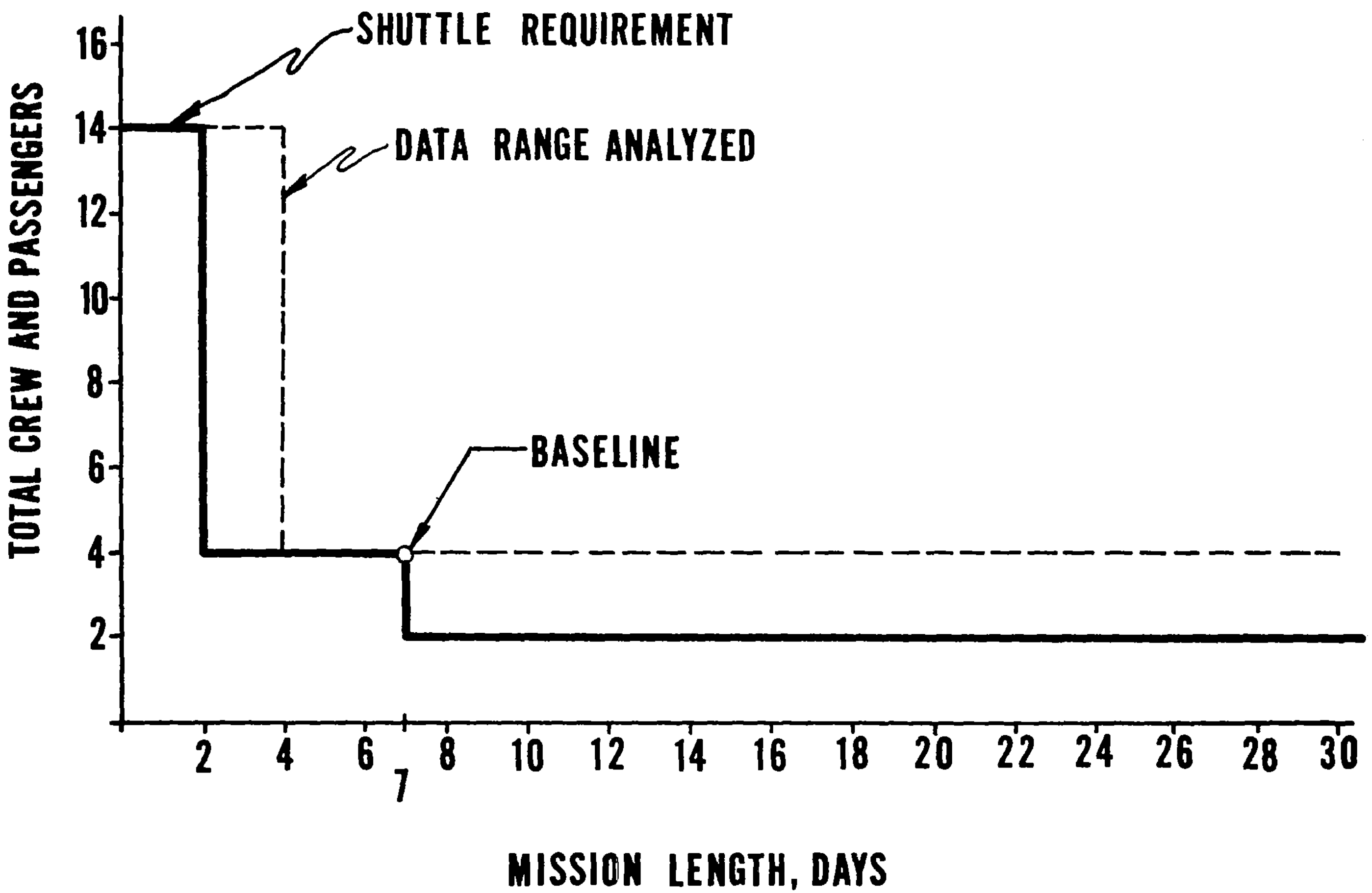


FIGURE 2. CREW SIZE AS A FUNCTION OF MISSION LENGTH

Electronic loads. - The effect of various total electronic loads and air heat loads to determine the impact on the subsystem concept is also examined.

Industry Support

Information from study reports, technical papers, and various government agencies used in preparing the candidate concept descriptions contained herein are listed in the Bibliography (appendix B).

STUDY METHOD

The trade studies using information generated for each candidate concept are conducted utilizing the selection criteria mentioned previously. Since the absolute selection criteria eliminate the unsuitable candidates, subsystem selections are made mainly on the relative merits of weight, cost and volume. This approach is taken to arrive at clear-cut choices of equipment types required for a baseline (7 day four-man mission) system.

The selection of subsystem concepts has been accomplished according to the procedure discussed below.

- The several competing concepts for each subsystem are first defined. Equipment is sized to meet the baseline (nominal) specification performance requirements. Concepts are roughly defined (at the component level) to determine such characteristics as flow rates, temperature levels, and pressure levels to permit determination of performance, safety, reliability, weight, cost and volume. Component redundancy must be added to most concepts to meet the fail operational-fail safe requirement. Preliminary schematics and component lists are then generated, yielding basic subsystem concepts.

- Further equipment is added or the arrangement modified, as required to meet the subsystem specification interface requirements. All competing subsystems must accomplish the same task for valid comparison. Typical of such supplementary equipment are the following:

    a. Noise attenuation devices

    b. Electric heaters to provide high temperature heat sources where otherwise unavailable.

c. Supplementary contaminant control devices if one subsystem generates contaminants during some phase of operation.

- The data listed on the data sheet shown in figure 1 together with information relative to the criteria are then generated as required for evaluation among the candidate subsystems.

- All candidates that meet the absolute criteria are evaluated against the quantitative criteria and, if necessary, the qualitative criteria as described previously. The impact of mission parameters on the selected concept is also investigated and discussed.

- Upon completion of the subsystem trade-off evaluations, in which preliminary concept selections are made utilizing the selection criteria, the baseline (seven day four-man) system integration is performed. Subsystems selected for integration are first chosen on a preliminary basis subject to reconsideration as a result of system integration requirements. In the event of a significant system-level impact of a selected subsystem concept, the concept is recycled along with its original competitors for another evaluation considering the newly defined requirements. It is significant to note that several major elements cannot be fully evaluated until after this baseline is established. This includes such system dependent subsystems as cabin ventilation, cabin temperature control, cabin humidity control, heat rejection subsystems and instrumentation and controls.

- The first in a series of iterations may now be required due to the following:

  a. Equipment heat rejection to cabin atmosphere may require uncomfortably high ventilation rates.

  b. Coolant flows in the heat rejection subsystem may not be suitable for all subsystems.

  c. Subsystem interfaces, material, or thermal balance optimization.

Descriptions of the manner and philosophy of the subsystems integration are included as part of the Selected EC/LS system section of this report.

SPECIAL SYSTEM CONSIDERATIONS

As an introduction to the more specific discussions of the trade-offs and system integration, certain areas lend themselves to a general discussion covering their application to this study. These areas are vehicle configuration, reliability, maintainability, commonality, fire safety, and microbiology. The philosophy for each area has been implemented, when appropriate, and is discussed in the applicable subsystem or system sections.

Vehicle Configuration

The actual vehicle configuration will have significant impact on the EC/LSS. As noted previously, no specific vehicle configuration was considered, and every attempt was made to keep the subsystem designs as flexible as possible. However, it was generally assumed that the shuttle vehicle would have two (2) independent crew compartments which would be connected in some manner; i.e., hatchway, airlock, tunnel, etc.. This approach, while not the most optimum from a cost, weight, and power viewpoint for the EC/LSS, does appear to be the most practical when one considers the total mission of the space shuttle which includes many missions when a large amount of cargo and equipment is carried. This approach also is in line with the current shuttle prime contractor logic of having an independent cabin and a separate cargo-passenger module. Therefore, the crew cabin considered has a provision for two (2) to four (4) crew members and the payload compartment for one (1) to 10 passengers. This approach minimizes the EC/LSS impact on the shuttle vehicle by providing for a greater degree of flexibility on the shuttle design, utilizes a minimum amount of volume when a cargo payload is carried, and imposes less penalty when long missions are conducted with small crews (2 to 4 men).

The parametric weight data presented herein is for a single cabin approach. The separate compartment approximate EC/LSS total weight can be determined by obtaining the weight values for the selected crew size from the weight versus crew size data curves and adding them together.

Maintainability

Maintenance plays a large part in the overall space shuttle goals of reuseability to reduce costs and quick turnaround between flights. Unlike in-flight maintenance contemplated for space stations, the maintenance for shuttle will be accomplished almost exclusively on the ground.

The era of manned space flight, in its embryonic stages, has not concentrated on the problems of maintenance and reuseability. Rather, manned spacecraft systems design has been dominated by factors such as light weight, acceptable reliability, and functional capability, often at the expense of long life and cost considerations. Aircraft EC/LSS systems, having been in operation for many years, have evolved a maintenance philosophy dominated by economic return on investment, while not sacrificing vehicle airworthiness nor passenger safety. It is through similarities in operational objectives and hardware sophistication, in addition to this extensive maintenance experience, that the maintenance design philosophy has been established for the shuttle program.

The principal areas to implement this shuttle maintenance design philosophy are described in the following paragraphs.

Component life. - Long Life componentry is essential to the success of the shuttle mission. Even items susceptable to wear out must be designed with long life potential. As such, the following life requirements should be used as targets for hardware design:

- Wherever feasible, components and systems will be designed for a service life of 10 years and 100 missions with a minimum of maintenance and refurbishment.
- A 5, 000 flight hour minimum life shall be used as the target for components with inherent wear out potential.

There are a number of ways to achieve longer life, all of which embody execution in the design phase of the program. These design criteria are:

- Emphasize low operating stress with minimal component size and weight penalty.
- Select detail designs with few moving parts and minimize complexity.
- Select materials that do not have age control requirements.

In order to fully utilize this long life design, on-condition maintenance which is the basis of aircraft maintenance philosophy will serve as the basis of the shuttle philosophy. In this approach, as long as a component is operating on-condition (within specification), it will never be touched except for normal servicing. This is especially important for limited life items because it means that as long as these items operate on-condition, no action will be taken even though they may have exceeded their predicted useful life. As can be seen, this maintenance philosophy ties in very closely with a fault detection system.

Fault detection. - In order to comply with the fail operational - fail safe requirement and to reduce maintenance time to a minimum it will be necessary to detect and isolate failures to the line replaceable unit level. An automated system similar to an Airborne Integrated Data System (AIDS) will be required.

This system will provide in-flight checkout and performance monitoring of the EC/LSS including non-operating redundant hardware. This system will also provide trend analysis data by which wearout and some random failures are predicted. Corrective maintenance action will take place if the trend analysis indicates any component or subsystem will fail or provide marginal performance during the next flight mission.

This AIDS type system will automatically detect and isolate failures to the line replaceable unit level (failed component or assembly). The line replaceable unit level may depend on the limitations of the AIDS (number of computer channels or complexity of instrumentation). If a failure can only practically be isolated to a group of components, then this group would be the line replaceable unit level. This whole group would be replaced should any member component fail. The AIDS will also provide trend analysis data by which wearout failures can be predicted. Replacement of wearout items will be based on the trend analysis rather than scheduled replacement.

Although the AIDS should automatically isolate the first failure, manual overrides, in the cabin area, should be used to guarantee a fail safe operation upon the second failure. This results in all isolation valves being automatically actuated and manual overrides on all isolation valves inside the pressurized compartment which have a critical second failure mode.

Component/Module Installation. - The replacement of line replaceable units is the essence of shuttle maintainability for this is the task that must be efficiently facilitated to assure quick vehicle turnaround. The secret to quick component replacement is accessibility and minimum manual operations. The two functions of major concern are interface connections and mounting.

The design criteria that facilitates the quick vehicle maintenance are:

- Visual manual accessibility/to equipment bays must conform to acceptable human factor requirements for maintenance and repair functions.

- Modules and component installation objective shall be singlepoint "plug-in".

- Component replacement shall not contaminate the vehicle or require the de-servicing (draining, etc.) of a system.

- Quarter-turn captive fasteners or self-locking plate nuts should be used with bolted fasteners to eliminate the need for two tools for component replacement.

- Look-alike or similar components which could cause installation errors will be designed non-symmetrical to prevent error at installation.

- Interface connection seals shall be designed to be redundant, accessible and replaceable. These seals shall be either captive or self-aligning so that special tools are not required to guarantee adequate sealing.

- Component or module replacement shall not require special crew skills, tools, or elaborate procedures that require repeated referencing to manuals.

- Component commonality will be stressed in the design of the EC/LSS. This will assure the availability of spare parts at Earth base. It will also reduce maintenance crew training requirements.

- Components or modules weighing less than 45 pounds shall be designed to be replaced by a single man. Items weighing more than 45 pounds should not require more than two men.

<u>Liquid circuit components.</u> - Normal maintenance schemes if applied to liquid loops could play havoc with quick turnaround requirements. Breaking and making standard fluid connections in these systems would result in liquid or gas spillage in the vehicle, air inclusion in the loop and possible contamination of both the loop and the vehicle. For the shuttle, this potential problem exists in the coolant loops, the potable water, and the fuel cell product water circuit. There are two possible solutions to this problem. The first requires draining and filling the system each time a component is replaced and the second would make use of special components with zero-inclusion connection features.

Draining and refilling a system is feasible for ground maintenance where the gravity field assists in the operation, but even so, special ground support equipment and time consuming procedures are required to fill and vent the system. In addition, this approach would require deservicing of a system for component replacement.

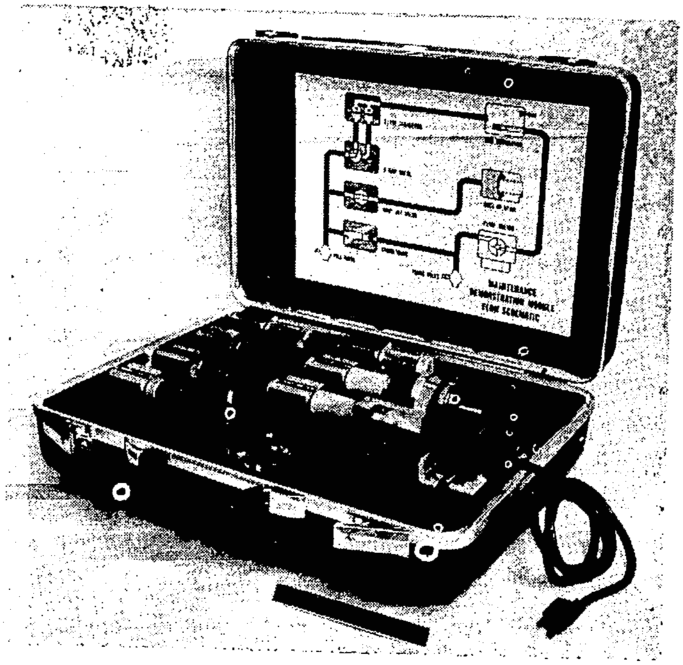
The use of components with zero inclusion connection features greatly simplifies the vehicle maintenance tasks on these systems. Figure 3 illustrates a typical unit configuration which contains valves (3 types), flow indicator, gas separator, accumulator and pump. The basic housing is identical for all components and also for other system components such as pumps or heat exchangers. Although the unit shown is component oriented, module replacement can be accomplished in a similar manner. All components within this system have been designed to provide for removal and replacement of components in a pressurized system with a minimum of fluid loss and contaminant/atmosphere inclusion.

Commonality

Commonality is an approach to system design whereby the number of different components is minimized by using a particular component to perform as many functions as possible. This approach results in major advantages in the spares and maintenance areas. The number of components used to perform these same functions warrants a study to determine the feasibility, applicability, and weight penalties associated with using identical or common components for different subsystem applications within the shuttle.

The hardware projected for the shuttle flight period cannot be expected to operate continuously for 10 years without failures occurring. For continuous functional operation of all subsystems, the failed parts have to be repaired or the faulty components replaced. Due to the inherent complexity and the short turnaround time anticipated detail component disassembly of shuttle hardware is not planned. Rather replacement at the line replaceable level is selected as the primary means of maintenance.

It is advantageous to use as many identical components as possible to reduce the total number and types of spares required. The commonality approach to system design can only be applied to those items which are sufficiently adaptable to different functions. Each item must have a single configuration throughout its size range, and the configuration should be similar to that of items with similar but not identical functions; e.g., small two-way valves should have a configuration similar to that of small three-way valves. This family approach to component design has advantages in the design, manufacturing, and development areas, but primarily in the maintenance area.



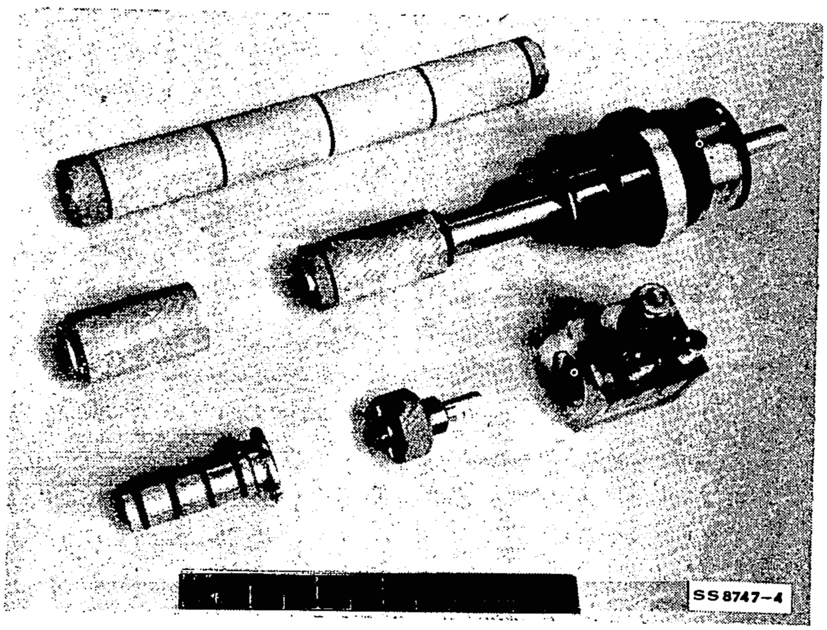


FIGURE 3. TYPICAL UNIT CONFIGURATION

As all similar items have identical mounting schemes, maintenance time is reduced by minimizing replacement procedures. This family approach combined with component need, provides the essential requirements of the commonality approach.

In order to obtain the ideal common item, material compatibility with all anticipated temperatures, pressures, and vehicle fluids is essential. The components considered as common for this purpose are valves, fans, and pumps. Unfortunately, oxygen compatibility in high pressure systems requires special design techniques with respect to configuration and materials, and, as a result, must be handled separately. Other components which experience frequent use but do not lend themselves to the commonality approach are considered special equipment. These include: pressure regulators, temperature control and other modulating type valves, and equipment which require definite design limits and operating bands. These components cannot be approached in the general manner of the common items and require specific investigation into each application.

In summary, the major advantage of commonality is the minimization of spare components and replacement procedures. In contrast, the only disadvantage of the commonality approach is that the extra effort required to achieve acceptable maintenance features results in a slight increase in component weight penalty. However, reduced costs, and maintenance time, obtained through a minimum of replacement procedures, more than off-sets any weight penalties incurred.

Fire Safety

As with any space vehicle the possibility of fire cannot be ignored. The increased demands for crew comfort, multi-missions, and short equipment maintenance time of the shuttle missions necessitate treating the entire subject of fire safety on a systems basis.

This system approach gives priorities to the two broad categories: 1) design for the prevention of ignition and 2) design for a defensive capability. This approach has several advantages. It allows flexibility for optimum solution of many safety problems very early in the design phase and it minimizes the risk to mission objectives. It also will make a fire a very improbable event, even with the flexibility of solution. In addition, it recognizes that fire hazards cannot be completely eliminated from a life supporting atmosphere and gives complete protection by requiring design of an adequate means to combat any possible fires.

Design for the prevention of ignition requires careful control of: all of the materials used in the cabin, the design of electrical circuits, the location and packaging of high temperature elements, and a critical review of all items within the vehicle for potential fire hazards early in the design phase.

Design for a defensive capability requires consideration of auxiliary breathing devices, installation of adequate fire extinguishers in critical cabin locations, (these can be either automatic or manual), adding adequate design margin into the atmosphere contaminant control subsystem, providing means to cleanup the cabin after a fire and consideration of the longer term impact of the fire on all the EC/LSS equipment and other equipment inside the cabin.

Microbiology

Man and the microorganism interact in a manner dependent upon the nature of the microorganism and the conditions prevailing in man at the time of contact. The microorganism can be antagonistic, symbiotic, or inactive in its relationship with man. Conversely, man's defensive mechanisms, a hostile environment, or chemotherapy can neutralize or destroy the microorganism or be ineffectual. A delicate balance of nature exists between man and microorganisms.

In space vehicles, this balance tips toward microorganism supremacy. Isolation in a weightless. closed environment causes physiological changes in man. The skin loses its elasticity and bacteriostatic properties. The derma and mucosa are more sensitive and irritable. In addition, the "normal" residual microbial flora changes spontaneously or through dietary influence and other factors. These conditions seriously affect man's resistance and ability to avoid, diagnose and treat microbially induced diseases.

Therefore, under these circumstances, all microorganisms must be considered pathogenic unless proven otherwise. It follows that strong emphasis must be placed on prevention and/or control of microbial contamination during manned space missions even for relatively short missions. The specific microbiological control methods for each subsystem, when appropriate, are discussed in each subsystem analysis.

Reliability

The reliability requirements for a space shuttle can be affixed after an examination of the capability and flexibility of this new generation of reusable space transport vehicles. Previous space missions utilized non-reusable, single mission vehicles.

Their successful operation was dependent on all systems functioning properly during the scheduled mission. If a malfunction causing abort of mission did occur during launch, boost, or orbit insertion the crew aborted the mission using the command module for reentry. The booster vehicle, supplies and supporting hardware were jettisoned and destroyed.

This required that a high numerical mission completion reliability be assessed to each subsystem. Redundancy, spares, and backup modes of operation were added until the numerical requirement was satisfied.

The high numerical mission completion reliability resulted in an inherently high crew safety reliability and only minor equipment modification was required to meet the crew safety goals. These factors tended to make crew safety reliability a passive rather than an active controlling criterion.

The reusable shuttle concept allows a relaxation in mission completion reliability goals since the vehicle and cargo can be returned, refurbished, and launched again.

Crew safety reliability, however, takes on the dominate role in the shuttle's design. Since the safety of the crew must not be compromised, backup equipment is added until the crew safety reliability is met. The redundant, spare or backup equipment will be activated (after component failures) until the last spare is activated. At this point an abort is initiated and the mission curtailed.

To implement these objectives the dynamic system components must fail to an acceptable operational level after one component failure. The second similar component failure must only degrade thesystem to a safe operating level. At this time the mission will be aborted.

Static system components such as gaseous pressure vessels, heat exchangers, hydraulic and pneumatic lines, and static line connections, were found to have very low failure frequencies because they incorporate no dynamic seals or relative motion mechanisms. These components, therefore, must fail to a safe operating level only, after the first failure and the mission aborted.

System reliability. - The system reliability goal (for crew safety) of 0.9999 for the EC/LSS for a seven-day baseline mission was established to insure that a positive constraint is provided for the shuttle. The mission completion reliability, or the probability of completing the mission without resorting to any fail safe equipment, will be determined by the crew safety reliability constraint, and will not be restricted to a numerical goal.

Subsystem reliability. - The functional EC/LSS equipment is composed of six major subsystems. Since each subsystem is of equal importance in competing the mission, the reliability of these subsystems is apportioned equally, resulting in a reliability of 0.999984 for each. To establish the reliability of the candidate concepts in the subsystem trades, the reliability of each component is determined in each of the concepts evaluated. The predicted equipment failure rates used assume that all hardware is fully developed and qualified. This is done for consistency and to identify those concepts with the highest potential reliability, regardless of the hardware's current development status. The failure rates are calculated on the basis of similarity to existing aerospace hardware and by synthesis of individual piece parts with a known failure rate. The probability of failure for each component is determined by combining the predicted failure rates, estimated operating times, and applicable "k" factors to reflect environmental severity.

The reliability analyses and redundancy/spares optimization studies are based on the following assumptions:

a. Equipment failures are independent; i.e., failure of one item will not generate a failure in a downstream item.

b. Rapid fault detection/localization is available

In order to make fullest utilization of the redundancy and spares, these features must be designed into the EC/LSS.

The calculated MTBF and reliability estimates for each concept under evaluation are provided on the concept data sheet as part of the subsystem concept evaluations. The MTBF is related to the unspared or inherent subsystem reliability by the equation:

$$R = e^{-168/MTBF}$$

Detailed application and results of the reliability considerations are given in the EC/LS Subsystem sections of this report.

Noise Control

The acoustic environment in spacecraft is becoming more and more important. In addition to providing a background noise level suitable for communications, noise control measures are being required to eliminate hearing problems and psychological disturbances and annoyances.

Noise generation by environmental control system components is unavoidable. Aerodynamic noise generation in the form of periodic pressure pulsations, for example, necessarily accompanies processes which add energy to or remove energy from a gas. Noise generated aerodynamically is particularly troublesome because the mechanisms of generation are not completely understood, and because acoustic treatment, such as mufflers, in the path between source and receiver is often costly in performance or weight.

To meet past noise level specifications, (i.e. LM and MOL) considerable muffling was often required for fans and gas valves. With larger spacecraft and ECS units and more stringent noise requirements, it is evident that measures will have to be taken to reduce noise generation at the source in order to minimize the need for external attenuation equipment.

Sound level definitions. - The extremely non-linear response of the ear makes sound pressure level versus frequency relationships of great importance in defining noise levels, and a number of ways to relate "noise" to sound level measurements have been postulated. Among those having wide acceptance at the present time are Beranek's Noise Criteria (NC) curves which attempt to define desirable sound-pressure level versus frequency relationships. A reading available from most sound level meters, the "A" scale, is also of some use in indicating the subjective loudness of a sound. On the "A" scale, the sound is electrically filtered to approximate the ear's frequency response at moderate sound levels.

The frequency range important for intelligibility in voice communication is of special importance in spacecraft noise control. The complete spectrum of speech frequencies extends from about 200 to 10,000 cps or Hertz (Hz), but articulation tests have shown that the range most important for intelligibility is from about 1000 to 2500 Hz. A criterion for noise which interferes with speech is the Speech Interference Level (SIL), which is the average of the three frequency band levels, 600 to 1200 to 2400 and 2400 to 4800 Hz. A more current form of SIL is PSIL (Preferred Speech Interference Level) based on the new standard octave bands of figure 4.

Certain "kinds" of noise normally cause little or no annoyance at reasonable loudness levels. Broad band background noise from fans sometimes has this quality, which may be characterized by a broad frequency range centered at fairly low frequencies. It is sometimes possible to create a more favorable environment by masking annoying noises with non-annoying ones. A cycled on-off noise source has been found to be more annoying than the same noise experienced continuously, probably because it calls attention to itself.

Noise Measurements. - The measured decibel level in an all-inclusive band that includes the entire frequency range of the source is the Overall Sound Pressure Level (OASPL). For purposes of noise control the overall level alone may be completely inadequate, since it may be determined by the level at one or two frequencies and it is important to know the frequencies of the noise source.

The most commonly used contiguous frequency bands for measurements are octave bands. Measurements are most often made in band widths one octave wide. Measured decibel levels only have meaning in terms of the band widths since the amount of energy passed by a filter is a function of the band width of the filter. The NC curves and SIL (below) were developed in terms of octave band numbers which

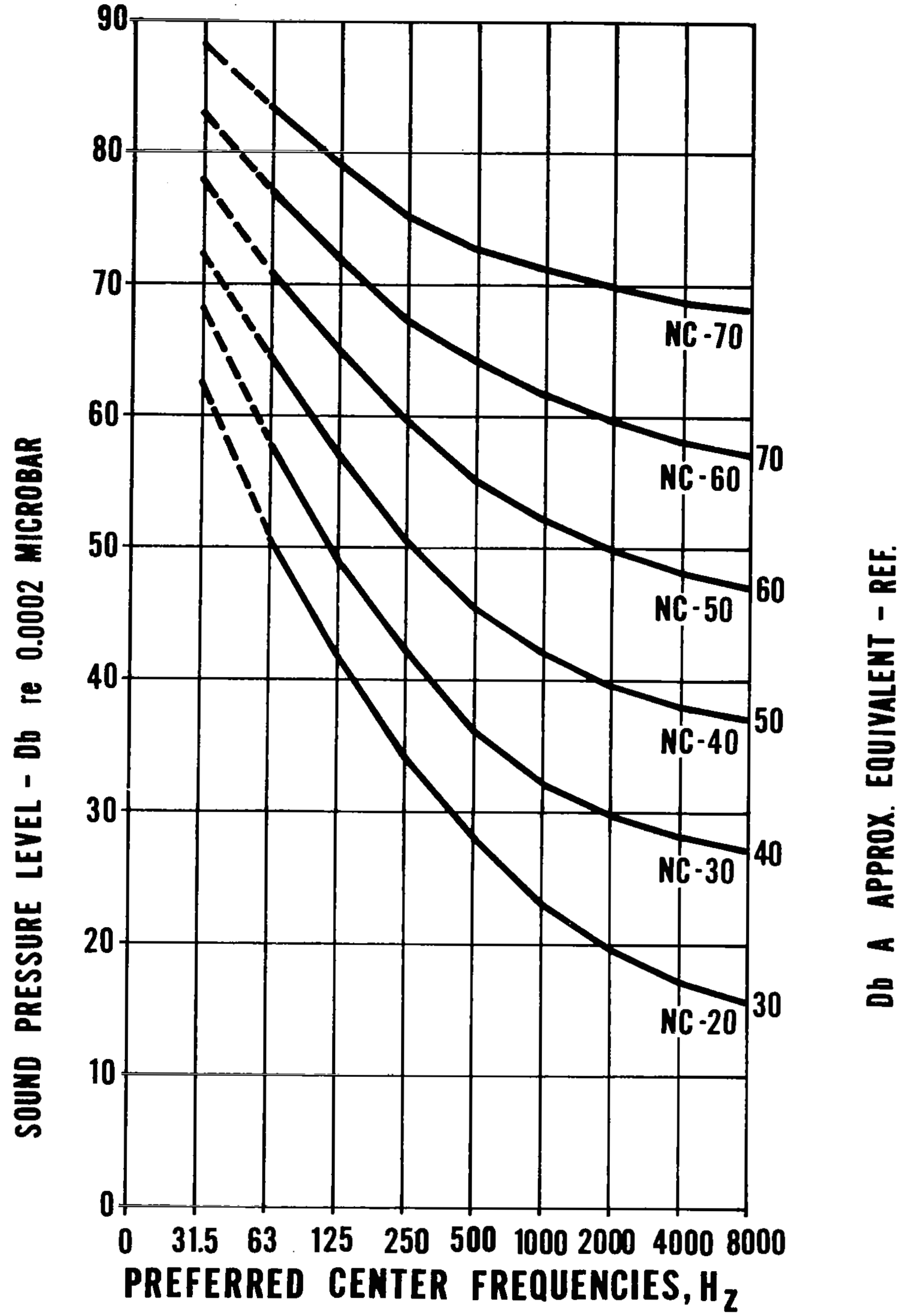


FIGURE 4. SOUND PRESSURE LEVEL VERSUS MID—FREQUENCY OCTAVE BAND

have since been replaced by newly adopted standard bands. The MOL and LM noise specifications were given in terms of the older octave bands (figure 4). The preferred center frequencies of the new standard octave bands are 31.5, 63, 125, 250, 500, 1000, 2000, 4000, 8000 and 16,000.

Noise criteria. - Preferred Speech Interference Level (PSIL) is the arithmetic average of the octave band sound pressure level in the preferred center frequencies of 1000, 2000, and 4000 Hz.

Noise criteria (NC) curves have been found to be desirable for specifying acceptable noise levels for office spaces. The numerical designation of each curve is approximately equal to the PSIL. The NC curves are presented with the original octave bands in figure 5.

Sound level meters generally have three electrically filtered overall sound pressure level scales which are normally available on sound level meters. The response obtained with the A scale (dbA) is roughly the inverse of the ear's equal loudness contours at low sound levels. Consequently, the A scale reading is the measurable single number which most nearly represents subjective loudness or annoyance.

If spacecraft noise is maintained at a favorable or lower NC level, the frequency spectrum of the NC curves assure an acceptable background level for intelligible voice communication, as well as what is thought to be a psychologically desirable sound-level versus frequency relationship.

The current LM acoustical noise level requirements as measured at ear level of crew members are plotted as Curve A and are the NC-50 curve. The MOL acoustical noise level requirements as shown in Curve B where the "Max. Allowable -- Single Item Operating, is measured 18 inches from source in an Anechoic Chamber". This is approximately NC-45. Curve C is "Max Allowable -- All Equipment Operating" and is NC-55.

An indication of the significance of these levels in terms of statistical testing done is that NC-levels above 55 are not recommended for any type of office environment. At NC-55 telephone use may be slightly difficult, and communications in normal voice above two feet or raised voice above six feet may be difficult.

An "Ideal" noise target for the space shuttle orbiter vehicle will be in the range of NC-45 which is designated as a desirable level for medium sized offices and allows communications in normal voice at distances of six feet. This is plotted on figure 6.

Considering that a single cabin will likely have to accommodate both crew and equipment, and that the noise environment will also have to be suitable for sleeping,

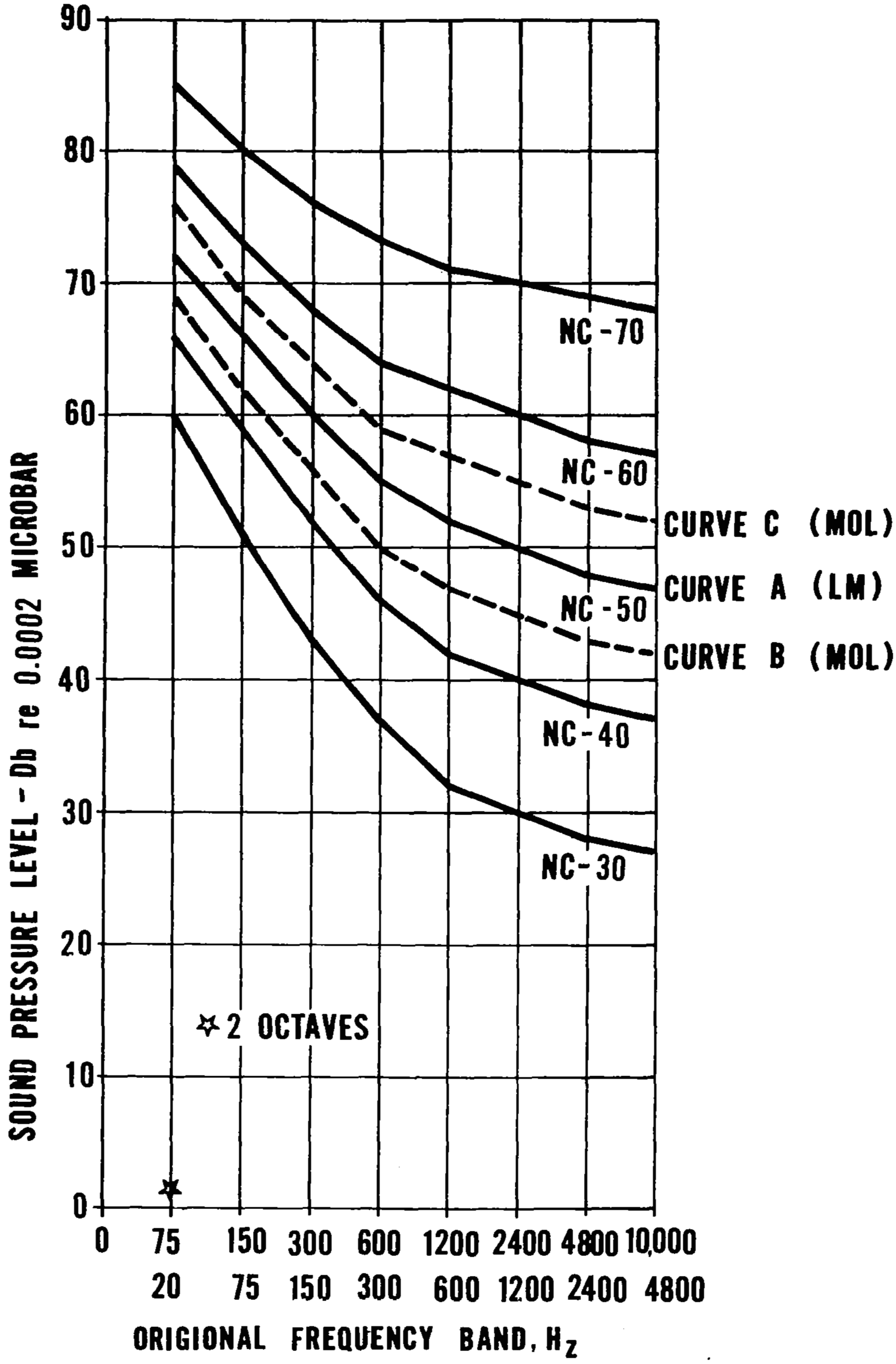


FIGURE 5. SOUND PRESSURE LEVEL VERSUS FREQUENCY BAND

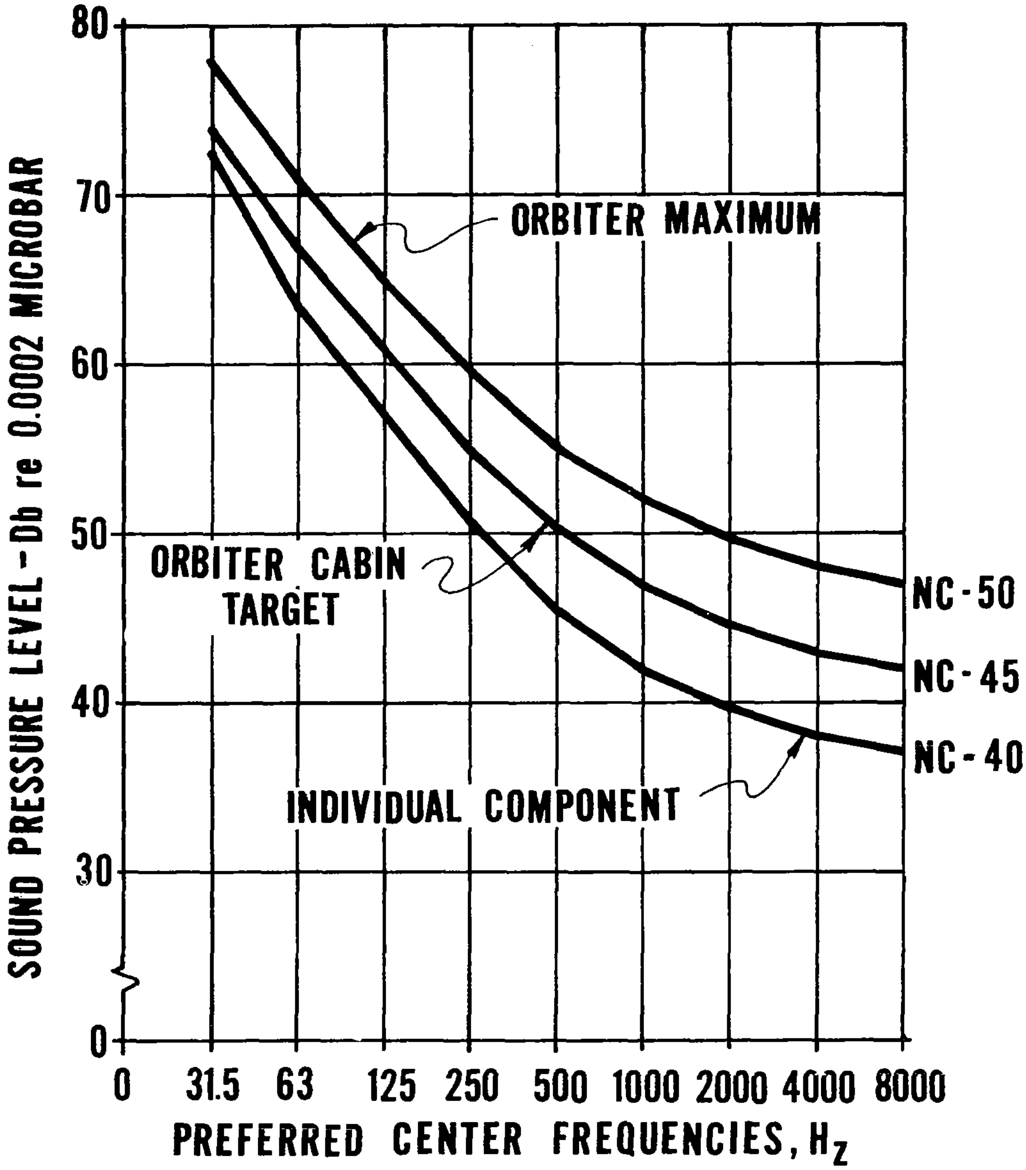


FIGURE 6. SOUND PRESSURE LEVEL VERSUS MID—FREQUENCIES OF OCTAVE BAND

the NC-45 curve appears to represent a compromise between what is desirable (least noise) and what can, in fact, be achievable at reasonable weight, power, and cost penalty. This curve represents the allowable noise level of all equipment operating in the spacecraft. Individual components should produce lower noise levels, i.e. NC-40 maximum, in order to allow for superposition of noises and uncertainties of the acoustical qualities of the complete cabin. Even so, if silencing to these levels proved impractical (from a weight standpoint), a relaxation of requirements to NC-50 should not be unduly annoying to the crew.

Noise from equipment reaching a listener may differ considerably when it is installed in a spacecraft. This difference may occur because of the reverberant character of the spacecraft and the occurrence of standing waves at certain locations due to reflections from walls or other equipment, or because vibrations from equipment find their way to resonant structures and are radiated as acoustic noise.

Noise generated by spacecraft environmental control system components may be roughly divided into those generated by solid to solid contact or vibration of solids (structure generated noise) and those generated by gas turbulence or other periodic gas pressure disturbances due to interaction between gas and solid surfaces (aerodynamic noise). A possible third source, similar to aerodynamic noise, is noise produced by flowing fluids.

Structure generated noise: Structure generated noise usually consists of solid to solid impact or vibration caused by rotating and reciprocating machinery. The most effective way to shield the receiver from structure generated noise is placing an acoustic barrier between the source and all possible paths to the receiver. The primary requirement for this shield is mass; in general the greater the mass the more effective the barrier. In practice, maximum use is made of existing vehicle mass by strategic location of the potential noise source (i.e., locating coolant pumps external to the cabin pressure shell, if possible). In this way, additional mass need not be added to the spacecraft exclusively for noise reduction.

Aerodynamic noise: Aerodynamic noise is mainly propagated to the receiver (ear) through the atmosphere, and is generated by gas turbulence or other periodic gas pressure disturbance due to interaction between the gas and solid surfaces. Although a great deal of research has been applied to this problem (i.e. in jet engine noise abatement programs), aerodynamic noise generation mechanisms are not yet fully understood.

The two main sources of aerodynamic noise in spacecraft are gas valves and fans.

Gas valves - High pressure gas valves remove energy from the fluid, and can be very noisy devices (>100 db) especially with sonic flow. The high frequency, high sound pressure level noise emitted by jets from choked valves will almost invariably require muffling if operated near personnel.

Lightweight means of external noise suppression of high-pressure valve exhausts are limited both in availability of concepts and effectiveness. The exhaust may be directed into an already acoustically-lined duct; typical duct lining materials are quite effective at high frequencies. Or the valve inlet pressure may be reduced so that the flow will be subsonic. These quieting measures are a function of system design, and those alternatives are not always available to the designer. Porous materials, such as Feltmetal, have proved effective in valve exhaust silencers used on the MOL program. These devices, compact but heavy, represent a brute force approach which has reduced valve noise by as much as 40 db.

Fans - Fans typically produce two types of aerodynamic noise: A broad-band turbulence noise and discrete frequency tones related to the frequency at which an interaction occurs between a fan blade and the air at a given point in space (and to harmonics of this frequency). Factors which improve the aerodynamic efficiency of a fan tend to reduce the aerodynamic noise generated by the fan. Noise can be reduced by using external silencers or by design of the fan.

External silencing techniques generally used in moving gas streams are described below:

- The acoustic lining sound "absorber" is a broad-band noise reduction device. Depending on frequencies to be attenuated and duct configuration, lining the duct with a sound absorbing material (i.e., acoustical fiberglass) can attenuate noise by as much as 0.5 to 2.0 db per foot of duct length.

- The Helmholtz resonator or "trap" consists of a tuned chamber connected to the ductwork, and attenuates by changing the acoustical impedance of the system at a particular frequency. There is no flow in the tuned chamber, and no duct pressure drop, but the physical size of the chamber can become large at low frequencies.

- Ductwork at both the inlet and outlet of the item promote rapid decay of the "spinning mode" noise phenomenon peculiar to fans.

- Ducting design which precludes "line-of-sight" transmission of noise has increasing attenuation effectiveness at higher frequencies.

Fan design techniques outlined below, are available to reduce the inherent noisiness of a given fan. These techniques should result in fans which require less external attenuation to meet a given noise requirement:

- Reducing tip speed is the most effective single measure available to reduce noise generation in fans. However, reducing the fan rotor tip speed, runs counter to optimizing the fan with respect to performance, weight and volume. A tradeoff study is usually necessary to determine if it is advantageous to sacrifice fan efficiency and weight to achieve a lower noise generation level.

- Eliminating upstream flow obstructions will reduce turbulent wakes in the flow stream for several duct diameters, reducing the noise level.

- Proper location and placing of stators and rotors will reduce discrete frequency tones.

In summary, sound control must be considered at the very initiation of the equipment design process, in order to minimize the eventual penalty incurred for the vehicle and its crew.

ATMOSPHERIC STORAGE

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ATMOSPHERIC STORAGE

The atmospheric storage subsystem provides gaseous oxygen and nitrogen, for crew metabolic consumption, vehicle gas leakage, and repressurization. These requirements must be satisfied for both the normal or "primary" mission and for a 48-hour emergency contingency. Detailed requirements for oxygen and nitrogen gas to maintain an acceptable two-gas (14.7 psia) atmosphere and gas supply are shown in table 4.

Consideration was given to three general classifications of atmospheric storage systems: high pressure gas, cryogenic and chemical. The demand for quantities of makeup gas is determined by a cabin total pressure and composition controller whose configuration is dependent on the particular storage candidate selected. Pressure and composition control is discussed in the following chapter of this report.

Carbon dioxide reduction for oxygen was not considered in this study because of the relatively low quantities of oxygen required and the low-penalty availability of oxygen from the vehicle propellant oxygen storage system. Since the EC/LSS oxygen requirement amounts to less than 0.5% of the oxygen stored in the vehicle propellant oxygen storage system, it was decided to utilize this source as the primary EC/LSS oxygen supply. As a result, further evaluation of oxygen supply concepts was conducted for an emergency 48-hour contingency use only. The nitrogen supply, on the other hand, is exhausted only as a primary diluent gas supply, and has no emergency provisions, due to the non-critical nature of the loss of this subsystem for a 48-hour period.

For the baseline four-man, seven-day mission and all other missions under consideration, the following concept selections were made:

- Primary Oxygen Supply - Vehicle propellant oxygen storage system using subcritical oxygen.

- Emergency Oxygen Storage - High pressure storage using tanks made of composite material.

- Nitrogen Storage (all) - High pressure storage using tanks made of composite material.

TABLE 4
ATMOSPHERIC STORAGE REQUIREMENTS

	Pounds of Usable Gas					
	14 Men-2 days		4 Men-7 days		2 Men-30 days	
	O_2	N_2	O_2	N_2	O_2	N_2
Normal Use						
Metabolic Use	51.5	--	51.5	--	110.5	--
Leakage Makeup						
Main Cabin & Airlock	1.55	5.45	5.42	19.08	23.25	81.75
Payload Module	2.21	7.79	*	*	*	*
Repressurizations						
Main Cabin (1)	16.6	58.4	16.6	58.4	16.6	58.4
Air Lock (4)	16.6	58.4	16.6	58.4	16.6	58.4
Payload Module (1)	24.9	97.6	*	*	*	*
Primary Supply - Total	113.36	227.64	90.12	135.88	166.95	198.55
48-Hour Contingency						
Metabolic Use	51.5	--	14.7	--	7.36	--
Leakage Makeup						
Main Cabin & Airlock	1.55	5.45	1.55	5.45	1.55	5.45
Payload Module	2.21	7.79	*	*	*	*
Emergency Supply - Total	55.26	13.24	16.25	5.45	8.91	5.45

*Not Manned

This Atmospheric Storage Study is divided into six (6) subsections:

- Primary Oxygen
- Emergency Oxygen
- Nitrogen
- Combined Oxygen and Nitrogen
- Evaluation and Selection
- Impact of Mission Parameters

PRIMARY OXYGEN

The oxygen storage requirements for EC/LSS usage present a unique situation because of the anticipated large capacity of the orbiter vehicle propellant oxygen storage system. At this writing, the best estimate of the capacity of this tank is in the range of 25, 000 to 40, 000 pounds of cryogenic oxygen, which is used chiefly for the orbital maneuvering system (OMS).

This large amount of oxygen is stored in a subcritical cryogenic state in a single central insulated tank, as part of the vehicle structure. The oxygen storage weight penalty, will fall in the range of 0.01 to 0.1 pound of tankage per pound of additional oxygen stored, depending on how the structural value of the tank is prorated against its storage capacity by the airframe contractor. These weight penalties are several orders of magnitude lower than an independent EC/LSS oxygen storage system. In addition, the cost, volume and other penalties are substantially reduced because the tank and delivery system are already "on board" the vehicle.

For a 4-man, 7-day nominal mission, the EC/LSS oxygen requirements are 90.12 pounds or approximately 0.3% of the available vehicle oxygen supply (an amount which will not significantly increase the existing oxygen supply penalty).

The use of the propellant oxygen for metabolic consumption requires that the quality of oxygen present be reviewed. Liquid oxygen (LOX) is generally available in three grades, according to NASA MSFC Spec. 399. The various grades of oxygen are summarized in table 5. If the EC/LSS and propulsion supplies were combined, then Grade B oxygen would be necessary to satisfy the metabolic oxygen cleanliness requirements. This poses no significant problems, in terms of segregating LOX supplies or increased logistics expenses, since virtually all LOX delivered to ETR (Eastern Test Range -

TABLE 5
LIQUID OXYGEN CHARACTERISTICS

Grade A	The "cleanest" LOX available in quantity, generally specified for use as a Fuel Cell reactant and for other critical uses.
Grade B	Essentially "standard" grade C LOX, but with controlled storage/shipping equipment cleanliness levels, and certified to meet certain contamination levels, especially low hydrocarbon levels. This grade is specified for breathing oxygen, and is equivalent to MIL-O-27210C.
Grade C	Standard grade LOX, used for propulsion.

Cape Kennedy) presently meets grade B standards. Therefore, it is recommended that the vehicle's propellant supply serve as the primary EC/LSS oxygen source. The emergency oxygen requirements will be met by an independent storage subsystem as discussed in the next section.

Although not a part of this study, the fuel cell oxygen supply represents a much more severe problem, in terms of the LOX quality, than does the EC/LSS breathing oxygen supply. Fuel cell electrolyte matrices appear to suffer some life reduction attributable to reactant impurities, and so require extremely pure grade (Grade A) oxygen for reliable operation. These reactants may have to be stored and supplied independently, or require purification equipment. Efforts by fuel cell contractors are presently underway to reduce the sensitivity of fuel cells to reactant impurities.

EMERGENCY OXYGEN

Emergency oxygen is required to provide oxygen for metabolic consumption and vehicle gas leakage for a period of 48 hours in the event of a loss of the primary oxygen supply. The quantity of oxygen required (16.25 lbs) for the 4-man baseline EC/LSS requirement is shown in table 4. A single storage supply system is acceptable for emergency use (fail safe mode) because if this system is required, the equivalent of two failures must have occurred previously within the vehicles oxygen supply system.

The candidates evaluated for the storage of emergency oxygen are:

- High Pressure Gaseous Oxygen
  - a. Stainless steel tanks
  - b. Composite material tanks
- Cryogenic Oxygen
  - a. Subcritical
  - b. Supercritical
- Alkaline earth peroxides/superoxides
- Sodium chlorate candles
- Hydrogen peroxide
- Electrolysis of water

High Pressure Gaseous Oxygen

High pressure gaseous storage of oxygen at ambient temperature is an inherently simple storage approach. A general data sheet and a schematic for high pressure gaseous oxygen storage are shown in figure 7. The optimum oxygen storage pressure is 3000 psia because a minimum gaseous tankage weight is realized at this value, as indicated in figures 8 and 9. It applies to both pressure vessels made of stainless steel and composite material. Titanium tankage is not considered acceptable foı oxygen storage. A characteristic of titanium is that it oxidizes very rapidly when exposed to oxygen. A particle penetrating the oxide film which covers the tankage surface, will expose the metal (fuel) to the oxygen (oxidizing agent) thereby posing a highly combustible and hazardous situation. Therefore, because of the material incompatibility with oxygen, the use of titanium for oxygen storage was dropped from further consideration.

High pressure gaseous storage tank weights (as well as cryogenic storage vessel weights) are based on the use of spherical tanks. Composite (filament wound) material vessels are oblate spheroids. Material strength values and burst factors used in calculating the tank weights are shown in table 6. The strength of each candidate material is based on 1975 predictions as indicated in table 6.

An ullage factor of 5% was applied to the gas storage requirement, yielding a residual pressure of 150 psia to allow for proper gas pressure regulation. Therefore, the stored gas weight is

Emergency Oxygen	16.25 lbs.
Ullage	0.81 lbs.
Total Stored Oxygen	17.06 lbs.

The stainless steel tank calculations are based on using unaged, cryogenically formed AISI 1301 stainless steel. The ultimate tensile strength of this material is presently 210,000 psi with a 1975 projected strength of 250,000 psi. Artificially aged cryoformed 301 presently has a higher strength, 280,000 psi, but this material was not picked due to its somewhat lower resistance to stress corrosion, which may be incompatible with the 10-year life and multi-cycle (100) requirements.

Composite material tanks utilize the high strength/low weight properties of composite materials to obtain low weight storage vessels. The construction consists of bosses and a leaktight inner liner (0.004" thick) made of Inconel 718. The filament is wound from top to bottom around each boss giving a criss-cross appearance at the equator similar to a spool of twine. Due to the criss-cross effect a load in one direction is supported by only half the fibers resulting in a 50% winding efficiency.

SUBSYSTEM: ATMOSPHERIC STORAGE - EMERGENCY OXYGEN

CONCEPT: HIGH PRESSURE STORAGE
Stainless Steel (SS) and Composite (Comp.) material

FLIGHT AVAILABILITY: 1975

Mission Phase Application

Launch X Orbit X Reentry X Cruise X

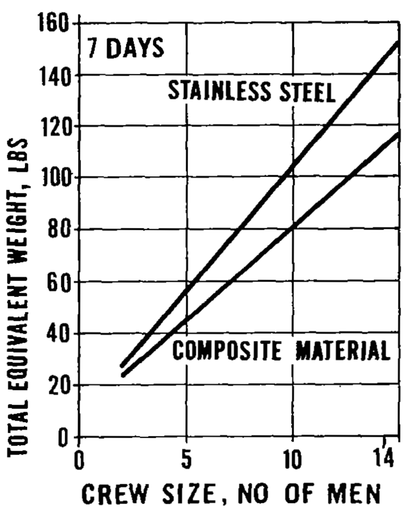
RELIABILITY: 0.999893 MTBF: 168, 000 hours
Both Concepts

4 Men - 7 Days Plus 48 Hours Contingency

	Total Equivalent Wt. (lb)		Volume (ft^3)		Power (watts)
	SS	Comp.	SS	Comp.	
Installed Unit	28.5	18.4	3.0	3.4	0
Expendables	17.1	17.1	—	—	—
Power Equiv. Wt.	—	—	—	—	—
Totals	45.6	35.5	3.0	3.4	0

Cost Factor	SS	Comp.
Recurring -	1.0	1.3
Nonrecurring -	1.4	1.8
Total -	1.1	1.4

Crew Time (hrs) — Both Concepts	
Scheduled —	0
Ground Refurbishment —	0



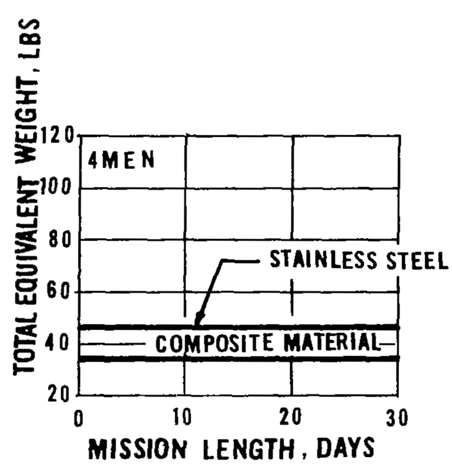


Figure 7. (Page 1 of 2)

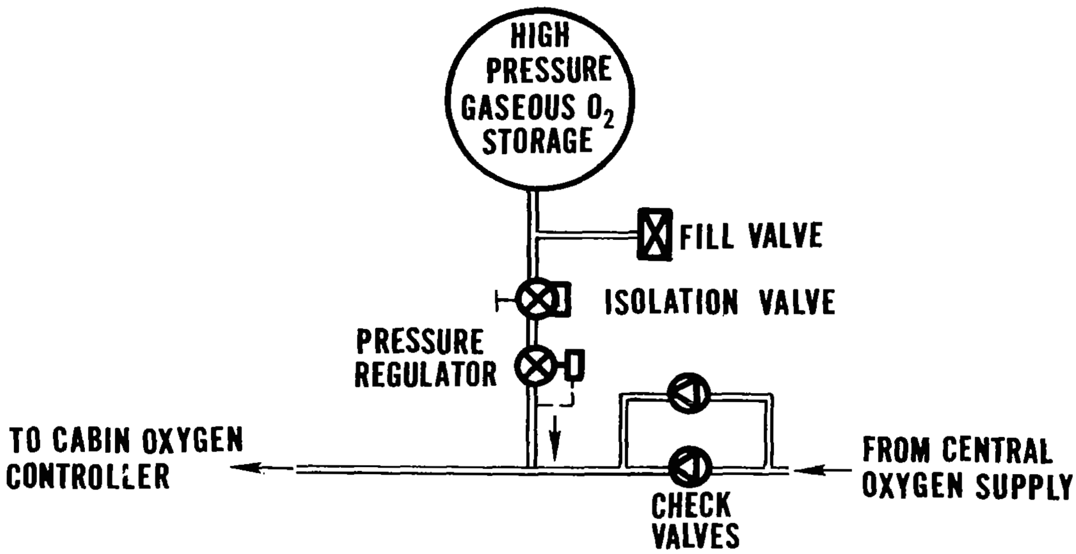


FIGURE 7. HIGH PRESSURE GASEOUS OXYGEN STORAGE (PAGE 2 OF 2)

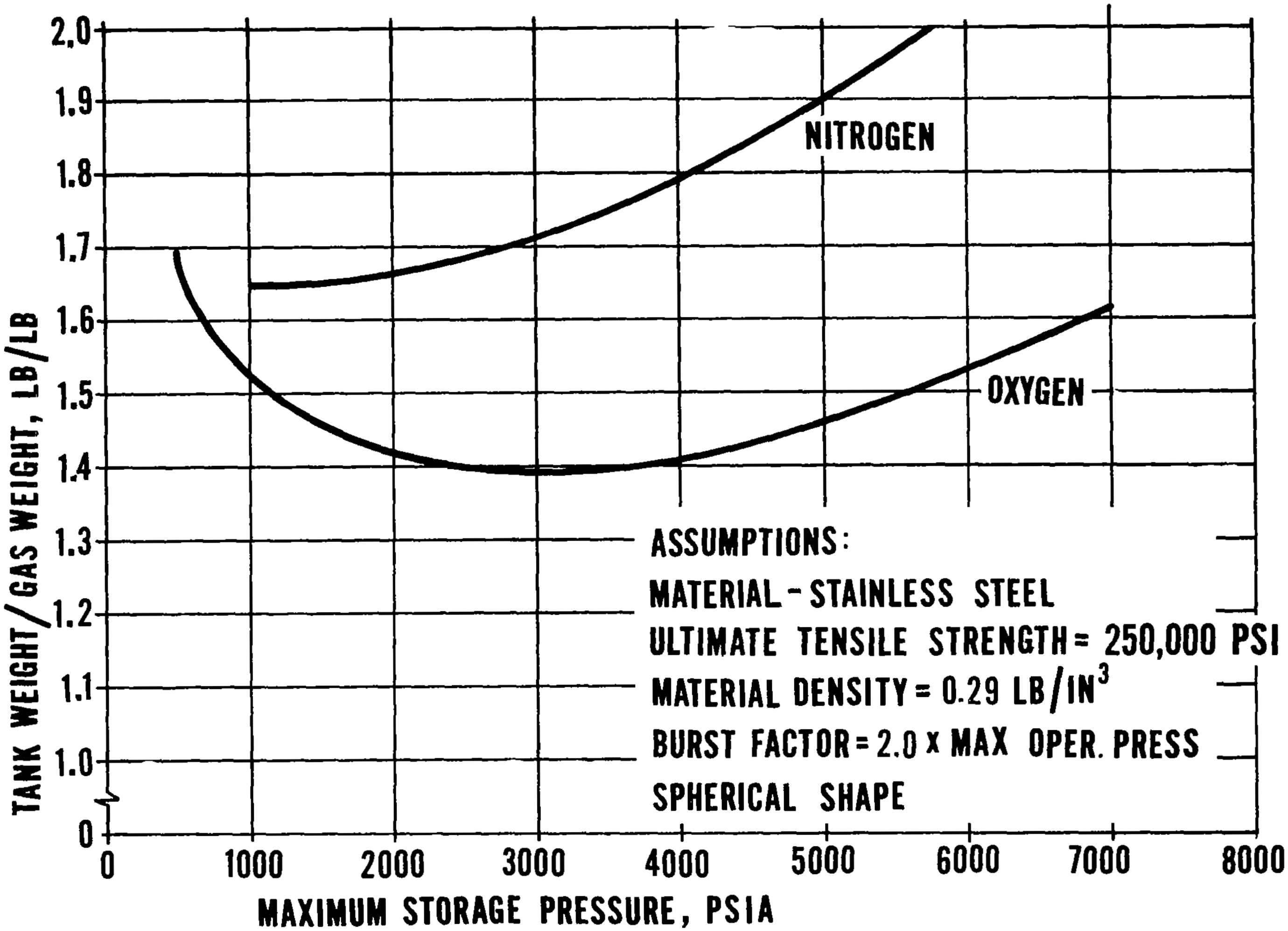


FIGURE 8. STORAGE WEIGHT FACTOR, HIGH PRESSURE STAINLESS STEEL TANKAGE

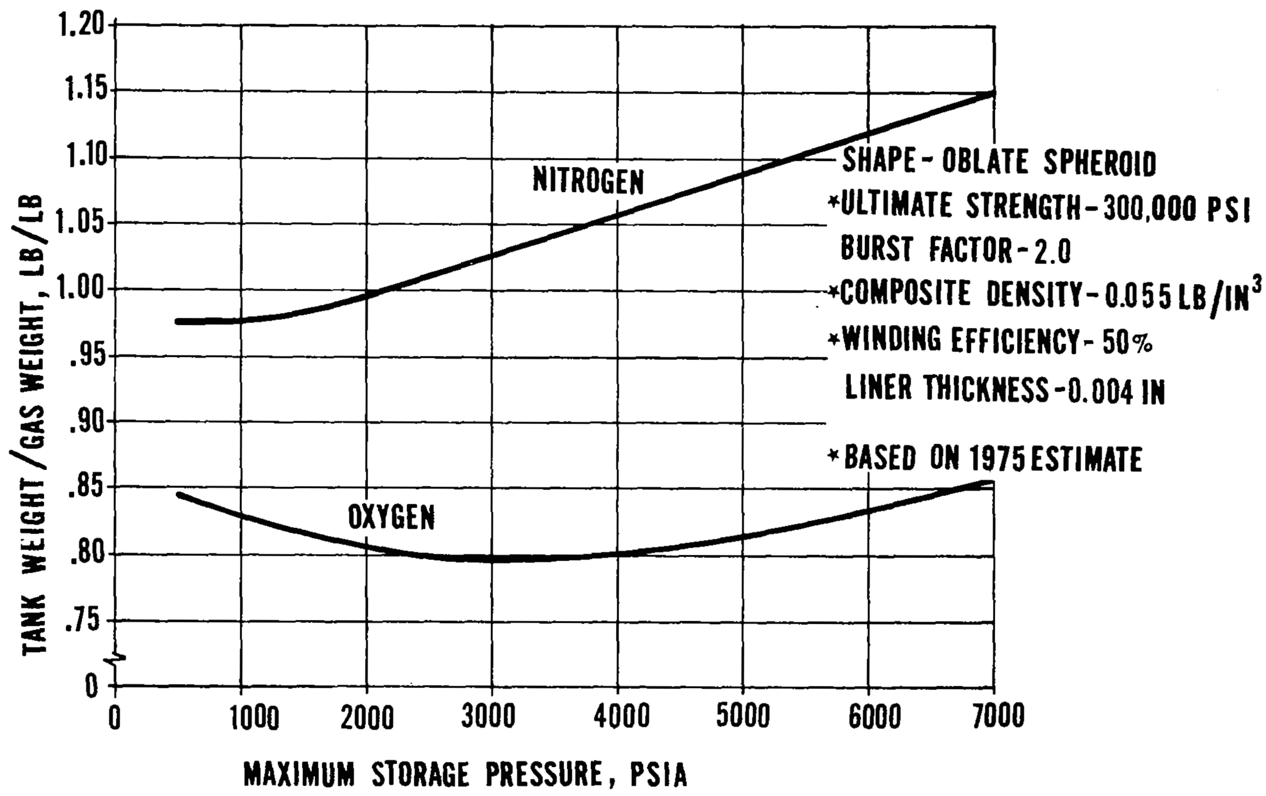


FIGURE 9. STORAGE WEIGHT FACTOR, HIGH PRESSURE COMPOSITE MATERIAL TANKAGE

TABLE 6
HIGH PRESSURE GAS STORAGE MATERIAL PROPERTIES

Material	Present Values Design Ultimate Stress psi	Present Values Burst Factor	1975 Predicted Values Design Ultimate Stress psi	1975 Predicted Values Burst Factor
301 Stainless Steel	210,000	2.0	250,000	2.0
6AL-4V Titanium (N_2 Storage Only)	165,000	2.0	180,000	2.0
Composite Material (Boron Filament)	225,000	2.0	300,000	2.0

Considerably more fibers build up at the bosses than at the equator. Optimization of the tank design can be obtained by changing the curvature around the bottle so that each fiber has the same stress in all areas of the tank. The resultant shape is an oblate spheroid with the major axis at the equator and the minor axis between the bosses. This shape optimizes tank weight per unit volume. This study assumed a boss diameter to equator diameter ratio of 0.20, which results in a minor/major axis ratio of 0.62. The net volume occupied by this optimized filament wound, oblate spheroid is somewhat greater than a spherial tank volume.

A curve of composite material tank weight as a function of pressure is presented in figure 9. The minimum tankage weight, occurring at 3000 psia, is 0.797 pounds of tank for each pound of stored gas. This value is used for all composite material tank calculations.

Absolute criteria. - High pressure gaseous storage is ideally suited to emergency systems when operation is characterized by long standby periods. Storage pressure is not sensitive to environmental heat, so indefinite standby with essentially zero use rate is possible. This approach does not require special pressure control concepts to prevent tank overpressurization. Furthermore, since delivery is not directly dependent on fluid heat addition, high repressurization flows can be achieved. Commercial high pressure bottles are used daily with a minimum of safety precautions, other than minimizing physical damage to the pressure vessel itself.

Availability/confidence is good and is a function of the strength to weight ratio desired. The availability of materials with the predicted strength values used in this study have been discussed earlier and is shown in table 6.

Quantitive criteria. - High pressure gaseous storage concepts have a low total equivalent weight, especially the composite material tanks. They are one of the lowest cost and least complex methods of oxygen storage. However, the relatively low density of stored fluid results in the high pressure storage concept occupying the largest volume of the concepts considered.

Qualitative criteria. - With only four (4) components required, this concept is among the least complex of all candidates considered. Its operation requires only a "push-button" start. Size is a direct function of the number of crewmen; from this standpoint, tanks can be added while maintaining a single set of valving. Refurbishment time is zero unless the unit has been used in an emergency. When necessary, the refilling procedure is quick and simple requiring only a high pressure source. Checkout is also simple, requiring only a pressure measurement to insure that the pressure vessel is full. No maintenance is required under normal mission operation.

Cryogenic Oxygen

Storage of oxygen as a high-density cryogenic fluid generally results in a compact and lightweight storage system. Cryogens may be stored either as a single phase homogeneous fluid (supercritical storage) or as a two-phase liquid/vapor mixture (subcritical storage) which requires separation.

Cryogens for aerospace use have generally been stored supercritically. This supercritical storage method (at pressures above the critical pressure of the gas), although heavier than the more conventional (on the ground) subcritical storage, solves the problem of phase separation and, hence, gas delivery in zero gravity, since the supercritical fluid does not undergo a phase change as it is being ejected.

The primary consideration in the design of supercritical storage vessels is in balancing the heat transfer properties of the insulation system with the thermodynamic properties of the stored cryogen for the specified mission requirements. Early supercritical oxygen storage systems utilized an extended surface electrical heater located within the inner storage sphere to provide the energy required to deliver the fluid. The specific heat required per unit mass of fluid withdrawn from a storage vessel at constant pressure is a function solely of the thermodynamic properties of the stored fluid. For oxygen, the specific energy requirements for withdrawal are increased with increasing constant pressures. During a typical delivery, the specific energy requirements for withdrawal at a constant pressure decreases to a minimum and then increases at lower densities.

Subcritical storage of oxygen is used in propellant tankage of contemporary spacecraft, where the use is intermittent, rather than a continuous demand. In a propellant tank, a gravity field is created by accelerating the spacecraft in a direction opposite that of the outflow duct in the tank to aid in phase separation. For a continuous supply, as the EC/LSS demands, a passive phase separation method is required to allow precise control of the small flows involved. Substantial effort is being expended in the areas of liquid-gas phase separation and quantity gauging in zero gravity, so that a subcritical storage system may be feasible for spacecraft application.

A data sheet and a schematic of the cryogenic oxygen supply system under consideration are shown in figure 10. It is assumed that a phase separation device is built into the subcritical tank. The following is a qualitative summary of subcritical and supercritical characteristics:

SUBSYSTEM: ATMOSPHERIC STORAGE - EMERGENCY OXYGEN

CONCEPT: CRYOGENIC STORAGE
Supercritical (Super) and Subcritical (Sub)

FLIGHT AVAILABILITY: 1974

Mission Phase Application

Launch X Orbit X Reentry X Cruise X

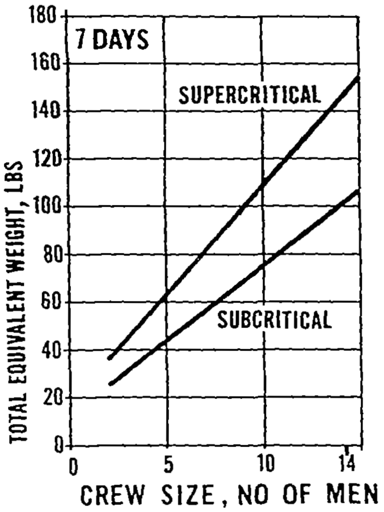
RELIABILITY: 0.999891 MTBF: 64,000 hours
Both Concepts

4 Men - 7 Days Plus 48 Hours Contingency

	Total Equivalent Wt. (lb)		Volume (ft^3)		Power (watts)	
	Super	Sub	Super	Sub	Super	Sub
Installed Unit	18.3	15.3	1.2	1.2	65	9.0
Expendables	20.0	20.0	—	—	—	—
Power Equiv. Wt.	14.8	2.0	—	—	—	—
Totals	53.1	37.3	1.2	1.2	65	9.0

Cost Factor	Super	Sub
Recurring -	3.9	4.7
Nonrecurring -	6.0	7.2
Total -	4.5	5.4

Crew Time (hrs) - Both Concepts	
Scheduled —	0
Ground Refurbishment —	1.0



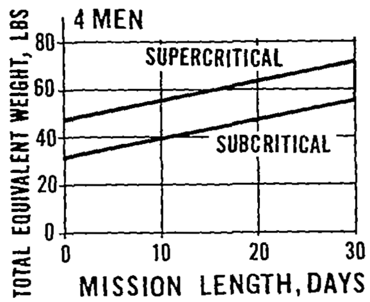


Figure 10 (Page 1 of 2)

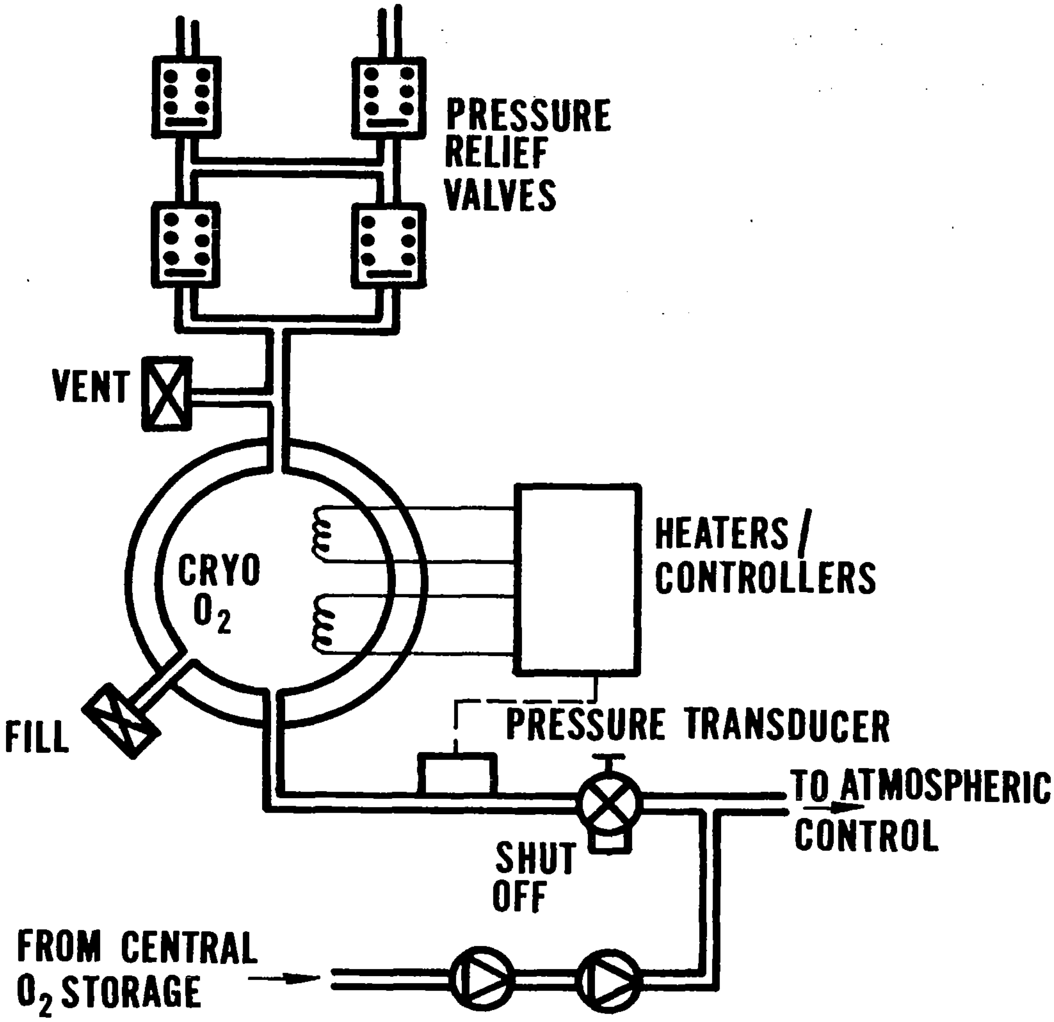


FIGURE 10. CRYOGENIC OXYGEN STORAGE (PAGE 2 OF 2)

	SUPERCRITICAL	SUBCRITICAL
Vessel Weight	Moderate	Low
Boil-Off Rate	Variable	Low-Constant
Power for Gas Expulsion	Moderate	Low
Gauging Complexity	Moderate	High
Phase Separation	Not Required	Required

Because of heat leaks into the primary vessel, continuous venting of the cryogenic tank is mandatory to limit pressure levels to safe values. For a system with a fixed minimum use rate, the tank heat leak is designed to allow delivery of this minimum rate, thereby minimizing insulation and fluid expulsion power requirements, and completely eliminating wasteful venting. However, for an emergency system in which the use rate is normally zero, certain disadvantages become apparent:

- Since zero heat transfer cannot be achieved, some venting of fluid will be required to limit pressure excursions when not in use. Thus, a larger initial tank capacity is needed (to make up lost fluid) and an active pressure relief system is required. An emergency system ideally should be completely passive.

- The system will require refill, checkout and topping-off prior to each flight, whether used or not during the flight.

- Special handling procedures for the cryogenic liquids are required, which are no more complex, however, than refilling the vehicle propulsion system between each flight.

A cryogenic vessel is provided with four (quad) relief valves to limit the internal pressures which might occur if the temperature should rise unexpectably during the flight. When oxygen is required, the in-flow valve is opened (by "push-button") and tank heaters are turned on. The tank heaters are automatically regulated to maintain the heat input for a desired pressurization and expulsion.

Absolute criteria. - The storage of low boiling point fluids such as oxygen and nitrogen, at cryogenic conditions has, in the past, provided a definite weight advantage over high pressure gaseous storage for large fluid quantities and continuous use. The higher fluid storage density at low to moderate pressures for cryogenic systems results in reduced storage vessel weight per unit of stored mass. This advantage is offset by limited rate of expulsion, sensitivity to environmental heat leak, increased complexity of delivery (especially in zero gravity), and limited periods of nonvented standby.

Performance of both subcritical and supercritical cryogenic systems is dependent on electric power for fluid expulsion, and some slight advance in the state of the art to minimize boiloff in small (10 inches diameter) vessels with high surface area to volume ratios. Subcritical cryogenic storage further requires development of a passive phase separation device. Reliability is somewhat hindered by the need for continuous venting.

The major portion of the reliability penalty is incurred in the pressure control section which is required for safety purposes. This equipment consists of quad-relief valves, a pressure transducer voting circuit, caps for the fill and vent valves and an internal heater.

Quantitative criteria. - The cryogenic storage systems are sized to supply both metabolic and cabin leakage requirements, when in use. Overboard venting is required during stand-by. A cryogenic system, sized for repressurization only, has essentially the same equivalent weight as one sized for standby use since the boiloff either provides the leakage demand or has to be vented overboard to avoid tank overpressurization. These approaches both have fixed weights which are among the lowest of the candidates considered, but are hampered by power penalty, particularly the supercritical storage concept. The total equivalent weights are noted in figure 10.

The rough order magnitude (ROM) costs are the highest of any of the candidate concepts considered. However, the concept volumes are the lowest.

Qualitative criteria. - Basically more complicated than high pressure tankage, the cryogenic storage concepts require pressure sensors, heaters and heater controllers, and special relief valves to meet performance requirements. Flexibility is hampered by boiloff as a function of time, requiring larger capacity tanks for longer missions. Some flexibility can be achieved in that an increase in cabin leakage will reduce the required insulation (i. e., a greater heat leak can be allowed to the stored cryogen). However, the performance penalty for a lower-than-target leakage rate more than offsets this flexibility. Growth is limited to expected development gains. The withdrawal energy requirements of a subcritical system permits significant system insulation optimization, whereas the supercritical system does not afford such an advantage.

Both systems require refilling (ground refurbishment) after each mission, whether used or not. Topping-off and monitoring during the prelaunch phase is also required. Neither of these operations are desirable for an emergency system on the shuttle if they can be avoided.

Alkaline Earth Peroxides/Superoxides

Oxygen can be produced as one of the by-products of a solid chemical reaction which generally absorbs water and carbon dioxide. Typical chemicals in this class are lithium peroxide and potassium superoxide. Of the two, lithium peroxide (Li_2O_2) possesses a higher potential for CO_2 removal with a slightly greater oxygen yield. Theoretically Li_2O_2 can produce 0.35 pounds of O_2 and remove 0.96 pounds of CO_2 per pound of chemical. Therefore, it appears attractive as a combined CO_2 removal and oxygen generation subsystem and could serve at least as a potential back-up for either or both of these systems. In use, the Li_2O_2 canister would be permanently installed in a branch of the CO_2 removal subsystem, and interface with the coolant circuit. Cooling is required because the reaction is exothermic. The amount of cooling must be controlled to obtain the desired oxygen production rate. In use, the cabin CO_2 subsystem fan flow is diverted to the Li_2O_2 canister, where CO_2 is absorbed and O_2 is generated and is diverted into the cabin.

A concept schematic and a general data sheet are shown in figure 11.

Absolute criteria. - Performance and availability/confidence are closely related, since further development is required to realize the performance presumed in this study. However, it is anticipated that an acceptable concept could be ready by 1976. Other than the high internal temperatures (approximately 600 °F), which is controlled by a coolant circuit, no apparent safety problems exist.

Quantitive criteria. - This concept has the highest equivalent weight of all approaches considered, even after a substantial credit for the CO_2 removal function is allowed. Volume is low. The ROM cost is one of the lowest of the candidates considered.

Qualitative criteria. - The concept is among the more complex of those under consideration. Since the sizing criteria is a compromise between oxygen generation and carbon dioxide removal efficiency, the system possesses a limited flexibility in handling metabolic consumption rates other than the nominal value. Checkout of this concept, as well as all chemical storage concepts, is limited to a functional check on the valves. Refurbishment which is required only if the system has been utilized, is complex and requires breaking into the coolant circuit. Various other approaches which preclude the breaking of lines were not considered as it would result in an increased unit weight making the system less competititive.

SUBSYSTEM: ATMOSPHERIC STORAGE - EMERGENCY OXYGEN

CONCEPT: LITHIUM PEROXIDE CHEMICAL

FLIGHT AVAILABILITY: 1976

Mission Phase Application

Launch X Orbit X Reentry X Cruise X

RELIABILITY: 0.999173

MTBF: 91,000 hours

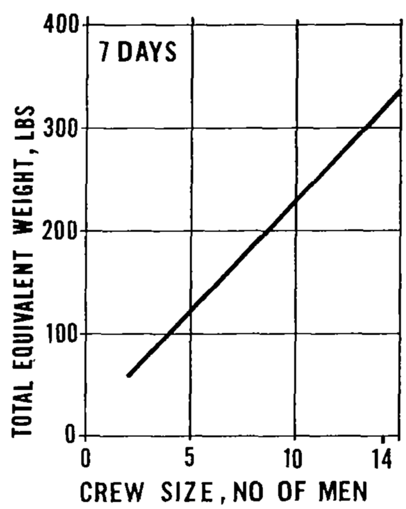
4 Men - 7 Days Plus 48 Hours Contingency

	Total Equivalent Wt. (lb)	Volume (ft^3)	Power (watts)
Installed Unit *	44.0	1.5	0
Expendables	55.0	—	—
Power Equiv. Wt.	—	—	—
Totals	99.0	1.5	0

*Includes credits for CO_2 removal

Cost Factor	
Recurring -	1.2
Nonrecurring -	1.5
Total -	1.2

Crew Time (hrs)	
Scheduled —	0
Ground Refurbishment —	0



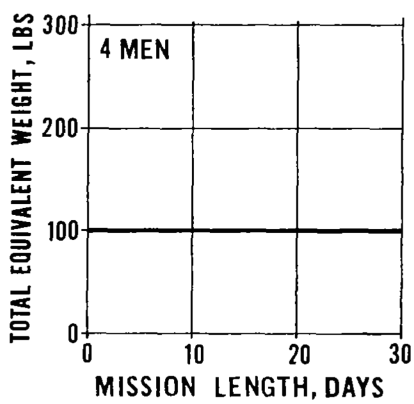


Figure 11. (Page 1 of 2)

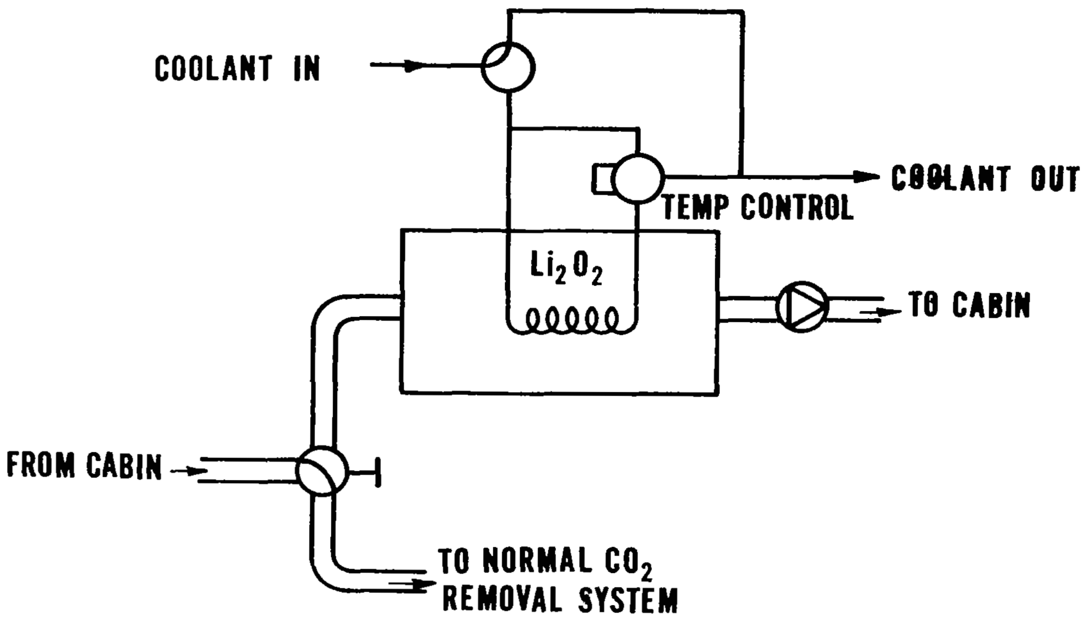


FIGURE 11. LITHIUM PEROXIDE CHEMICAL STORAGE (PAGE 2 OF 2)

Sodium Chlorate Candles

Oxygen can be generated by the decomposition of certain chemicals at elevated temperatures. The best known of these substances is Sodium Chlorate, ($NaClO_3$) and, in the form usually referred to as "chlorate candles", it has been in use for nearly fifty years as an emergency oxygen generator in mines and submarines. Although the theoretical yield of oxygen is 45% by weight, the actual yield is somewhat lower (about 36%). Generally, these oxygen generators are available in the form of continuous burning "candles", and once ignited (electrically or with pyrotechnic devices) they burn to completion, making control of the output limited to preselection of "candle" characteristics, and frequency of use. A major problem is in the contamination of the effluent oxygen especially with chlorine compounds, so that the use of chlorate candles has, up until now, necessitated scrubbing of the output oxygen to yield a breathable, non-toxic gas. Recent development efforts to improve oxygen quality without post-scrubbing have been promising, and linear burn rates, much too fast for aerospace use in the past, have been slowed to approximate 0.3 in/min. while maintaining reliable combustion. Heat generation should not represent a significant problem with the low oxygen generation rates involved.

The schematic and system characteristics of a chlorate candle approach are shown in figure 12. The system is electrically ignited by the crew upon a low O_2 partial pressure indication.

Absolute criteria. - The contamination of the effluent oxygen is the principal area of concern with respect to adequate performance of this concept. Otherwise, it is acceptable in all other absolute criteria.

Quantitative criteria. - Equivalent weight is very high, but volume occupied is low due to the high density of the material. The ROM cost is the lowest of the candidates considered.

Qualitative criteria. - The chlorate candle concept is a very simple concept with an unlimited storage life. The concept has a fixed uncontrollable output rate, yielding a low ranking in flexibility. Ground refurbishment is required if the system has been used and consists only of replacing the filter and the spent "candles". Checkout is limited to continuity checks on the electrical igniters.

Hydrogen Peroxide

When passed over a catalyst, hydrogen peroxide (H_2O_2) decomposes into oxygen and water vapor. This oxidizer compound, in high concentration (95% H_2O_2) is semi-

SUBSYSTEM: ATMOSPHERIC STORAGE - EMERGENCY OXYGEN

CONCEPT: SODIUM CHLORATE CANDLES

FLIGHT AVAILABILITY: 1973

Mission Phase Application

Launch X Orbit X Reentry X Cruise X

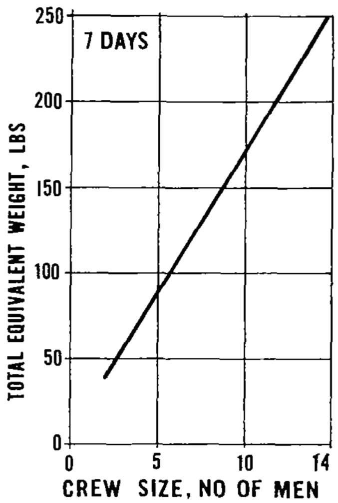
RELIABILITY: 0.999934 MTBF: 122,000 hours

4 Men - 7 Days Plus 48 Hours Contingency

	Total Equivalent Wt. (lb)	Volume (ft^3)	Power (watts)
Installed Unit	8.0	0.2	0
Expendables	63.5	1.5	—
Power Equiv. Wt.	—	—	—
Totals	71.5	1.7	0

Cost Factor	
Recurring -	1.0
Nonrecurring -	1.0
Total -	1.0

Crew Time (hrs)	
Scheduled —	0
Ground Refurbishment —	0



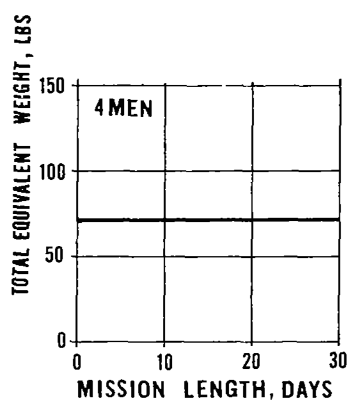


Figure 12. (Page 1 of 2)

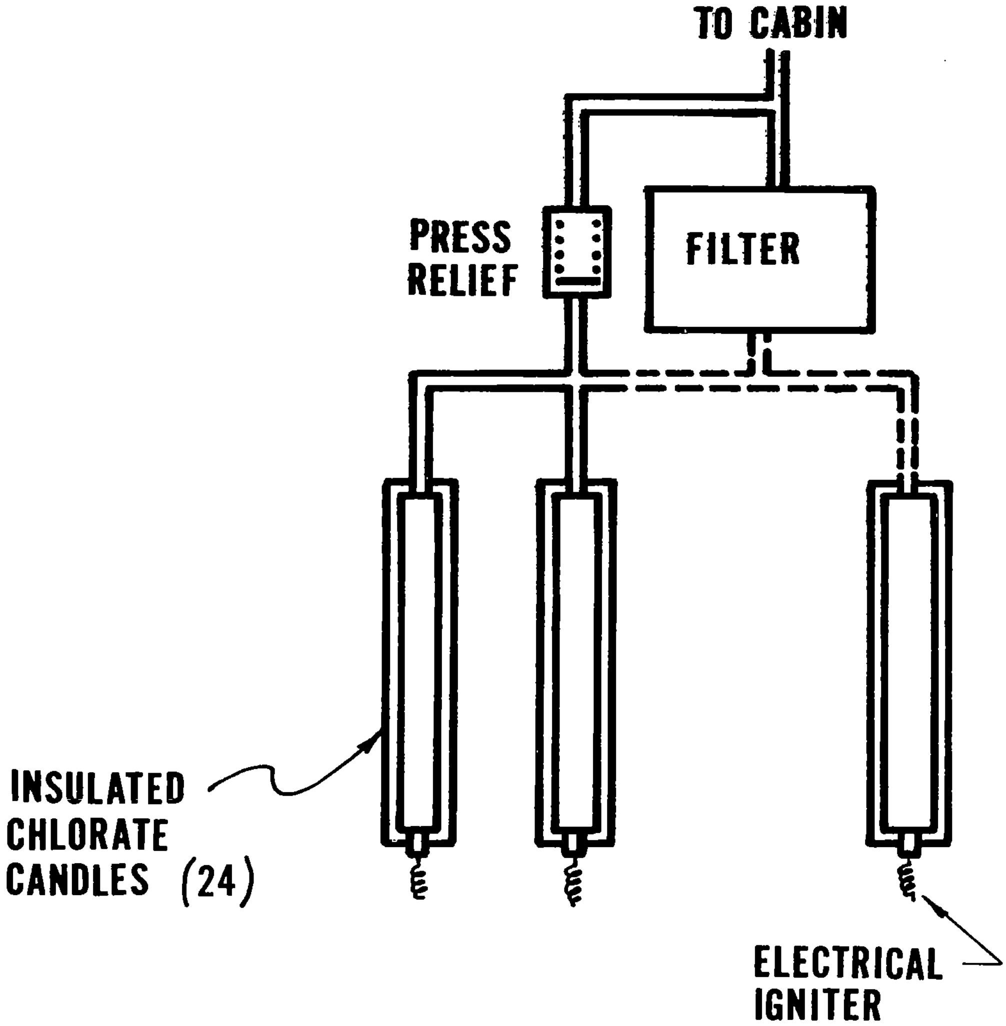


FIGURE 12. SODIUM CHLORATE CANDLES (PAGE 2 OF 2)

stable, and reacts with virtually all common materials (exceptions: pure aluminum, and teflon). Its stability is somewhat marginal, and storage facilities must be vented with pressure relief devices. The products of decomposition usually include some unreacted H_2O_2, a highly toxic vapor.

The culmination of these performance/safety jeopardies, and the lack of any obvious system advantages, eliminated this concept from further consideration based on the failure to meet the absolute evaluation criteria.

Electrolysis of Water

The electrolysis of water is an electro-chemical process which, with the application of substantial amounts of DC power, generates oxygen and hydrogen. At predicted efficiency levels, the power penalty for an emergency electrolysis unit would be approximately 160 pounds. Depending on the particular electrolysis concept, this technique is likely to yield the most complex and least reliable of all emergency oxygen supply concepts considered. Some potential safety problems from acidic or basic electrolyte leakage and the presence of hydrogen also exists.

Because of the above reasons and its complexity and extremely high power penalty (approximately twice the total equivalent weight of the next heaviest approach), this concept was eliminated from further consideration.

NITROGEN

Since nitrogen is the major atmospheric constituent and not metabolically consumed, its storage capacity requirements are a function of cabin leakage, mission duration, and cabin or airlock repressurization requirements. Table 4 indicates that the repressurization requirements, although minimal in number of occurrences, represent the greatest portion of the nitrogen storage capacity.

Unlike the oxygen storage subsystem function, which is provided largely by the propulsion cryogenic oxygen supply already on-board the vehicle, the nitrogen storage subsystem for the EC/LSS apparently represents the sole requirement for nitrogen onboard the shuttle orbiter vehicle, and as such, it must provide both nominal and the 48-hour contingency requirements. The stored gas weight for the baseline mission is

Nitrogen Storage	141.33 lbs.
Ullage	7.17 lbs.
Total Stored Nitrogen	148.50 lbs.

Only one nitrogen storage tank, which is extremely reliable, is required by definition to meet the redundancy Requirement/Guidelines (appendix A).

Redundant accessories i.e. valves and controls are provided in order to meet the fail operational requirements. A subsequent failure of either part of the system (a fail safe situation) requires dependency on the oxygen supply system to supply the gas makeup requirements. With no nitrogen available, the total cabin pressure will only fall from 14.7 psia to 13.6 psia during the 48-hour contingency period presuming specified use rates.

The following nitrogen storage concepts were considered:

- High Pressure Gaseous Nitrogen
  - a. Stainless steel tanks
  - b. Composite material tanks
  - c. Titanium tanks
- Cryogenic Nitrogen
  - a. Subcritical
  - b. Supercritical

High Pressure Gaseous Nitrogen

The characteristic data and schematic describing the high pressure gaseous nitrogen storage concepts, are shown in figure 13 for the three tankage materials under consideration. Nitrogen does not exhibit an optimum storage pressure * like oxygen does, so an arbitrary storage pressure of 3000 psia was chosen for purposes of comparison. Utilizing this pressure level allows for the possibility of equipment commonality between oxygen and nitrogen tankage and valving. Minimum operating tank pressure is 150 psia, below this figure the tank is considered empty.

Each system consists of a main nitrogen supply tank, with redundant valving and regulators, to reduce supply line pressure to a low value (50 to 100 psia) compatible with the pressurization controller.

The three candidate concepts differ only in choice of pressure vessel material. The candidates materials are cryogenically formed 301 stainless steel, 6 AC-4V titanium alloy, and composite (filament wound) material.

*Actually, an optimum storage pressure for nitrogen exists at approximately 500 psia, but this pressure results in an excessive storage volume penalty.

SUBSYSTEM: ATMOSPHERIC STORAGE - NITROGEN

CONCEPT: HIGH PRESSURE STORAGE
Stainless Steel(SS) Titanium (Ti) Composite (Comp) material

FLIGHT AVAILABILITY:

1974

Mission Phase Application

Launch X Orbit X Reentry X Cruise X

RELIABILITY: 0.999997 MTBF: 155,000 hours
All Concepts

4 Men - 7 Days Plus 48 Hours Contingency

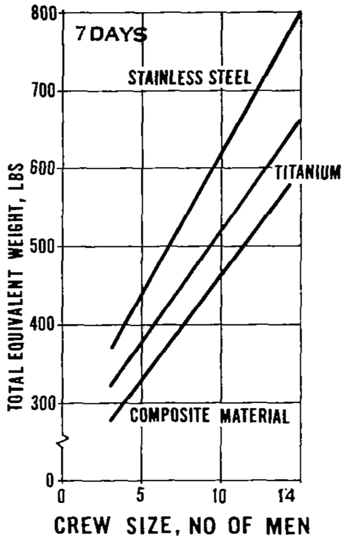
	Total Equivalent Wt. (lb)			Volume (ft^3)			Power (watts)
	SS	Ti	Comp	SS	Ti	Comp	
Installed Unit	258	205	158	21	21	24	0
Expendables	144	144	144	-	-	-	-
Power Equiv. Wt.	-	-	-	-	-	-	-
Totals	402	349	302	21	21	24	0

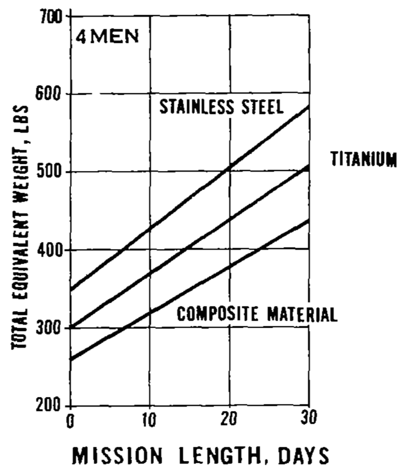
Cost Factor	SS	Ti	Comp
Recurring -	1.0	1.3	1.2
Nonrecurring -	1.0	1.3	1.2
Total -	1.0	1.3	1.2

Crew Time (hrs) - All Concepts

Scheduled - 0

Ground Refurbishment - 0





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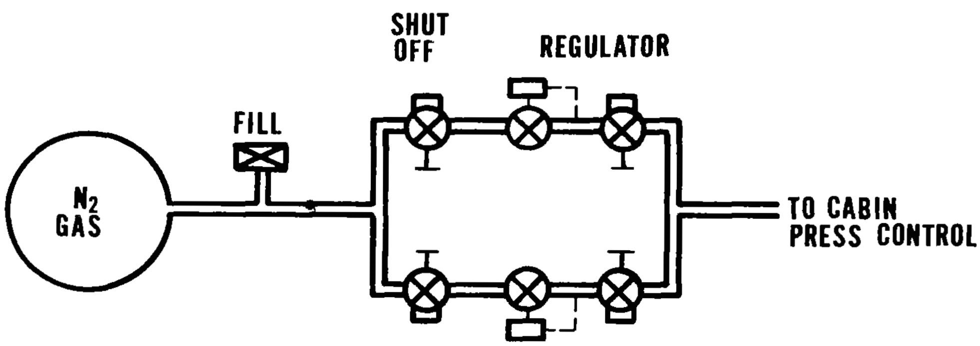


FIGURE 13. HIGH PRESSURE GASEOUS NITROGEN STORAGE (PAGE 2 OF 2)

Absolute criteria. - The same comments expressed earlier in the section on High Pressure Oxygen Storage apply to the characteristics and availability of high performance materials to meet the performance stated. The systems are relatively simple, with no apparent safety problems, and the Reliability is very good.

Quantitative criteria. - The total equivalent weight as a function of crew size shown in the data sheet assumes that the cabin volume varies linealy as the crew size is increased. Equipment weights are among the lowest of systems considered, on a total equivalent weight basis. In general ROM costs vary inversely with the material weights considered. Volume is high, due to the relatively low density of the stored fluid.

Qualitative criteria. - High pressure gaseous storage systems are inherently simple and durable. The refilling procedure is quick and simple requiring only a high pressure source of nitrogen. No special handling equipment is necessary. Ground checkout is easily accomplished by checking tank pressure level and outlet pressure of each regulator.

Cryogenic Nitrogen

Nitrogen diluent for the atmospheric supply can be stored at cryogenic temperatures, generally resulting in a lightweight, compact system. Cryogenic storage takes on two distinct forms.

Subcritical storage is the lightest system hardware under consideration. Nitrogen is stored as a cryogenic liquid at low pressure, ($<$ 50 psia) allowing the use of a thin wall pressure vessel. The liquid and the gaseous phases exist simultaneously, requiring some phase separation device to assure withdrawal of only gaseous fluid. The zero gravity phase control problem, and the associated quantity measurement problem, are not yet fully resolved.

Liquid nitrogen stored supercritically, above the critical pressure, does not undergo a phase change when fluid is withdrawn from the storage vessel. This single phase fluid, then is manageable in zero gravity. The price for this advantage is a heavier basic storage vessel. The increased weight is a result of the insulation required to obtain thermal performance (boil-off) comparable to the subcritical storage approach.

A schematic and characteristic data for the cryogenic approaches and presented in figure 14.

SUBSYSTEM: ATMOSPHERIC STORAGE - NITROGEN

CONCEPT: CRYOGENIC STORAGE
Supercritical (Super) and Subcritical (Sub)

FLIGHT AVAILABILITY:
1975

Mission Phase Application

Launch X Orbit X Reentry X Cruise X

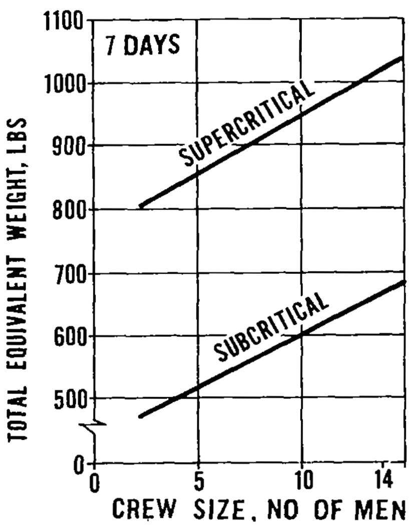
RELIABILITY: 0.999994 MTBF: 62,000 hours
Both Concepts

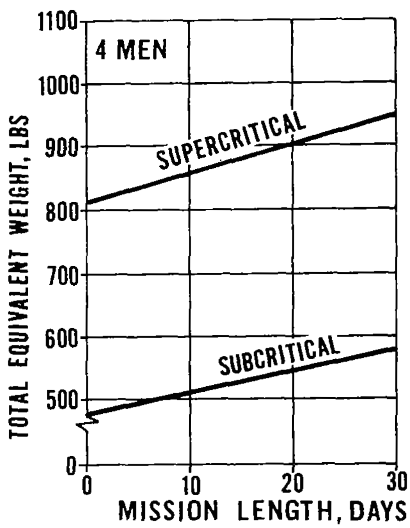
4 Men - 7 Days Plus 48 Hours Contingency

	Total Equivalent Wt. (lb)		Volume (ft^3)		Power (watts)	
	Super	Sub	Super	Sub	Super	Sub
Installed Unit	61.0	52.5	6.0	6.0	4000(Max)	1930 (Max)
Expendables	138.0	138.0	-	-	-	—
Power Equiv. Wt.	650.0	312.5	-	-	-	—
Totals	849.0	503.0	6.0	6.0	4000	1930

Cost Factor	Super	Sub
Recurring -	2.2	2.6
Nonrecurring -	2.4	2.6
Total -	2.6	3.0

Crew Time (hrs)— Both Concepts	
Scheduled —	0
Ground Refurbishment —	2.0





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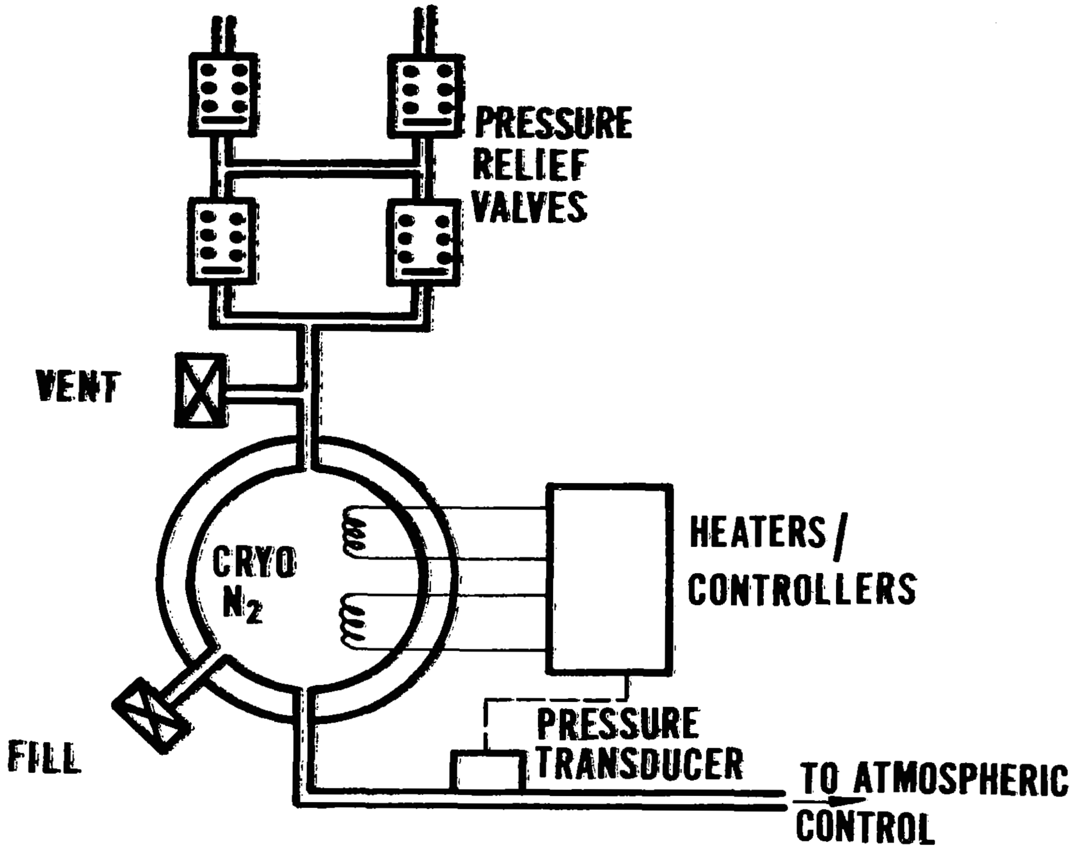

FIGURE 14. CRYOGENIC NITROGEN STORAGE (PAGE 2 OF 2)

Absolute criteria. - The system has been designed to have the boil-off equal to the cabin leakage rate so that no penalty is incurred. Other than a positive zero gravity phase separation device for the subcritical storage concept, availability/confidence of the cryogenic storage concepts is very good. Thermal performance requirements are not at all demanding. As in the case of cryogenic oxygen storage, there is a potential safety problem in that heat is required to expel the cryogenic fluid. Although cryogenic nitrogen presents a less hazardous situation than cryogenic oxygen storage, it is considered less safe than the high pressure gas storage approach.

Quantitative criteria. - Although fixed weight is low, repressurization requirements impose a tremendous power penalty on these cryogenic concepts and especially on the supercritical cryogenic approach. The volume is lowest of the candidates considered. Eliminating the need for cabin repressurization would make these systems very competitive from an equivalent weight standpoint.

Heater power consumption and power penalties do not allow for simultaneous repressurization of the main cabin and payload module; such a requirement would nearly double the already exorbitant power penalty.

Qualitative criteria. - Because of the need for redundant electric heaters and controllers, the systems are somewhat complex. This tankage concept is not as flexible as other concepts, since repressurization rates are dependent on heater power. Refurbishment and checkout capability are as previously stated in the section on cryogenic oxygen storage.

COMBINED OXYGEN AND NITROGEN

Two methods are considered for supplying both oxygen and nitrogen to the vehicle cabin. These are mixed gas storage and decomposition of hydrazine with hydrogen peroxide or nitrogen tetroxide. Neither method is considered competitive with an in-independent two-gas system because of the inherent advantage of using the oxygen from the vehicle primary propellant storage system and for the reasons discussed below.

Mixed Gas

Storage of the atmospheric gas constituents as a mixture was considered as an alternate candidate concept for the space shuttle. Basically, the concept has the potential of eliminating the active partial pressure controller (and its cost). It functions by supplying a constant flow of mixed oxygen and diluent (nitrogen) to the cabin at essentially the maximum anticipated cabin leakage rate. The oxygen is proportioned in the mixture such that, at this supply rate, maximum metabolic requirements are satisfied. With a "tight" cabin, a cabin outflow regulator valve opens to artificially maintain the leakage rate. The actual gas consumption, while higher than a more conventional system, is not actually a penalty since in any event, enough atmospheric expendables must be carried to accommodate the maximum leakage rate.

The concept has several basic deficiencies which are:

- It requires in effect, storage of the oxygen supply separate from the central vehicle supply, at a considerable weight penalty. (Approximately 170 lbs.)

- The pre-mixed gas cannot actively control PO_2 independently of total cabin pressure. The supply must therefore bleed into the cabin at a relatively fixed rate to satisfy oxygen consumption demands, and likewise bleed out through an active cabin pressure relief system if the cabin leakage is less than maximum.

- To satisfy the repressurization PO_2 level requirement within the specified time requires total cabin repressurization in two minutes.

- It does not have the flexibility of changing cabin total pressure and mixture ratio in flight to operate at 10 psia cabin pressure.

Because the mixed gas storage approach presents no significant advantages over independent storage, exhibits performance limitations and is considerably heavier, it was dropped from further consideration.

Hydrazine/Nitrogen Tetroxide Reaction

A concept which extends the use of storable rocket bipropellants of hydrazine and nitrogen tetroxide into the life support areas was also considered. The system reacts hydrazine (N_2H_4) with hydrogen peroxide (H_2O_2) or nitrogen tetroxide (N_2O_4) as an oxidizer to produce an oxygen/nitrogen mixture and water. The heat rejection requirements utilizing nitrogen tetroxide are substantially lower than with hydrogen peroxide. Moreover, employing nitrogen tetroxide as an oxidizer results in a significantly lower total weight of reactants required (over hydrogen peroxide). Thus, nitrogen tetroxide is selected over hydrogen peroxide as an oxidizer for consideration here to react with hydrazine (the fuel).

The reactants of hydrazine and nitrogen tetroxide burn hypergolically over a wide range of mixture ratios and pressures to produce the desired oxygen and nitrogen flow rates required for leakage makeup and repressurization. One hundred percent pure oxygen is unattainable, but the concept can provide one hundred percent pure nitrogen. Adequate composition control, therefore, must be provided.

The possibility of unreacted nitrogen tetroxide and hydrazine entering the cabin represents an area of concern due to the nature of these fluids. Adequate provisions must be made to prevent crew exposure to the potentially unreacted quantities of fuel and oxidizer.

Little development work has been performed on the hydrazine/nitrogen tetroxide gas supply system described. Similar systems have been utilized, however, for rocket propulsion, but the requirements of supplying breathable gas for human consumption dictate that extensive development effort is required to produce flight hardware.

The problem of controlling the reaction rate to handle varying leakage, metabolic, and repressurization rates imposes severe control problems which result in unacceptable performance.

As a result of this performance problem, this storage system was considered as not meeting the absolute evaluation criteria and was not considered further.

EVALUATION AND SELECTION

Primary Oxygen

The use of oxygen from the vehicles propulsion supply is selected for the primary oxygen supply EC/LSS use because of its availability, low cost and weight.

Emergency Oxygen

High pressure tankage made of composite (filament wound) material is selected for emergency oxygen storage (48 hours). An evaluation summary chart of the eight candidates and their relative ratings with respect to the evaluation criteria is shown in table 7. Additional quantitative data is shown in table 8 and figure 15.

Absolute criteria. - Of the eight specific concepts evaluated; two, hydrogen peroxide and water electrolysis, are given unacceptable absolute criteria ratings and are rejected because their performance, safety and reliability relative to the other candidates were unacceptable or marginal. Concepts which deliver both oxygen and nitrogen (as a mixed gas) are evaluated under the nitrogen storage equipment selection discussion. All other candidates have acceptable absolute ratings.

TABLE 7

EVALUATION SUMMARY - EMERGENCY OXYGEN

Criteria		High Pressure Gas		Cryogenic		Chemical
		Stainless Steel	Composite Material	Supercritical	Subcritical	Sodium Chlorate Candle
Absolute	Performance	Very Good	Very Good	Very Good	Very Good	Fair
	Safety	Very Good	Very Good	Very Good	Very Good	Good
	Reliability	Very Good	Very Good	Fair	Fair	Very Good
	Avail./Conf.	Very Good	Good	Fair	Very Good	Good
Quantitative	Total Equivalent Weight	Good	Very Good	Very Good	Good	Fair
	ROM Cost	Very Good	Good	Poor	Poor	Very Good
	Volume	Fair	Fair	Very Good	Very Good	Good
				Eliminated	Eliminated	
Qualitative	Complexity	Very Good	Very Good			Good
	Flexibility	Very Good	Very Good			Fair
	Durability	Very Good	Good			Good
	Refurbishment	Very Good	Very Good			Very Good
	Checkout Capability	Very Good	Very Good			Good
	Maintainability	Very Good	Very Good			Very Good
		Eliminated	Selected			Eliminated

TABLE 7 (Concluded)

EVALUATION SUMMARY - EMERGENCY OXYGEN

	Criteria	Chemical		Other		
		Lithium Peroxide	Hydrogen Peroxide	Water Electrolysis		
Absolute	Performance	Fair	Unacceptable	Unacceptable		
	Safety	Good	Fair	Fair		
	Reliability	Fair	Fair	Unacceptable		
	Avail. /Conf.	Fair	Fair	Good		
			Eliminated	Eliminated		
Quantitative	Total Equivalent Weight	Poor				
	ROM Cost	Very Good				
	Volume	Good				
		Eliminated				
Qualitative	Complexity					
	Flexibility					
	Durability					
	Refurbishment					
	Checkout Capability					
	Maintainability					

TABLE 8
ATMOSPHERIC STORAGE (Four Men - Seven Days)
QUANTITATIVE SUMMARY

Concept	MTBF (hrs)	Fixed Wt. (lbs)	Power (watts)	Total Equivalent Wt. (lbs)	Total Program Cost Factor	Volume (ft^3)	Crew Time (hrs)
Emergency O2 Supply (16.25 lbs)							
High Pressure Stainless Steel	168,000	45.6	0	45.6	1.1	3	0
High Pressure Composite Material	168,000	35.5	0	35.5	1.4	3.4	0
Supercritical Cryogenic	64,000	38.3	65	53.1	4.5	1.2	1.0
Subcritical Cryogenic	64,000	35.3	9	37.3	5.4	1.2	1.0
Lithium Peroxide	91,000	99.0	0	99.0	1.2	1.5	0
Chlorate Candles	122,000	71.5	0	71.5	1.0	1.7	0
Nitrogen Supply (141.33 lbs total)							
High Pressure Stainless Steel	155,000	402.0	0	402.0	1.0	21	0
High Pressure Titanium	155,000	349.0	0	349.0	1.3	21	0
High Pressure Composite Material	155,000	302.0	0	302.0	1.2	24	0
Supercritical Cryogenic	62,000	199.0	4000	849.0	2.6	6	2.0
Subcritical Cryogenic	62,000	190.5	1930	503.0	3.0	6	2.0

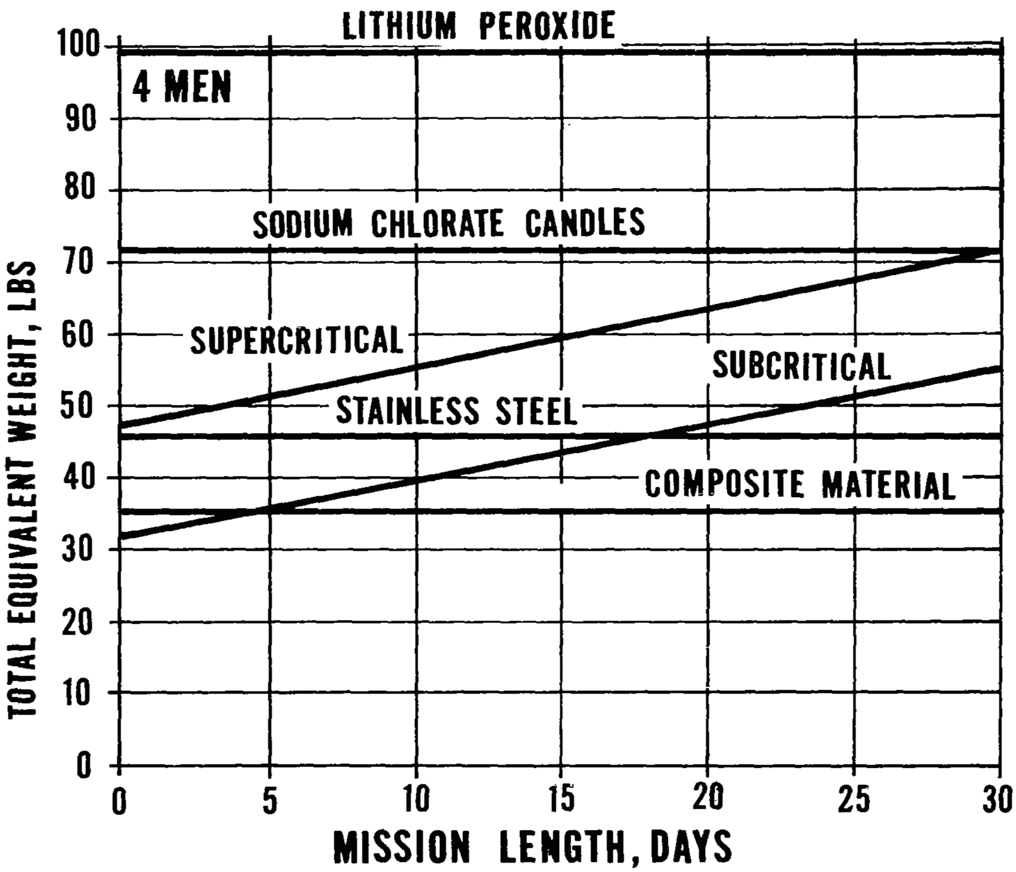

FIGURE 15. EMERGENCY OXYGEN STORAGE,
TOTAL EQUIVALENT WEIGHT VERSUS MISSION LENGTH

Quantitative criteria. - Of the six remaining oxygen storage concepts, three are eliminated due to excessively high total equivalent weights or costs. These are the cryogenic concepts and lithium peroxide. A summary of the quantitative criteria is shown in table 8.

Qualitative criteria. - The three remaining concepts are carried through the qualitative criteria level, where an oxygen storage concept is selected. Of these candidates: two, the high pressure gaseous storage concepts, received similar overall absolute and quantitative criteria ratings. The other, sodium chlorate candles, has less flexibility and a much higher weight and is eliminated on the basis of poorer overall characteristics. The two remaining concepts utilize high pressure gaseous storage and differ only in the tankage material utilized. The ratings of these two concepts are very similar with respect to both primary and secondary criteria. However, the lower equivalent weight and increased growth potential of the composite material tankage is considered sufficient to offset the increased development cost required and results in its selection for the shuttle. The stainless steel tank concept makes a very good back-up choice, if required, because of its overall acceptable ratings and low cost.

Nitrogen

A high pressure tank made of composite (filament wound) material is selected for nitrogen storage. A summary of the candidates and their relative ratings with respect to the evaluation criteria is shown in table 9. A discussion of the candidates evaluation follows. Included in the discussion is the mixed-gas storage concepts.

Absolute criteria. - The combined storage concepts, high pressure mixed gas storage and decomposition of N_2H_4 and N_2O_4 are eliminated because of marginal and/ or unacceptable performance and safety. The hydrazine/nitrogen tetroxide concept is eliminated because of unacceptable availability and marginal safety. All of the remaining concepts have competitive absolute characteristics.

Quantitative criteria. - Of the five remaining concepts, two are eliminated because of high total equivalent weights and high costs. These are the cryogenic concepts. The remaining concepts, all high pressure gas storage, have similar characteristics. A plot of the total equivalent weight of the candidates is shown in figure 16.

Qualitative criteria. - A review of the qualitative criteria shows that all concepts have about equal evaluations with composite material tanks considered less durable. Since no clear cut choice is evident, all the criteria were reviewed. A re-evaluation of the weight and cost eliminated the stainless steel and titanium material tanks. The

TABLE 9

EVALUATION SUMMARY - NITROGEN

	Criteria	High Pressure Gas			Cryogenic	
		Stainless Steel	Titanium	Composite Material	Subcritical	Supercritical
Absolute	Performance	Very Good	Very Good	Very Good	Very Good	Good
	Safety	Very Good	Very Good	Very Good	Very Good	Very Good
	Reliability	Very Good	Very Good	Very Good	Fair	Fair
	Avail. /Conf.	Very Good	Very Good	Very Good	Fair	Very Good
Quantitative	Total Equivalent Weight	Good	Good	Very Good	Fair	Poor
	ROM Cost	Very Good	Good	Good	Poor	Poor
	Volume	Fair	Fair	Fair	Very Good	Very Good
					Eliminated	Eliminated
Qualitative	Complexity	Very Good	Very Good	Very Good		
	Flexibility	Very Good	Very Good	Very Good		
	Durability	Very Good	Very Good	Good		
	Refurbishment	Very Good	Very Good	Very Good		
	Checkout Capability	Very Good	Very Good	Very Good		
	Maintainability	Very Good	Very Good	Very Good		
		Eliminated	Eliminated	Selected		

TABLE 9 (Concluded)

EVALUATION SUMMARY - NITROGEN

	Criteria	Mixed Gas Storage				
		High Pressure Gas	Decomposition of N_2H_4 and N_2O_4			
Absolute	Performance	Unacceptable	Unacceptable			
	Safety	Very Good	Unacceptable			
	Reliability	Very Good	Fair			
	Avail. /Conf.	Very Good	Poor			
		Eliminated	Eliminated			
Quantitative	Total Equivalent Weight					
	ROM Cost					
	Volume					
Qualitative	Complexity					
	Flexibility					
	Durability					
	Refurbishment					
	Checkout Capability					
	Maintainability					

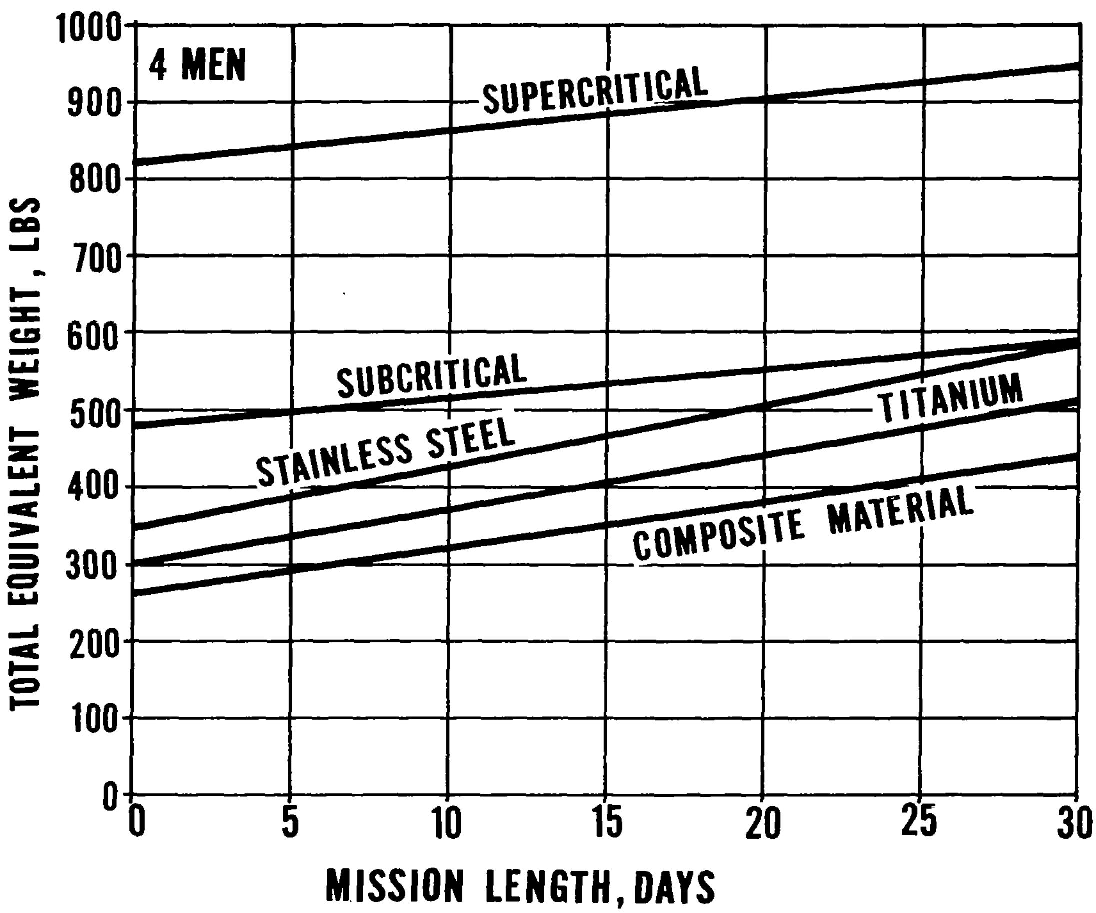

FIGURE 16. NITROGEN STORAGE, TOTAL EQUIVALENT WEIGHT VERSUS MISSION LENGTH

lower equivalent weight, increased growth potential, and reasonable cost, results in the selection of composite material tanks for the nitrogen storage subsystem.

IMPACT OF MISSION PARAMETERS

An investigation of the impact of mission length and crew size on the selected concepts for atmospheric storage was conducted. The investigation showed that the selected concepts are unaffected by variations in either crew size or mission duration.

The inherent advantages of the central cryogenic oxygen tankage to provide the primary oxygen requirements is not affected by the impact of either of the mission parameters. In addition, the basic criteria that the emergency oxygen system is required to satisfy is not affected significantly by either of the parameters.

The requirement for nitrogen storage is the only portion of the atmospheric storage subsystem affected markedly by varying crew size assuming a change in cabin volume as the crew size is increased. However, the relative characteristics of the concepts remain the same and so the concept selections do not change. For a fixed cabin volume, the effect of varying crew size is insignificant and therefore, has no impact on the selected concept (high pressure gas composite material tankage). The impact of mission length does not affect gas volume requirements significantly so that the candidate selections are not affected.

It is therefore concluded that the impact of crew size and mission duration on the selected concepts for atmospheric storage is inconsequential.

Historically, manned spacecraft have required the capability to cope with a meteoroid (or other) puncture of the pressure shell of the vehicle. This emergency has required maintaining minimum safe cabin pressure levels against the leakage of 1/2 inch diameter hole for a 5 or 10 minute period of time, while the crew ostensibly retreated into their space suits. The amounts of atmospheric gases exhausted, and the high delivery rates required to sustain a safe pressure level, have had an overpowering influence on gas storage requirements.

The point in the mission at which the cabin puncture occurs also has great influence on the welfare of the crew. In the early portion of the mission, when expendables are plentiful, full cabin pressure could be maintained for approximately one hour by the selected system before nitrogen supply depletion. Subsequently, there is enough oxygen on board (in the central cryogenic storage tankage) to maintain the cabin at reduced pressure (pure oxygen atmosphere) for far longer than the 48-hour contingency period.

If a failure occurred at the very end of the mission, when virtually all expendables are depleted, no nitrogen is available for sustaining cabin pressure. Since this is the main constituent of the cabin atmosphere, and it is not being replenished, cabin pressure falls rapidly to approximately half its original value in 20 minutes for a 1000 $ft.^3$ cabin. The leakage rate at 14.7 psia is approximately 150 lb/hr. Emergency oxygen storage would then have to be used to support cabin pressure.

This supply would provide an additional hour of use. Therefore, without spacesuits (and supporting ECS), the crew's life is in jeopardy unless reentry or a space rescue can be accomplished within one hour.

The implications of not providing for this emergency situation are serious. It means that the cabin structure must now have far greater meteoroid protection than past practices, so that the probability of puncture is virtually eliminated. On the other hand, it means that considerable savings in program costs, vehicle complexity and size can be effected through elimination of: spacesuits for both crew and passengers, associated spacesuit closed loop equipment, and supplementary gas supplies.

This study, in agreement with the prime shuttle contractors, has assumed that the cabin wall design will be such as to preclude the possibility of a meteorite puncture or similar leakage occurrence and no provisions for extremely high flows to maintain cabin pressure levels in the event of puncture have been made.

PRESSURE AND COMPOSITION CONTROL

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PRESSURE AND COMPOSITION CONTROL

The various functions associated with the task of pressure and composition control in the shuttle spacecraft are in general not amenable to trade. The only portion of the subsystem in which a trade study is applicable is the active atmospheric inflow section, where a study has been performed comparing the pulsed inflow and regulated inflow concepts. Otherwise, each piece of equipment performs a unique function. Equipment recommendations include:

- The use of manually overridable cabin pressure relief valves, with negative pressure relief provisions, to prevent cabin overpressurization.
- A high inflow oxygen regulator (3.1 psia) combined with an in-the-door manual pressure equalization valve between the airlock and main cabin for airlock repressurization.
- Pressure and composition control using a pressure regulated inflow valve concept.
- The use of a separate modulating cabin outflow valve (capped during orbital flight) for low altitude cabin purge flow if an air cycle concept is used for atmospheric cruise.

FUNCTION REQUIREMENTS

The pressure and composition control subsystem must operate during all phases of the mission. The various functional requirements are outlined below:

- Provide positive and negative pressure relief to maintain cabin pressures during launch, reentry and landing, or under failure conditions.
- Provide means for cabin and airlock depressurization and repressurization.
- Control inflow of atmospheric constituents to maintain proper total and oxygen partial pressures in the cabin.
- Provide a controlled intermediate pressure source for auxiliary functions; i.e., pressurization of potable water tanks. This function is assumed to be required even during a fail safe emergency.

- During descent, it must provide for negative pressure relief and/or outflow regulation of cabin gases if forced cabin ventilation (i.e., use of an air cycle unit with flush flow in the cabin, as in modern airliners) is used at lower altitudes.

The depressurization, airlock repressurization, pressure relief, and outflow functions are generally accomplished by equipment which is unique to the task. These functional elements are described below. This equipment is independent of the main inflow scheme which will be discussed later in this section.

Cabin/Airlock Depressurization

This function is accomplished by manual actuation of either a special dump valve (through the pressure wall of the spacecraft) or an override on the cabin pressure relief valve. An override is already required on the cabin pressure relief valve to meet the fail operational-fail safe requirements, and since it is desirable to reduce the number of wall penetrations to a minimum, the cabin pressure relief valve is used as the dump (depressurization) valve.

Cabin/Airlock Repressurization

The requirement for a fast emergency airlock repressurization (a 3.1 psia pure O_2 environment in 2 minutes) cannot be met with only a cabin-to-airlock pressure equalization valve (through-the-door). To satisfy this repressurization requirement, a minimum hardware concept, as shown in figure 17, would include a solenoid shutoff valve and a pressure regulator. In an emergency repressurization, the airlock is initially flooded with oxygen by opening the solenoid valve. The pressure regulator limits the airlock pressure to approximately 3.1 psia. At this pressure, the pressure equalization valve is manually opened, allowing the airlock pressure to rise to cabin pressure. Under these circumstances, the pressures in the cabin and airlock will be as shown in table 10. The pressure levels shown reflect an airlock whose free volume is 25% of the main cabin free volume. With a relatively smaller airlock, main cabin pressure excursions will be less than indicated. The cabin pressure will fall temporarily, but not to dangerously low levels. At the nominal cabin repressurization inflow rate, this condition will exist for less than 10 minutes. It is interesting to note that after diffusion and mixing of the cabin and airlock atmospheres, the PO_2 throughout the vehicle is satisfactory (even though the total pressure is low), no additional oxygen is needed to return the cabin to nominal pressure (only diluent nitrogen), and that no oxygen has been wasted. Because the equipment and procedures are so simple, and the total time duration so short, it is recommended that this method of airlock repressurization be employed as both the normal and emergency method of operation.

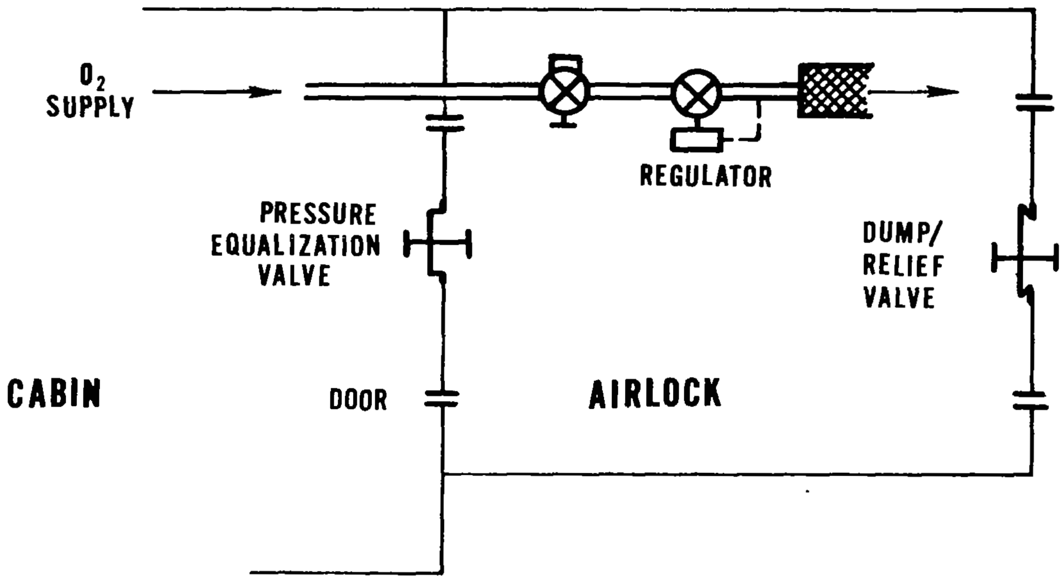


FIGURE 17. CABIN/AIRLOCK REPRESSURIZATION CONCEPT

TABLE 10
CABIN/AIRLOCK REPRESSURIZATION

Condition	AIRLOCK		CABIN	
	P_{total} psia	PO_2 psia	P_{total} psia	PO_2 psia
Prior to Repress.	0	0	14.7	3.1
After Oxygen Flood	3.1	3.1	14.7	3.1
After Equalization	12.38	5.06	12.38	2.51
After Mixing	12.38	3.1	12.38	3.1

Cabin Pressure Relief

The main cabin is a pressure vessel supplied from other pressure vessels (expendables tankage) at higher pressures. A relief valve is required to cope with failed open normal pressurization inflow valves to prevent structural failure of the cabin pressure shell. In addition to its normal pressure relief function, the cabin pressure relief valve generally performs the functions of launch relief and negative pressure relief.

Launch (ascent) relief. - In vehicles with normal operating cabin pressures significantly below sea level pressure (14.7 psia), this valve must vent the initial cabin atmosphere overboard as altitude is gained during launch, to prevent vehicle structural damage from cabin overpressurization. Unless the shuttle cabin requires initial (on-the-ground) pressurization (to above ground ambient) to maintain structural integrity during launch, there should be no need to provide an ascent relief function, since the cabin pressure shell will accommodate at least 14.7 psid, the highest nominal operating pressure. This is significant, because the launch relief case would become the design point for the relief valves, in terms of flow area required, and would necessitate the use of three cabin relief valves (two operating) instead of the two (non-operating during launch) now required for reliability purposes.

Negative pressure relief. - At low altitudes after reentry, the ambient pressure may exceed the internal cabin pressure, especially if the cabin is operated at reduced total pressure. This negative pressure relief valve function is sized by cabin volume and descent rate, and generally results in a small size which can easily be incorporated into the normal cabin pressure relief valve.

The negative pressure relief function can be deleted if a flush-flow cabin ventilation system is used at low altitudes, since in that situation, there is continuous overboard dump to maintain a slightly positive pressurization in the cabin.

A manual override is required on the cabin pressure relief valve to allow manual closing of a failed open valve.

Outflow Regulation

This outflow regulation function need be performed only if a flush-flow cabin conditioning concept is selected in conjunction with an air cycle turbocompressor for low altitude cabin pressure, ventilation, and temperature control.

This function is similar to the cabin pressure relief function, with the following exceptions:

- It is not a safety feature, but a normal method of operation during atmospheric flight.

- It handles much larger flows than the cabin pressure relief function (5 to 10 times the flow area of the cabin pressure relief valve). Therefore, it must be a separate valve, and should remain capped during all phases of the mission except the final atmospheric flight phase.

- It should be an absolute pressure regulating valve (the normal cabin relief valve is a differential pressure regulator) because it should maintain 14.7 psia cabin pressure regardless of outflow rate or atmospheric ambient pressure.

PRESSURE CONTROL

During the orbital phase of the shuttle mission, the cabin atmospheric total pressure and the oxygen partial pressure must be controlled simultaneously, yet independently, to accommodate all possible combinations of oxygen metabolic use rates and cabin vehicle leakage rates. Two basic concepts (with minor variations) are available to accomplish this function. Both concepts are characterized by the metering of gas inflow to the cabin to maintain a selected total pressure. The inflow control section also includes a regulation scheme for an intermediate pressure level. The intermediate pressure function must be closely associated with the inflow scheme to minimize the total number of components in each concept. Although the inclusion of the intermediate pressure control section tends to mask the outcome of the trade study, it is felt that in the final analysis, the subsystem will, in fact, require an integrated pressure control scheme. The following trade study, therefore, reflects the integration complexities encountered in combining these functions.

Regulated Inflow

In this concept, oxygen and nitrogen are independently regulated to moderate (20 to 50 psi) pressure levels from higher storage pressures with the nitrogen (or other diluent) maintained at slightly higher pressure than the oxygen. The gases are mixed and fed to an absolute pressure regulator, which allows sufficient flow into the cabin to maintain a pre-set total pressure. Nitrogen flow is turned on or off by a solenoid valve which is actuated by a signal from an electrical controller and oxygen partial pressure sensors (three sensors in a voting circuit for reliability). If the oxygen partial pressure is satisfied, the nitrogen solenoid valve is opened. Because the nitrogen is regulated to a higher pressure than the oxygen, nitrogen flows through the cabin pressure regulator in response to decreasing total pressure. If cabin total pressure decays chiefly from metabolic use of oxygen, the oxygen partial pressure decays; this decay is sensed by the oxygen partial pressure sensors, thus closing the nitrogen solenoid valve. The cabin pressure regulator then allows the cabin to fill with pure oxygen until the oxygen partial pressure is satisfied, in which case the nitrogen solenoid valve is opened to allow nitrogen gas to make up subsequent cabin pressure decay.

Relief valves allow "breathing" of the intermediate pressure line (i.e., when water tanks are filled, compressing this gas) and provide a safety device against failed open upstream components.

A general data sheet and a schematic are shown in figure 18.

Absolute criteria. - Adjustable regulators are used to control the cabin pressure level and maintain the required absolute pressure band. Reliability is enhanced by redundancy and by using a minimum of electronic components. Noise level is low, due to fairly constant low flow rates, minimizing noise attenuation requirements. Performance is excellent, because regulation is effectively a two-stage operation.

Quantitative criteria. - The total weight of this approach is estimated to be 41.1 pounds. Cost is moderately low, due to a minimum of electronic logic components. Volume is directly related to the number of parts, and is also low, although manual valve overrides (for fail safe operation) occupy significant panel space.

Qualitative criteria. - Flexibility is achieved by manually adjustable cabin inflow regulators. Durability is limited by the availability of reliable, long life oxygen partial pressure sensors rather than the valving and/or regulating devices. Maintenance time, both in orbit and for ground refurbishment, should be zero. Ground checkout time is low.

Pulsed Inflow

This concept consists of two independent inflow circuits, one each for oxygen and nitrogen. The oxygen supply requires regulation to provide relatively stable pressures for possible operation of auxiliaries, such as tank pressurization, valve actuation, etc.. The oxygen and/or nitrogen are "pulsed" into the cabin through solenoid valves, which are controlled by oxygen partial pressure sensors and cabin total pressure sensors through a controller. The control logic of this controller can be one of several approaches:

SUBSYSTEM: PRESSURE AND COMPOSITION CONTROL

CONCEPT: REGULATED INFLOW

FLIGHT AVAILABILITY: 1975

Mission Phase Application

Launch _X_ Orbit _X_ Reentry _X_ Cruise _X_

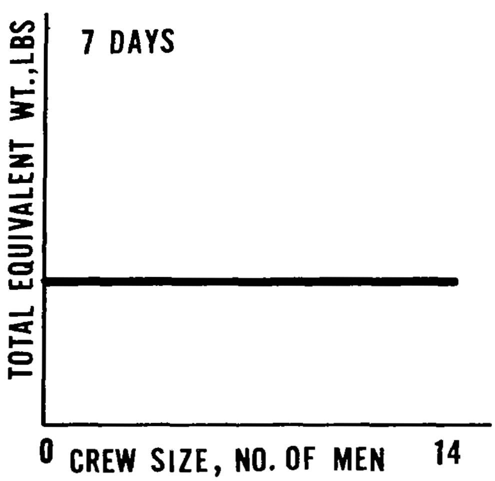
RELIABILITY: 0.999975 MTBF: 21,624 hours

4 Men - 7 Days Plus 48 Hours Contingency

	Equivalent Wt. (lb)	Volume (ft^3)	Power (watts)
Installed Unit	41.1	1.0	7.0
Expendables	—	—	—
Power Equiv. Wt.	1.2	—	—
Totals	42.3	1.0	7.0

Cost Factor	
Recurring -	1.0
Nonrecurring -	1.0
Total -	1.0

Crew Time (hrs)	
Scheduled-	0
Ground Refurbishment-	0



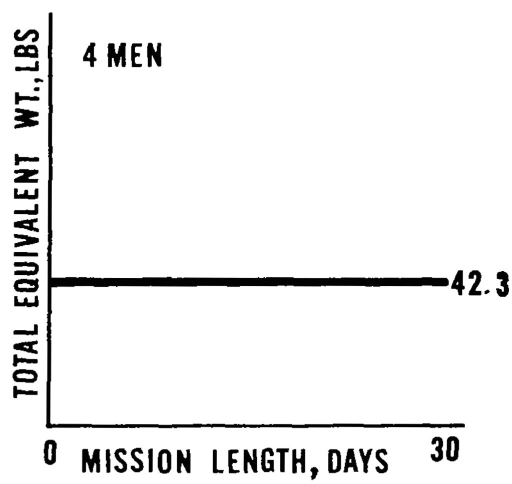


Figure 18 (Page 1 of 2)

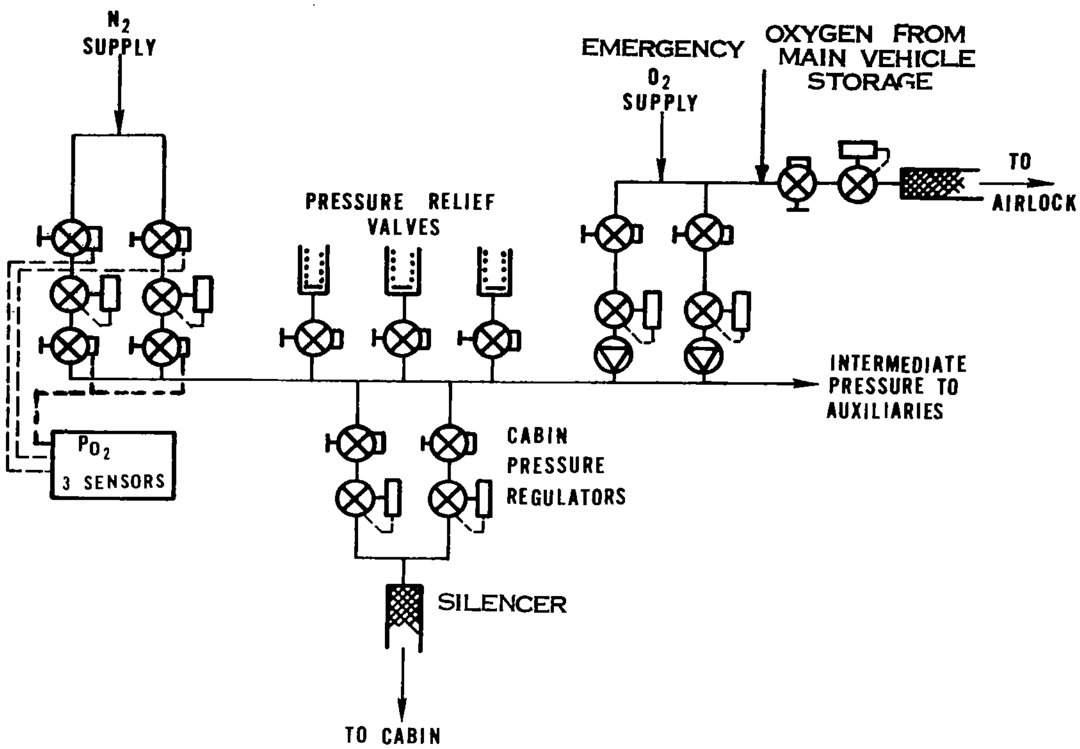


FIGURE 18. REGULATED INFLOW CONCEPT (PAGE 2 OF 2)

- The control may operate to satisfy oxygen partial pressure regardless of total pressure in the cabin. Such a circuit utilizes very simple logic, since the oxygen partial pressure sensors actuate the oxygen inflow valves, and the total pressure sensors actuate the nitrogen inflow valves, but only if the oxygen partial pressure is satisfied. A drawback is that a fast-reacting PO_2 sensor is required to turn the oxygen inflow off when satisfied, as well as on when PO_2 is low. This quick response is not available in current state-of-the-art PO_2 sensors. Furthermore, should the situation arise where the PO_2 becomes low with the cabin total pressure at the high limit, oxygen inflow is nevertheless initiated, causing the total pressure to increase to as much as 0.3 psia (the total PO_2 error band) above the high limit of cabin total pressure. These two problems can be partially overcome by introducing a timer into the controller to limit the O_2 inflow duration. With normal oxygen consumption and with a solenoid inflow valve sized for cabin repressurization flow, oxygen would be "pulsed" into the cabin for a duration of approximately four minutes every five hours. A timer, if utilized, would be activated by the oxygen partial pressure sensors, to allow oxygen inflow for approximately two minutes, after which it shuts off the solenoid valve and prevents an oxygen partial pressure signal for a period of time greater than the PO_2 sensor response time. This allows the sensor to reread the partial pressure, provides positive valve shutoff, and reduces the overpressurization (and reduces the PO_2 control band) by one-half.

- An approach which was to be utilized on MOL, opened both the oxygen and diluent gas inflow valves while cabin total pressure was low or at any oxygen partial pressure below the upper limit. If oxygen partial pressure was satisfied, only the diluent inflow valve was opened. In either case both inflow valves were turned off by a total pressure signal. This approach worked well, but only because the atmosphere was predominantly oxygen. In the shuttle situation, the instantaneous nitrogen inflow rate is approximately four times the oxygen inflow rate (based on valves sized to meet repressurization requirements), but nitrogen consumption is approximately 1/3 the rate of the oxygen consumption, at maximum leakage. Indeed, at low cabin leakage rates, the nitrogen inflow valve may actuate once a day or less, so the concept of operating both oxygen and nitrogen valves simultaneously, originally devised to reduce the previously mentioned control band error, is in reality, ineffective.

- A third logic scheme utilizes oxygen partial pressure signals to turn on oxygen inflow, and total pressure signals to turn on nitrogen inflow. Turnoff of both inflow valves is accomplished by a high cabin total pressure signal. This concept, although simple in operation, is somewhat deficient in coping with the major problem facing two gas controllers; i.e., the situation where the cabin total pressure is high, but oxygen partial pressure is low. While this situation is admittedly rare, it can occur, especially in the initial phase of the flight immediately after launch. Unless override logic is provided in the controller, oxygen inflow cannot be activated until the total pressure falls to a low limit. In a low leakage vehicle, the PO_2 under these conditions, would fall to as low as 2.8 psia, and would not be self-arresting, but would keep oscillating between 2.8 and 3.1 psia. A simple priority system, under these circumstances, causes cabin pressure to vary between 14.7 and 15.0 psia, still an out-of-band condition, but preferable to the low PO_2 situation. The pulsed inflow concepts described above all have the same schematic, only the internal controller logic varies.

A general data sheet and a schematic are shown in figure 19.

Absolute criteria. - Performance is acceptable, and can be significantly improved by use of narrow band pressure transducers to reduce cabin pressure transients. Noise level however, will still be moderately high. Equipment, such as solenoid valves, is available. Electronic logic controllers are the prime source of the concepts unreliability.

Quantitative criteria. - The total weight of this approach is estimated to be 52.5 pounds. Moderately high cost is the result of the electronic logic controllers. Volume is related to parts count, and is moderately high.

Qualitative criteria. - Selectable pressure control can easily be incorporated into the electronic controller, providing good flexibility. Ground checkout can more easily be accomplished on the on-off valves of the pulse system. As in the regulated inflow concept, the life limiting element is the oxygen partial pressure sensor. No maintenance time, both in orbit and for ground refurbishment, is expected. System complexity results in a lower rating than the competing regulated approach.

EVALUATION AND SELECTION

An evaluation summary is presented in table 11. The regulated inflow concept shows a definite advantage over the pulsed inflow approach in the areas of total equivalent weight, reliability, and cost. Other areas of comparison are quite similar, although the regulated concept does appear to provide an edge in crew comfort (not a criterion). During normal operation, noise levels are inherently lower, and a stable regulator does not allow the sometimes annoying up and down pressure excursions of the pulsed inflow approach. On this basis, the regulated inflow concept is the recommended approach for inflow control for the shuttle orbiter vehicle.

SUBSYSTEM: PRESSURE AND COMPOSITION CONTROL

CONCEPT: PULSED INFLOW

FLIGHT AVAILABILITY: 1975

Mission Phase Application

Launch X Orbit X Reentry X Cruise X

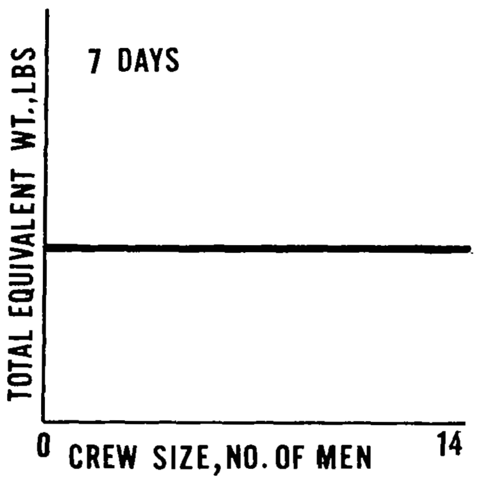
RELIABILITY: 0.999972 MTBF: 18,754 hours

4 Men - 7 Days Plus 48 Hours Contingency

	Equivalent Wt. (lb)	Volume (ft^3)	Power (watts)
Installed Unit	52.5	1.6	7.0
Expendables	—	—	—
Power Equiv. Wt.	1.1	—	—
Totals	53.6	1.6	7.0

Cost Factor	
Recurring -	1.2
Nonrecurring -	1.2
Total -	1.2

Crew Time (hrs)	
Scheduled -	0
Ground Refurbishment -	0



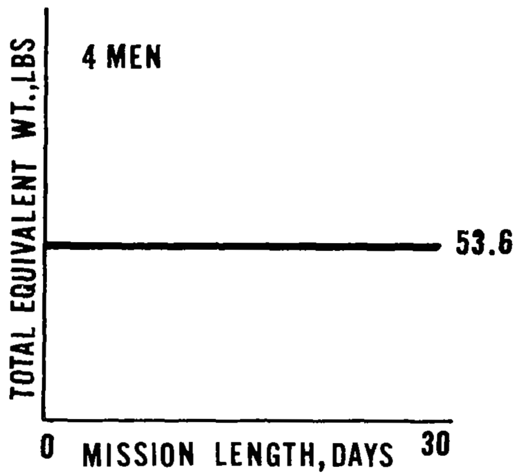


Figure 19 (Page 1 of 2)

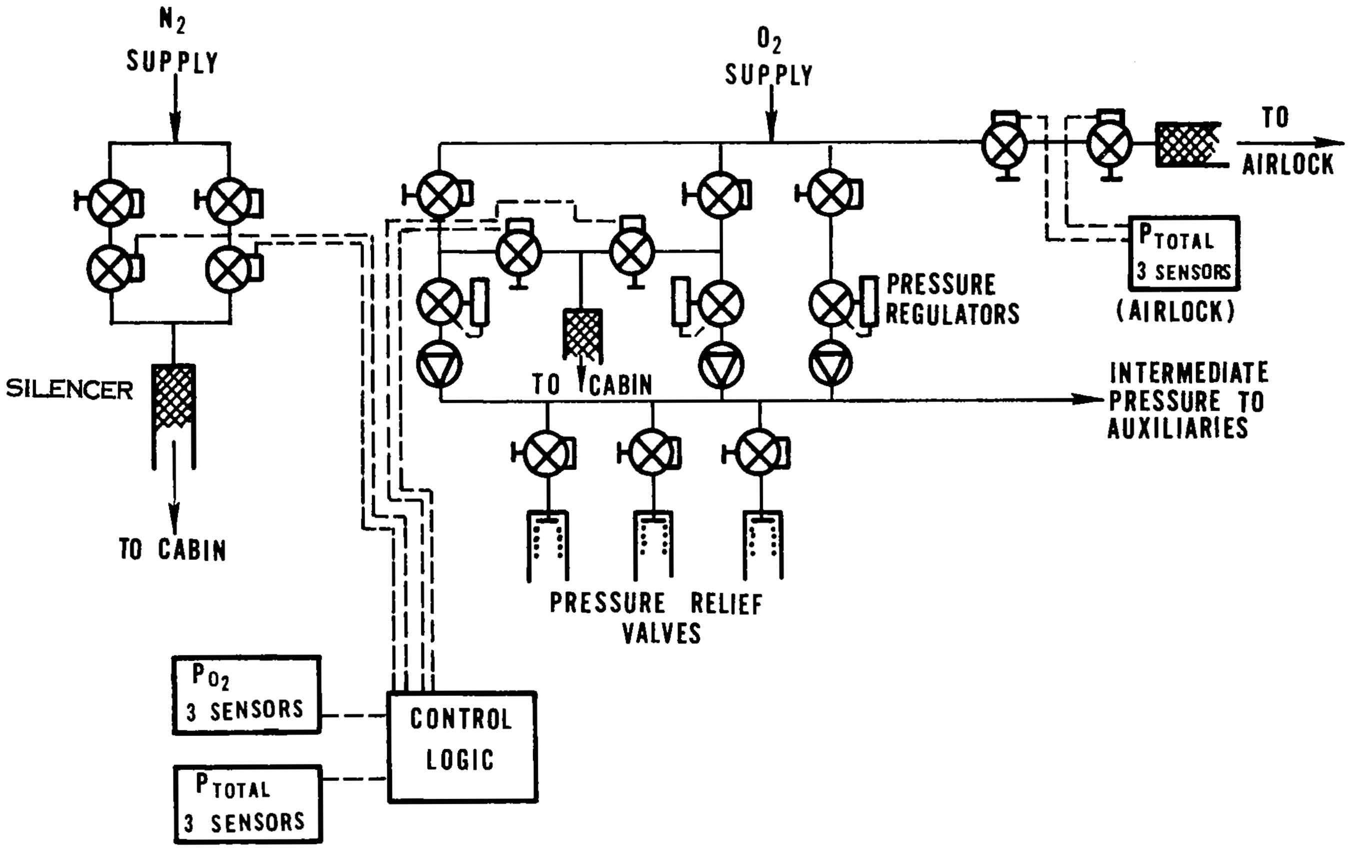


FIGURE 19. PULSED INFLOW CONCEPT (PAGE 2 OF 2)

TABLE 11

EVALUATION SUMMARY - PRESSURE CONTROL

	Criteria	Candidate Concepts				
		Regulated Inflow	Pulsed Inflow			
Absolute	Performance	Very Good	Good			
	Safety	Very Good	Very Good			
	Reliability	Very Good	Good			
	Avail. /Conf.	Very Good	Very Good			
Quantitative	Total Equivalent Weight	Very Good	Good			
	ROM Cost	Very Good	Good			
	Volume	Very Good	Good			
Qualitative	Complexity	Good	Fair			
	Flexibility	Good	Good			
	Durability	Good	Good			
	Refurbishment	Good	Good			
	Checkout Capability	Good	Very Good			
	Maintainability	Very Good	Very Good			
		Selected	Eliminated			

IMPACT OF MISSION PARAMETERS

Mission length and crew size have no impact on the selected subsystem assuming a single cabin. If an independent payload module for passengers is used it would be preferable to provide it with an independent pressure and composition control subsystem for more accurate atmospheric control and increased reliability and safety.

CO_2, HUMIDITY AND TEMPERATURE CONTROL

TABLE OF CONTENTS

CO_2, HUMIDITY, AND TEMPERATURE CONTROL

The purpose of this section is to select a method of controlling carbon dioxide (CO_2), humidity and cabin temperature. The equipment and functions affected by this selection, such as the radiator, heat rejection loop, cabin temperature and humidity control and ventilation flow were considered in this evaluation.

A lithium hydroxide (LiOH)/condenser concept was selected for CO_2, humidity and temperature control in the baseline system for the orbital shuttle vehicle. This concept was selected because it has the immediate advantage of low cost through first flight and good availability. Another concept, solid amine (HS-C) which is a regenerative sorbent has an almost equivalent quantitative evaluation including a lower weight than the LiOH concept. It could be selected if mission requirements or heat loads increase as the total program costs and weight would become much less than the selected LiOH/ condenser concept.

CO_2 removal can be accomplished by a number of concepts as shown in table 12. Many of these concepts affect the cabin humidity significantly and have an impact on the cabin temperature control system. Candidate concepts (listed in table 13) that provide the function of CO_2, humidity, temperature control must also consider trace contaminant control and ventilation concurrently in order to establish a complete evaluation. The reason these functions are combined is due to the interactions between them. For example, LiOH produces water when it removes CO_2 thereby increasing the latent load on the humidity control equipment, while molecular sieve dumps water overboard when it is desorbing, hence reducing the latent load on the humidity control equipment. The CO_2 removal and humidity control approach also affects the size of the cabin heat exchanger used for temperature control and the total ventilation flow rate. All candidate concepts are capable of meeting the minimum (400 cfm) ventilation flow requirement for the nominal baseline condition. The heat rejection portion of the EC/LSS is greatly affected by the CO_2, humidity and temperature control approach selected with the major impact falling on the radiator. Radiator weight, a major contributor to the heat rejection subsystem weight, is dependent on coolant flow rate and radiator outlet coolant temperature. Coolant flow rate and radiator outlet temperature are set by cabin temperature and humidity control requirements. Other coolant loop equipment that are affected include the interface heat exchanger (between the heat rejection and cabin coolant loops) and the coolant pumps.

The equipment for contaminant control was incorporated into the competing CO_2, humidity and temperature control concepts and/or the waste management subsystem. Where applicable (when utilizing the waste management subsystem) a penalty was assessed to the CO_2, humidity and temperature control concept under consideration for evaluation purposes. The actual sizing and discussion of atmospheric contamination control is contained in the chapter of that heading in this report.

TABLE 12

CLASSIFICATION OF CO_2 CONCENTRATION CONCEPTS

Concept	Control Method	Nature of Operation	Characteristics
Molecular sieve	Regenerable solid adsorption	Cyclic - Uses 2 desiccant & 2 CO_2 removal beds	Requires coolant loop
Solid amine (HS-C)	Regenerable solid absorption	Cyclic - Uses 2 beds	Controls cabin humidity Requires coolant loop
Lithium Hydroxide	Expendable solid absorption	Continuous until expended - 1 day life	Requires no power - no cabin ullage loss
H_2 Depolarized Cell	Electrochemical - immobilized electrolyte	Continuous - generates power & water but requires H_2 & O_2	Requires no power Generates electrical power
Membrane Diffusion	Gaseous diffusion	Continuous - staged membranes	Dehumidifies cabin air excessively

TABLE 13

CO_2, HUMIDITY, AND TRACE CONTAMINANT CONTROL CONCEPTS

CONCEPT		Trace Contaminant Control	Expendables*
CO_2 Control	Humidity Control		
Lithium Hydroxide	Condenser	Charcoal integrated with Waste Management subsystem	LiOH (daily).
Lithium Hydroxide	Desiccant	Separate charcoal canister	LiOH (daily).
Molecular Sieve	Condenser	Charcoal integrated with Waste Management subsystem	
Molecular Sieve	Desiccant	Separate charcoal canister	
Solid Amine (HS-C)	Solid Amine (HS-C)	Separate charcoal canister	
Hydrogen Depolarized Cell	Condenser	Charcoal integrated with Waste Management subsystem	
Hydrogen Depolarized Cell	Desiccant	Separate charcoal canister	
Membrane Diffusion	Membrane Diffusion	Separate charcoal canister	

*All concepts require replacement of charcoal, bacteria filters, and a particulate filter after each mission.

CONCEPT DESIGN

Figure 20 presents a schematic of that portion of the total system affected by this section of the study. The schematic shows dual cabin and radiator cooling loops connected by an interface heat exchanger. The heat rejection loop contains electronic equipment cold plates, fuel cell, circulating pumps, a radiator and auxiliary heat sinks. The cabin coolant loop contains electronic cold plates, circulating pumps and associated heat exchangers. CO_2, humidity and temperature control equipment are shown within the cabin area.

The design requirements and range of conditions considered in this evaluation are shown in table 14.

The procedures used to optimize the system weight for each candidate concept are shown in table 15. Included in the optimization were the radiator, coolant pumps and interface heat exchanger, as well as the CO_2, humidity and temperature control and ventilation portions of the subsystem. A typical optimization curve of total equivalent weight versus heat rejection loop flow rate and radiator outlet temperature is shown in figure 21. Each candidate concept has an optimization curve similar to that shown for the LiOH/condenser concept. At a constant radiator outlet temperature. there is an optimum flow rate. As the heat rejection loop flow is lowered, the radiator size and weight decreases as radiating temperature increases. The cabin heat exchanger weight increases as the heat rejection loop flow decreases because the "log-mean-temperature-difference" in the heat exchanger has decreased. The optimum flow rate for the nominal design condition for the LiOH/condenser concept shown is 2095 lb/hr. As the radiator outlet temperature is lowered the radiator gets larger, but the cabin heat exchanger gets smaller. The optimum radiator outlet temperature for the nominal design condition is 42°F.

If the cabin air heat load decreased, the maximum fuel cell outlet temperature of 150°F would limit the heat rejection loop flow rate. The optimum radiator outlet temperature would increase above the lowest allowable radiator outlet temperature of 34°F. The cold plate outlet temperature limit of 120°F was never reached for the heat loads considered for any of the candidate concepts.

WATER SEPARATION AND TRANSFER

Liquid-gas separation is a necessary function for all of the CO_2, humidity, and temperature control concepts utilizing a condenser as the means of cabin humidity control.

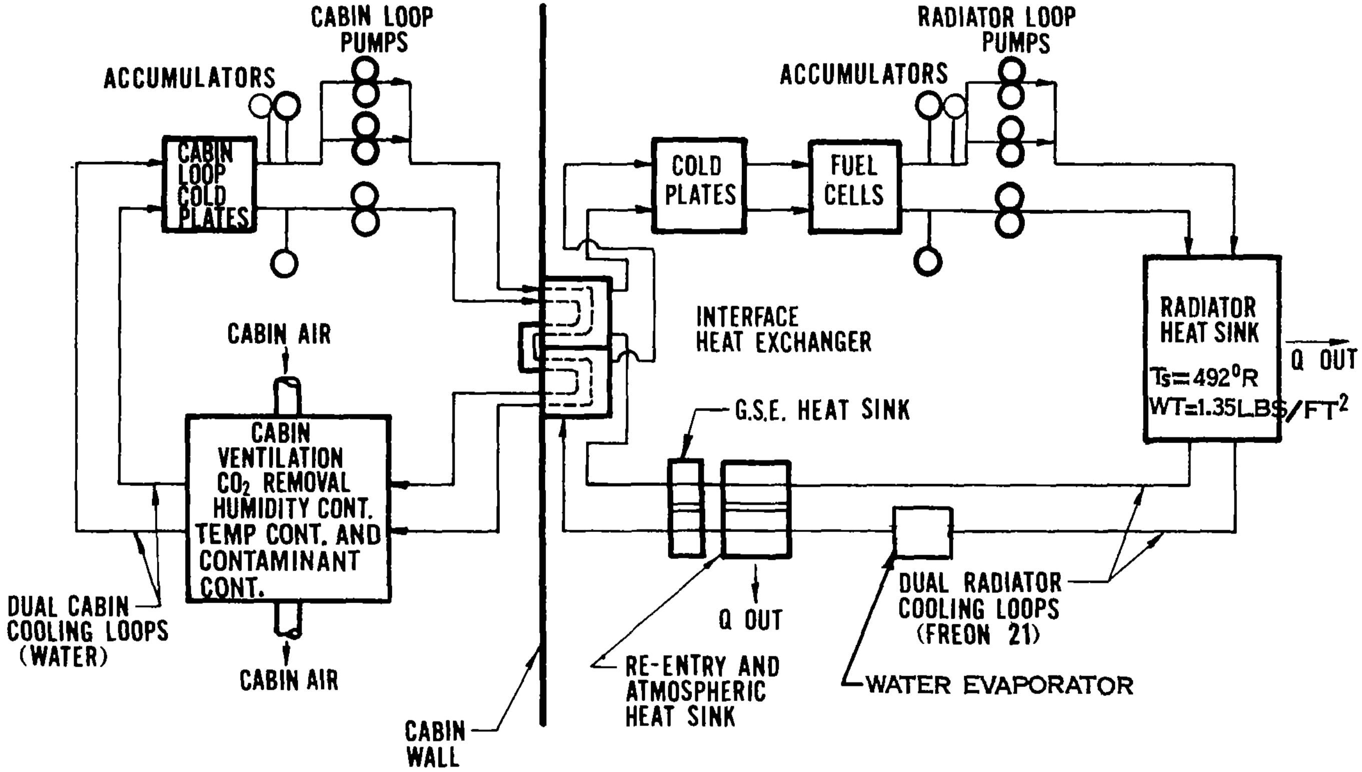


FIGURE 20. COOLANT LOOP SCHEMATIC

TABLE 14

DESIGN REQUIREMENTS

CREW DATA	
Crew Size (men)	2 - 14
Total Metabolic Heat Generation (per man)	647 Btu/hr peak
Sensible Metabolic Heat Generation (per man) (@ 65°F design point)	402.5 Btu/hr peak
Latent Metabolic Heat Generation (per man) (@ 65°F design point)	244.5 Btu/hr peak
Carbon Dioxide Production Rate	
average	2.2 lb/man-day
maximum	3.8 lb/man-day
PRESSURIZED COMPARTMENT DATA	
Total Pressure	14.7 psia
Oxygen Partial Pressure	3.1 psia
Atmosphere Diluent Gas	Nitrogen
Carbon Dioxide Partial Pressure Levels	
Nominal	5.0 mm Hg
Maximum normal	7.6 mm Hg
Maximum with single failure	10.0 mm Hg
Maximum emergency (2 hour duration)	15.0 mm Hg
Cabin Temperature (Design Point 65°F)	65° to 75°F
Cabin Humidity (dew point temp.)	40° to 57°F
Design point - 65°F cabin temperature (12°F less than dry bulb temp.)	53°F maximum
Cabin Volume (4 men)	1000 ft^3
Minimum Ventilation Flow Rate (see ventilation section)	400 cfm
Trace Contaminant Control Penalty (charcoal only)	0.167 lb/man-day
VEHICLE DATA	
Cabin Wall Heat Load (Except for reentry)	1700 Btu/hr
Air Cooled Electronics Heat Load (less EC/LSS load)	5000 ± 4500 Btu/hr
Cold Plate Cooled Electronics Heat Load (cabin)	17,800 ± 3,000 Btu/hr
Fuel Cell Heat Load	23,260 ± 13,000 Btu/hr plus 3.414 x EC/LSS Electrical load (watts)
Power Penalty	
Fixed Weight	160 lb/kW
Expendables	1.333 lb/kW-hr
Maximum Allowable Coolant Temperatures	
Electronics cold plate outlet	120°F
Fuel cell outlet	150°F
Coolant	
Cabin cooling loop	Water
Radiator cooling loop	Freon-21

TABLE 14 (Concluded)

Radiator Weight Penalty(WT)

WT	=	$A \times W \times C_p \times (B-C)$ ~ lbs.
A	=	$F \times T_s/K$ ~ lbs-hr-°R/Btu
Ts	=	Equilibrium surface temp ~ °R
K	=	Radiator Influx ~ Btu/hr-ft^2
W	=	Radiator coolant flow rate ~ lbs/hr
Cp	~	Radiator coolant flow specific heat ~ Btu/lb-°R
B	=	$1/4\ \ell n \left[\dfrac{\left(\dfrac{TRO}{T_s} + 1\right)\left(\dfrac{TRI}{T_s} - 1\right)}{\left(\dfrac{TRO}{T_s} - 1\right)\left(\dfrac{TRI}{T_s} + 1\right)} \right]$
C	=	$1/2 \left[\tan^{-1}\left(\dfrac{TRI}{T_s}\right) - \tan^{-1}\left(\dfrac{TRO}{T_s}\right) \right]$
TRI	~	Radiator Inlet Temp ~ °R
TRO	~	Radiator Outlet Temp ~ °R
F	=	lbs/ft^2/Fin efficiency ~ lbs/ft^2

For Nominal Conditions

A	=	3.62 lbs-hr-°R/Btu
Ts	=	492°R

TABLE 15

OPTIMIZATION PROCEDURE

1. Assume heat rejection loop flow rate. (freon)
2. Assume radiator outlet temperature.
3. Calculate interface heat exchanger heat rejection loop inlet temperature (size sublimator, if required).
4. Assume interface heat exchanger water outlet temperature.
5. Size/optimize CO_2 and water removal components.
6. Optimize cabin heat exchanger to find optimum air flow and outlet air temperature.
7. Calculate water loop temperatures and pump power and weight.
8. Size interface heat exchanger.
9. Calculate heat rejection loop temperatures and pump power and weight.
10. Size radiator (use cryogenics if area exceeds 900 ft^2).
11. Calculate total system equivalent weight.
12. Repeat steps 4 through 11 until optimum temperature is found.
13. Repeat steps 3 through 12 until optimum radiator outlet temperature is found.
14. Repeat steps 1 through 13 until optimum flow rate is found.

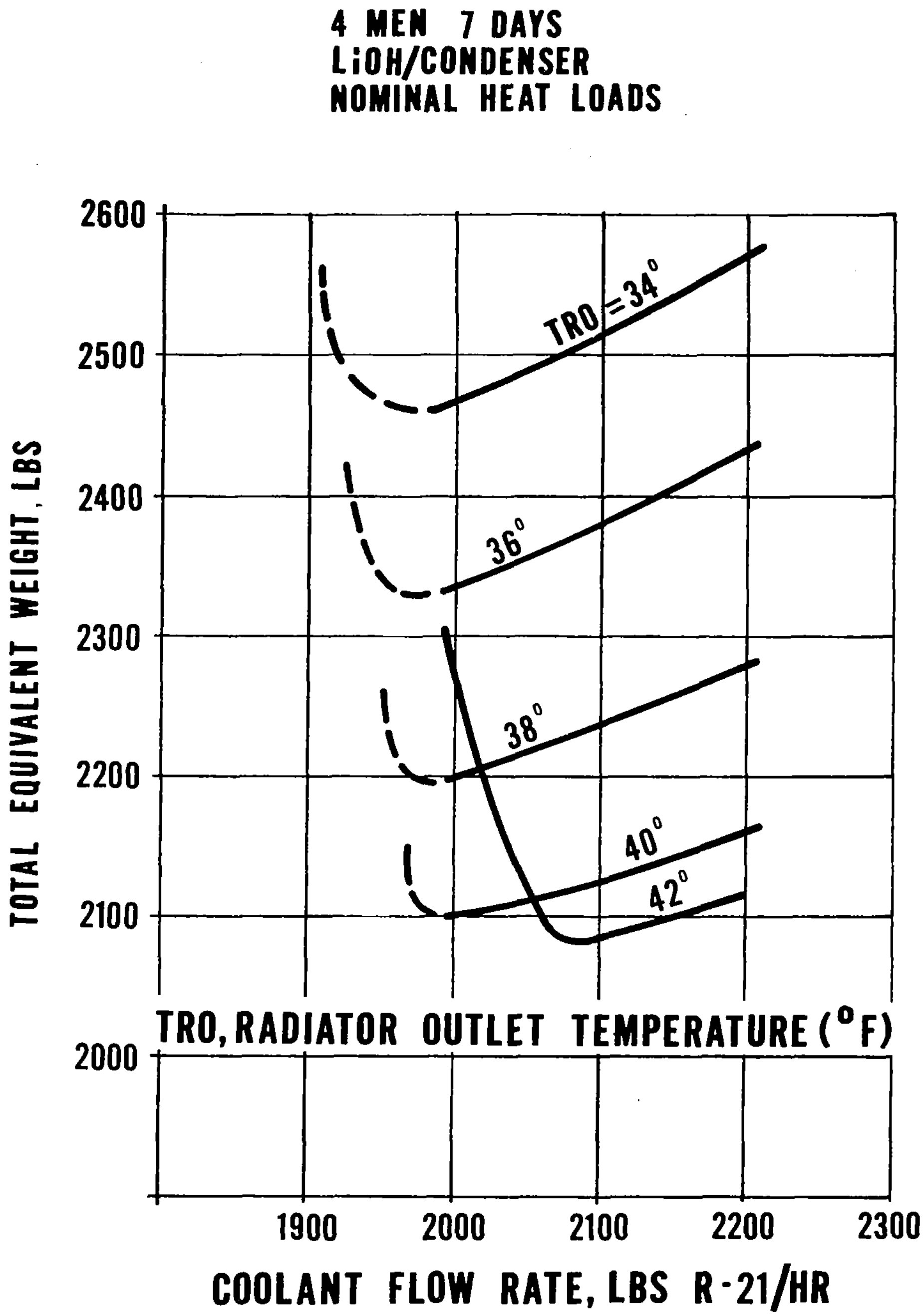


FIGURE 21. OPTIMIZATION CURVE, LiOH /CONDENSER CONCEPT

The candidates considered for zero gravity operation are shown in Figure 22. and fall into two general categories: Those utilizing capillary forces (static devices) and those relying primarily on inertial forces (dynamic devices) to achieve liquid-gas separation and transfer. In some applications, a combination of these two methods is utilized. A motor driven rotary water separator downstream of an elbow collector is selected for use in conjunction with the condensing heat exchanger. This is the optimum method determined by an investigation into potential water separator and transfer candidates.

The various water separation and transfer concepts considered are discussed in detail in the following sections.

Capillary Concepts

The two major capillary candidates are the integral wick and face wick concepts.

The integral wick heat exchanger combines the condensing and separation functions into a single unit. This unit contains a gas side layer consisting of a metal wick (metal felt or porous plates) sandwiched between fin sheets. The wicks feed into a side-mounted sump which acts as a wick drainage manifold. A hydrophillic transfer disc in contact with the wick sump uses an applied pressure differential to transfer water to the collection system. The transfer disc prevents gas from entering the collection system. The important feature of all these concepts is the transfer disc. This disc, due to its hydrophillic characteristic, passes only liquid to the collection system. As such, a disc failure is critical to both the water separator and water transfer subsystems. Failure modes for this device are either gas breakthrough due to disc rupture or drying out or clogging caused by contamination in the cabin. As a result, the discs require special design attention, a method to keep the disc wet for proper startup, and periodic maintenance. Wick and transfer disc degradation presents a problem in that flight maintenance of the integral wick heat exchanger is precluded.

The addition of face wicking at the air outlet face of a conventional heat exchanger is a compromise between the integral wick and the elbow concepts. Using a hydrophillic coating on the air side fins of the heat exchanger causes the condensed water to form a film rather than droplets. Water flows to the heat exchanger outlet face, contacts the strips of wicking, enters the wick, and is transported to a hydrophillic transfer disc, similar to that previously discussed. The wicking may be installed as sheets forming a vaned elbow, minimizing free moisture carryover. In the event of excessive wick degradation, the wick and transfer disc assembly can be easily replaced.

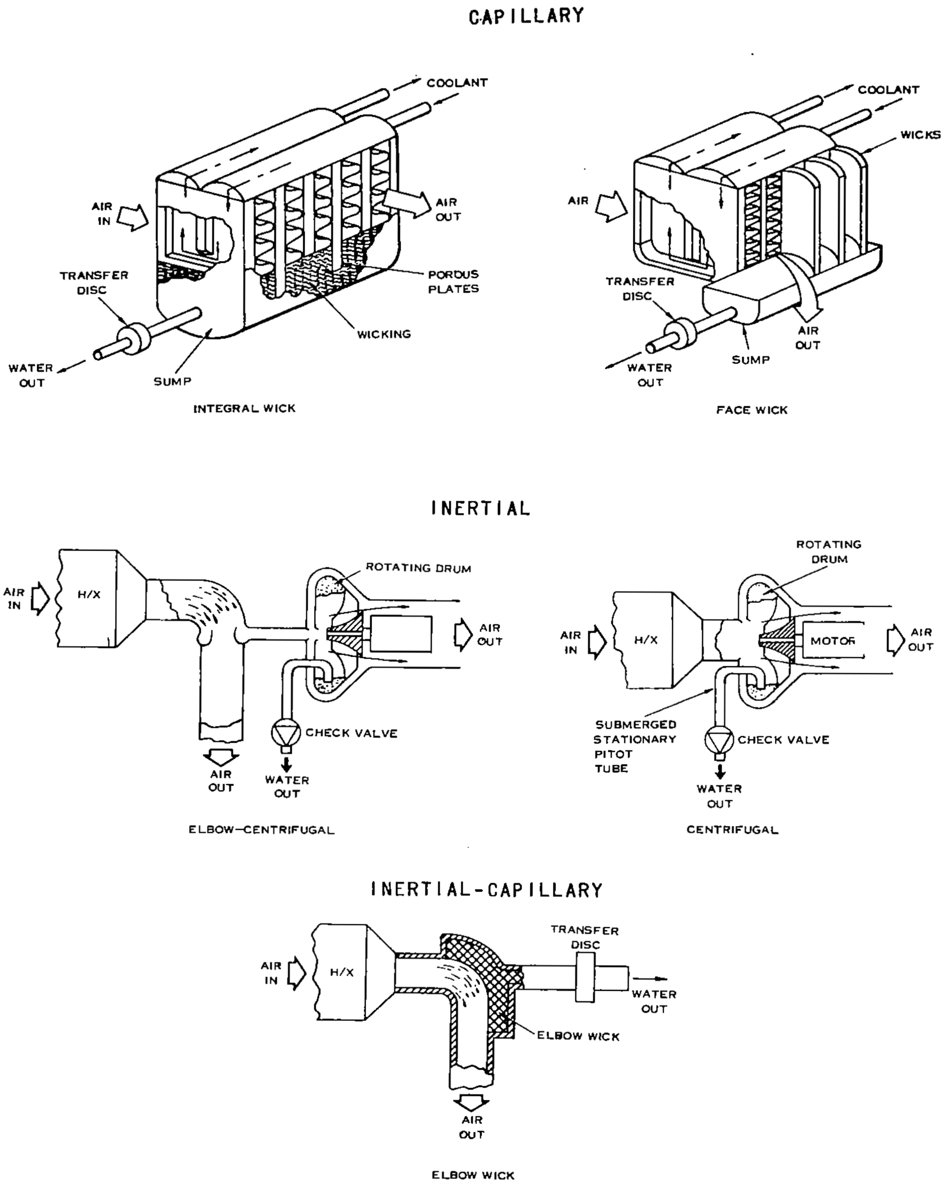


FIGURE 22. WATER SEPARATOR CONCEPTS

Of the two capillary concepts, the face wick is considered the best approach for the Shuttle because it minimizes hardware weight, complexity and makes wick replacement easier. The integral wick heat exchanger is a complex, heavy component. A clogged wick also requires the replacement of the entire heat exchanger unit whereas the face wicks can be replaced separately, and not jeopardize the integrity of the condensing heat exchanger.

Inertial Concepts

In the inertial concepts, the required flow velocity in the condensing heat exchanger is greater than the capillary approach so that the water condensed in the unit is blown from the heat exchanger face. Once in the discharge stream, the air-water mixture passes through an elbow wick separator or directly into a centrifugal separator for water collection and transfer.

The elbow wick separator employs inertial and capillary forces to separate and transfer liquid. As the gas stream leaves the condensing heat exchanger with entrained, free moisture, it enters the 90-degree elbow lined with wicking. Inertial forces cause the heavier water particles to move to the duct wall where capillary forces in the wicking drain the water to a hydrophillic transfer disc. Capillary forces, in conjunction with a pressure differential across the disc, transfer liquid to the collection system. As previously mentioned, the transfer disc prevents gas from entering the collection system.

The centrifugal separator, the other inertial water separation concept, combines the functions of water separation and transfer into one unit. The separator may be driven by an air turbine or a motor. Both concepts employ a rotating vaned drum (or other rotating device) which imparts a centrifugal force to the water in the entering gas stream, forcing the liquid drops to the wall of the rotating drum. A rotating gutter collects the drops as they are spun off the vanes. A stationary pitot tube collects the water from the gutter. The velocity head at the pitot tube is converted to a static head, and the water flows out of the separator to the collection system. As long as the pitot tube remains submerged in liquid and a minimum back pressure is maintained on the pitot tube outlet, there will be no air inclusion in the delivery flow. Test experience has indicated that the motor driven approach is preferable to the air turbine approach in reducing stalling conditions during start-up by having higher torque. Furthermore, the rotary separator is also ideal in handling contaminated water as it is not as susceptible to clogging as capillary concepts.

Another version under consideration is an elbow-centrifugal separator, consisting of a centrifugal separator downstream of an elbow collector. The elbow collector (rather than a wick) located downstream of the condensing heat exchanger, utilizes a gutter to collect the water on the duct walls. This concept eliminates the requirement for a high flow (500 cfm) centrifugal separator in that a small flow (5 cfm) is adequate for operation. It eliminates the need for an expendable wick and transfer disc. It permits more subsystem installation flexibility, requires no new development cost and results in a subsystem which does not contain expendable items.

Concept Selection

The elbow-centrifugal concept is selected for use on the shuttle. This concept, although it has a total equivalent weight which is 8 pounds heavier than a face wick separator, requires no maintenance, expendables, or new development effort. The elbow-centrifugal concept can be integrated on a system basis with the liquid-air separator in the waste management subsystem with the result that program cost will be reduced by development of only one liquid-gas separator for the EC/LSS.

VENTILATION

Cabin ventilation flow is required to accomplish the following functions:

- Collection and distribution of temperature and humidity control air, CO_2 process flow, and trace contaminant and bacteria control flow.
- Avoidance of hot and cold spots in the cabin.
- Provision of equivalent free convection film coefficients for metabolic and air cooling of electronics.

Although a specific compartment configuration definition is required for final ventilation system design, the following estimates were made in order to determine the minimum ventilation flow rate. The cabin was considered to be a cylinder with length equal to diameter. As illustrated in figure 23, a down and back flow through the cylinder was assumed. A nominal velocity of 25 feet per minute results in a minimum air flow requirement of 400 cfm. If the system flow required for CO_2, humidity and temperature control is less than 400 cfm, additional ventilation fans are added to bring the total air flow to the required level.

At the nominal baseline design condition, none of the concepts evaluated required ventilation fans as the normal air flow rates were approximately 500 cfm.

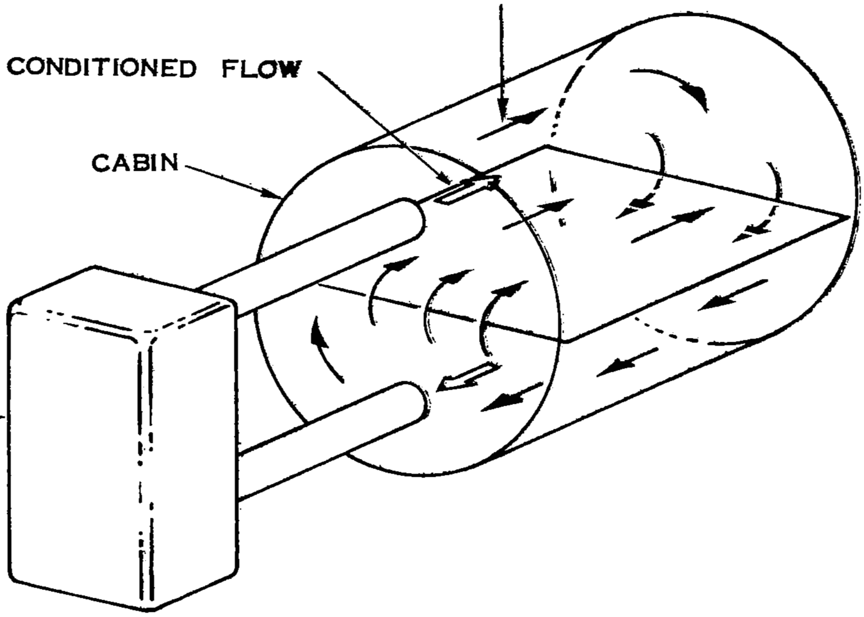


FIGURE 23. VENTILATION FLOW PATTERN

CO_2, HUMIDITY AND TEMPERATURE CONTROL SUBSYSTEM CONCEPTS

Eight candidate concepts were considered for CO_2, humidity and temperature control and are listed in table 13. These concepts can be classified as non-regenerable solid absorption, regenerable solid absorption, electrochemical concentration, membrane permeation. Alternative versions of many of these concepts were investigated, although only the most competitive versions were included in the selection process. The solid absorption processes use beds of granular chemicals contained in canisters. As air containing CO_2 passes through these beds, the granules remove the CO_2 by physical adsorption or by forming a chemical bond. The CO_2 is desorbed from the granules in the regenerable concepts by application of heat and/or vacuum. The electrochemical processes remove CO_2 from air by absorbing it in an alkiline electrolyte or water. The resulting ions are electrochemically transferred across a membrane, converted to pure, gaseous CO_2, and dumped overboard. The membrane diffusion process removes CO_2 by diffusion of CO_2 through a special membrane faster than oxygen or nitrogen.

A study flow chart that depicts the order in which the study comparisons were made is presented in figure 24. The first set of comparisons was conducted to select the lowest weight desiccant and molecular sieve approaches for independently removing water vapor and CO_2 from the atmosphere. The best solid amine approach for both water vapor and CO_2 removal was selected by similarity to the desiccant selection.

The final step was to compare the eight candidates, as listed, on a total system level including cabin temperature control, ventilation and heat rejection and to select the optimum concept.

The following sections discuss the characteristics of the candidates concepts. Where preliminary comparisons of alternate versions were made to arrive at a definition of the final candidates, the alternatives are also discussed.

Lithium Hydroxide/Condenser

This candidate concept utilizes lithium hydroxide for CO_2 removal and a condensing heat exchanger for temperature and humidity control. The condensed water is concentrated in a smaller air stream by an elbow collector and the mixture is ducted to the waste water centrifugal separator for final liquid-air separation. A data sheet and a schematic of this concept including provisions for cabin ventilation and temperature control are shown in figure 25.

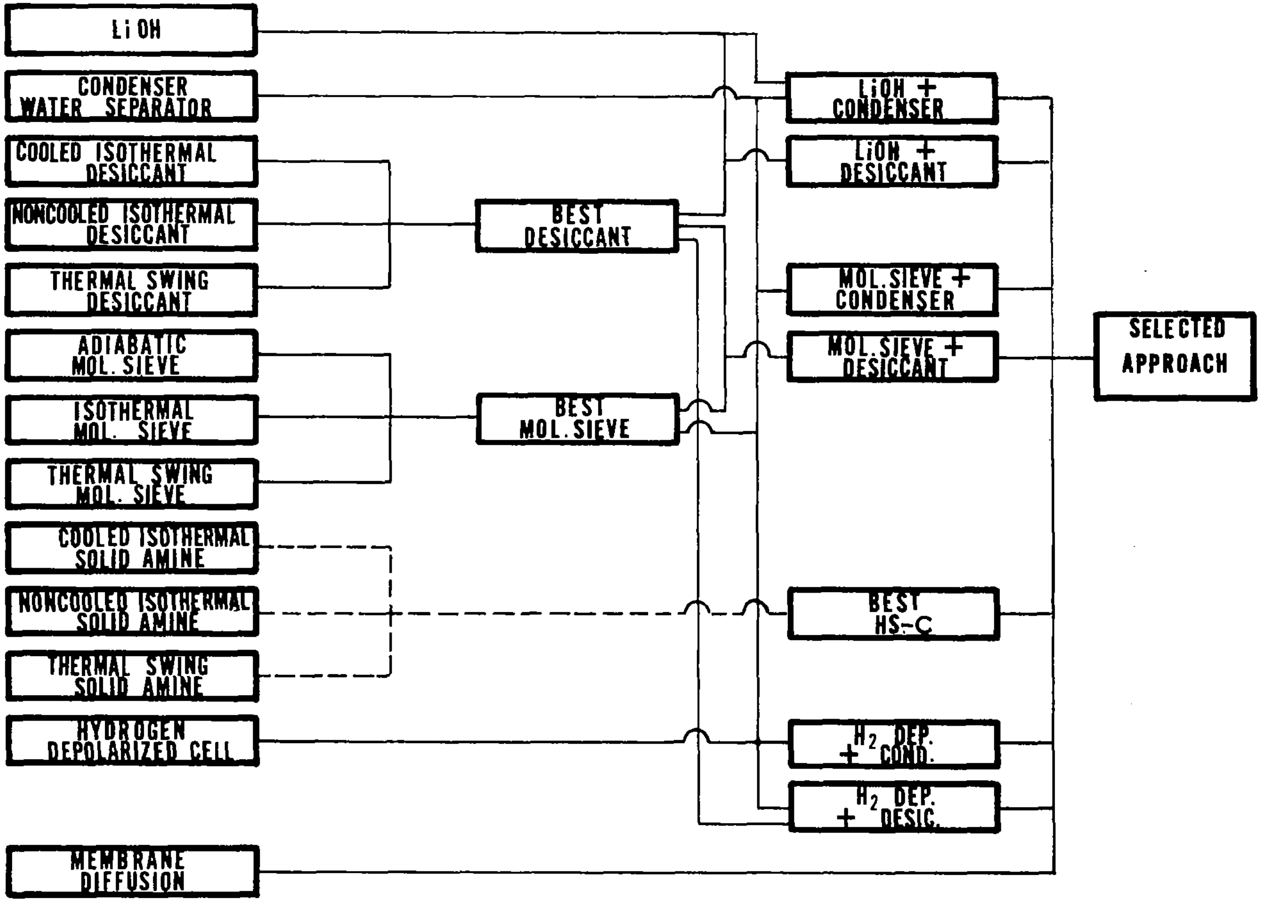


FIGURE 24. STUDY FLOW CHART

SUBSYSTEM: CO_2, HUMIDITY, & TEMPERATURE CONTROL

CONCEPT: LiOH/CONDENSER

FLIGHT AVAILABILITY: 1974

Mission Phase Application

Launch X Orbit X Reentry X Cruise X

RELIABILITY: 0.999653 MTBF: 41,625

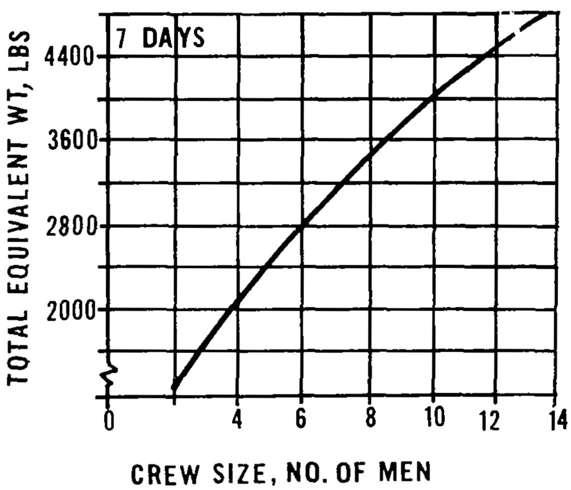
4 Men - 7 Days Plus 48 Hours Contingency

	Total Equivalent Wt. (lb)	Volume (ft^3)	Power (watts)
Installed Unit*	1577	36	722
Expendables	189	8	—
Power Equiv. Wt.	323	-	—
Totals*	2089	44	722

*Includes 996 pounds radiator penalty

Cost Factor	
Recurring -	1.5
Nonrecurring -	1.0
Total -	1.0

Crew Time (hrs)	
Scheduled -	1.17
Ground Refurbishment -	0.67



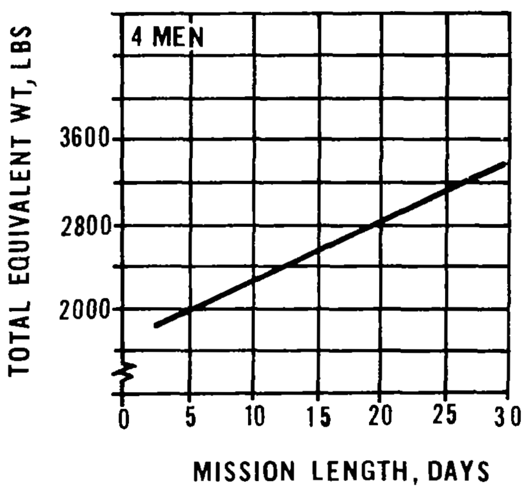


Figure 25. (Page 1 of 2)

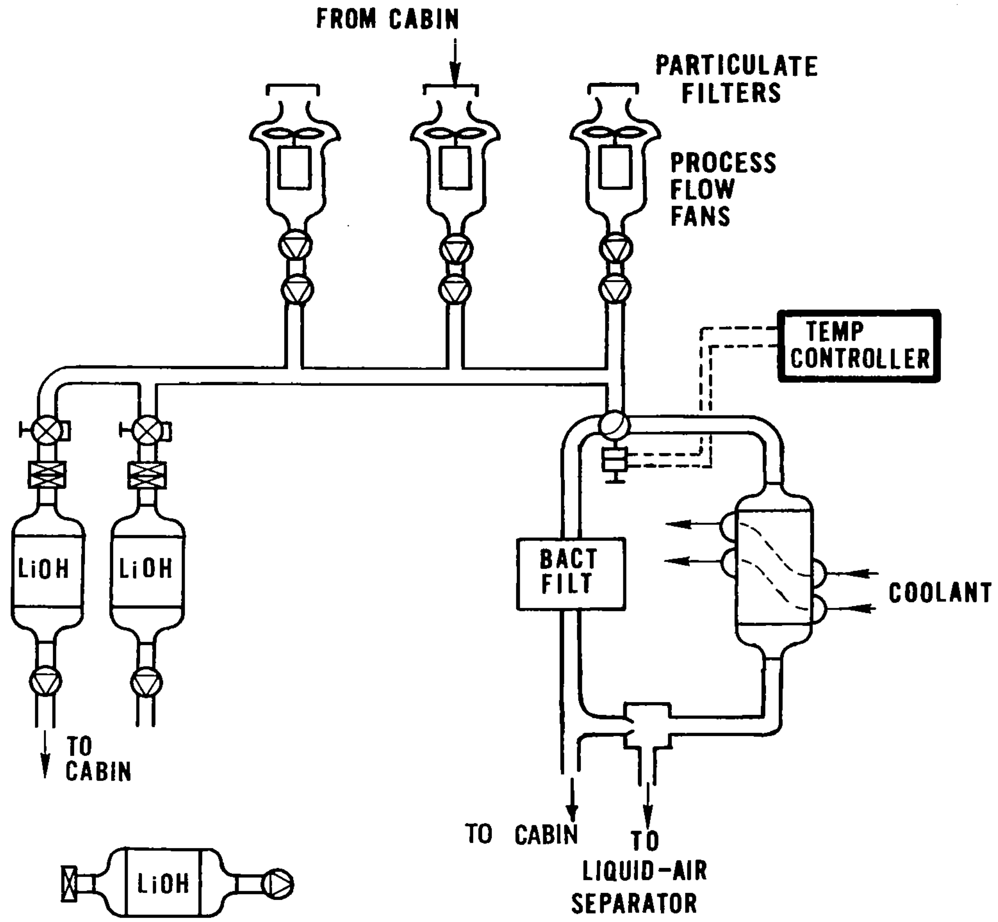


FIGURE 25. LITHIUM HYDROXIDE/CONDENSER CONCEPT (PAGE 2 OF 2)

The LiOH canister and condensing heat exchanger are operated in parallel, utilizing a common fan to supply the total flow required for CO_2, humidity and temperature control. Three fans are provided to meet the fail operational-fail safe requirement. Redundant check valves at each fan outlet prevent back flow through a nonoperating fan and a failed open check valve.

Two LiOH canisters are installed in the subsystem with one canister on line at all times. Each canister contains the capacity of four man-days of CO_2 absorption and, therefore, canister replacement is required only once per day for the baseline mission. The four man-day size canister was chosen for its ease of handling during replacement in orbit and on the ground. The canister weight and volume are approximately 17.5 lbs and 0.5 ft^3, respectively. A total of nine canisters is required for the nominal seven-day mission and two-day contingency period. Each canister contains a quick disconnect half at the inlet and a check valve at the outlet to seal the canister during storage. The canister selector valves are operated electrically by the crew once per day when the on-line canister is expended. Replacement of the expended canister can then be accomplished by the crewman at their convenience. All spent canisters are replaced at the end of the flight and repacked for future use.

The humidity control portion of the subsystem consists of a condensing heat exchanger with an elbow collector water separator. The condensing heat exchanger is of stainless steel material for life considerations. It has dual coolant passages (one for each of the two cabin coolant loops). The condensed water is blown out of the heat exchanger passages and inertial forces carry the water on along to the discharge air elbow duct walls. A gutter in the discharge air duct collects the water and directs it to the centrifugal separator in the Waste Management Subsystem.

Temperature control is achieved by bypassing air around the condensing heat exchanger with a diverter valve (with manual override). The valve is a flapper design with dual actuators and requires no sealing. This approach for temperature control permits use of a single heat exchanger for both sensible and latent heat control and does not require valving in the coolant loop.

As the air bypass flow around the cabin heat exchanger is increased, the cabin dew point initially decreases. This decrease is due to the heat exchanger outlet temperature decreasing and drier air entering the cabin. As more air is bypassed, the humidity level starts to rise as a minimum outlet air humidity level is reached. Figure 26 shows the variation in cabin dew point as a function of electrical and wall heat loads. For a 65°F cabin temperature at maximum metabolic heat loads, the electrical and wall heat loads can be reduced from 6700 Btu/hr to 1000 Btu/hr before the cabin dew point goes above the specification limit. With a 75°F cabin temperature, the electronic and wall heat loads must be negative before the cabin dew point goes out of specification. Therefore, an air bypass for temperature control will also adequately control humidity. A liquid bypass control cannot be used in conjunction with a condenser because humidity cannot be controlled.

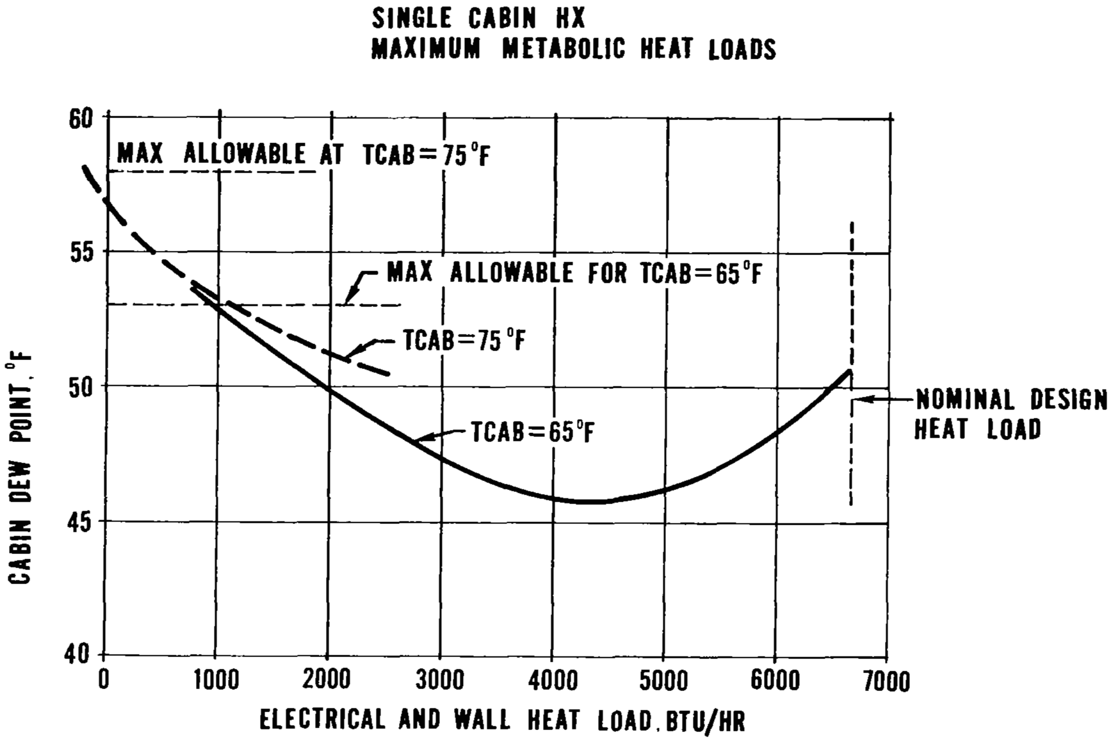


FIGURE 26. CABIN DEWPOINT VERSUS ELECTRICAL AND WALL HEAT LOAD

For airborne bacteria control, a flow of approximately 100 cfm is required to be processed. The EC/LS system has a bacteria filter in the water and waste management subsystem which is constantly processing 45 cfm. Therefore, for adequate control, a second bacteria filter is placed in the condensing heat exchanger air bypass line. For nominal cabin temperatures and heat loads, this filter will process approximately 200 cfm of air. For the minimum cabin temperature-maximum heat load condition, the bypass air flow can drop to zero. However, it is unlikely that this condition will last any appreciable length of time. Furthermore, the nominal condition has a much higher flow rate than required and, therefore, it is considered that this system is satisfactory for adequate bacteria control.

For contaminant control, approximately 45 cfm of air is required. Since the flow through the continuously operating centrifugal separator in the water and waste management subsystem maintains this flow, the contaminant control charcoal was added to the odor control canister (required for the water and waste management subsystem) thereby combining all charcoal requirements into one canister. In performing the tradeoff evaluation, the weight and power of one centrifugal separator continuously operating were charged against the applicable CO_2, humidity, and temperature control subsystem (condensing concepts).

Absolute criteria. - The design point for this subsystem is a 65°F cabin temperature with a 51°F dew point (maximum) and nominal heat loads. A flow diagram of the optimized system is shown in figure 27.

This system meets performance requirements during all mission phases including ferry. During the prelaunch phase, ground support equipment (excluding the heat sink) is not required to condition the cabin atmosphere for CO_2 and humidity control.

Since LiOH is toxic, adequate filters are required to prevent contamination of the cabin atmosphere. This concept has the highest MTBF of all the approaches considered; it has been flight qualified and has been used on the Mercury, Gemini, and Apollo programs.

Quantitative criteria. - This concept is the median in total equivalent weight of the seven concepts examined (the membrane diffusion approach was not considered past the absolute criteria). It is 149 pounds heavier than the lightest concept for the nominal design conditions. It has the lowest initial cost due to its simplicity and high state of development. Furthermore, it has one of the lowest total program costs, and the lowest volume of the concepts considered.

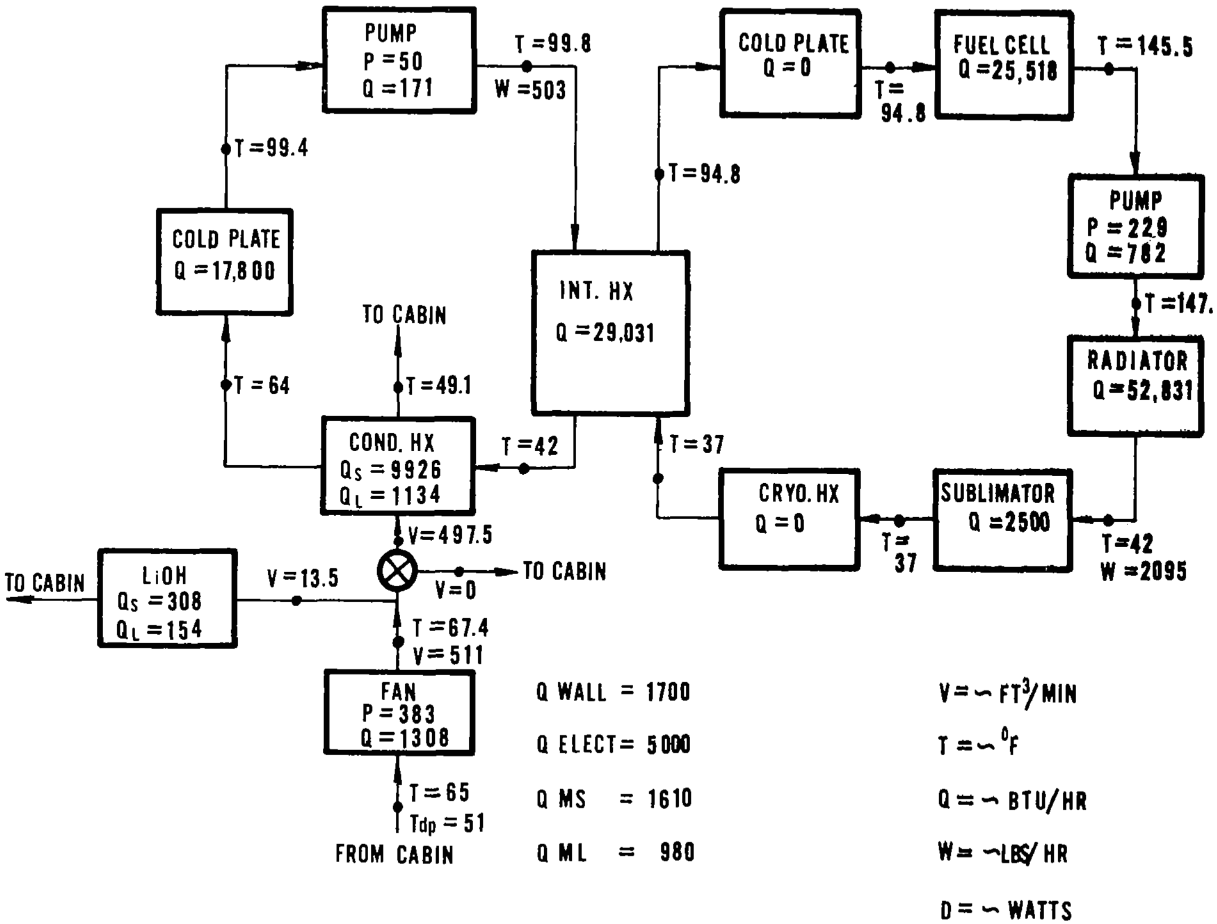


FIGURE 27. DESIGN POINT FLOW CHART, LiOH/CONDENSER CONCEPT

Qualitative criteria. - The LiOH/condenser concept is the least complex of all those considered. It has about half as many parts as other equivalent approaches. There is only one set of fans, and a minimum of components in the coolant loop. It is flexible in that it can handle increased mission length and/or crew size by carrying more expendable LiOH cartridges for CO_2 control and can utilize a number of alternate heat rejection concepts to maintain the required low condenser coolant inlet temperature. It may be necessary to either design the LiOH cartridges to a lower pressure drop or to provide a separate fan for larger crew sizes and accept the penalty. The total equivalent weight of this concept is more sensitive than the desiccant approaches to changes in air heat loads, crew sizes, radiator influxes, etc.

Refurbishment time is minimal since only the LiOH cartridges and the bacteria and particulate filters will require replacement. The contaminant control requirement is considered part of the water and waste management subsystem. Checkout is relatively easy because of the few components involved. In-flight maintenance time is high compared to regenerative subsystems since the LiOH cartridges must be replaced on a daily basis.

Lithium Hydroxide/Desiccant

This candidate utilizes lithium hydroxide for CO_2 removal and a regenerable desiccant (silica gel) for humidity control. A data sheet and a schematic of this approach including provisions for cabin ventilation and temperature control are shown in figure 28.

A single set of dual flow fans is used to supply the air flow for all of the system requirements. The dual flow fan has a single motor and rotor, but has two outlet flow streams with different pressure levels. A fan of this type had completed its performance development tests before cancellation of the MOL program. The low pressure rise-high flow section of the fan provides flow for the sensible heat exchanger. A liquid bypass temperature control is approximately five to six pounds lighter than an air bypass temperature control. While it is less desirable to have valves in the coolant circuits than in the air circuit, the liquid bypass method was selected for the temperature control in order to establish the lightest weight version of this concept. Flow from the high pressure rise-low flow section of the fan passes through a bacteria filter before dividing to the contaminant control, CO_2 control, and the humidity control subsystems. Cabin humidity level is controlled by varying the air flow to the humidity control subsystem with an air bypass valve. The air bypass valve has two actuators and a manual override. The operation of the LiOH canisters is similar to that of the LiOH/condenser concept. The contaminant control canister is sized for the nominal design mission and does not have to be changed in flight.

SUBSYSTEM: CO_2, HUMIDITY & TEMPERATURE CONTROL

CONCEPT: LiOH/DESICCANT

FLIGHT AVAILABILITY: 1975

Mission Phase Application

Launch X Orbit X Reentry X Cruise ____

RELIABILITY: 0.999755

MTBF: 12,578

4 Men - 7 Days Plus 48 Hours Contingency

	Total Equivalent Wt. (lb)	Volume (ft^3)	Power (watts)
Installed Unit*	1547	37	595
Expendables	193	8	—
Power Equiv. Wt.	266	—	—
Totals*	2006	45	595

*Includes 954 pounds radiator penalty

Cost Factor

Recurring - 2.1

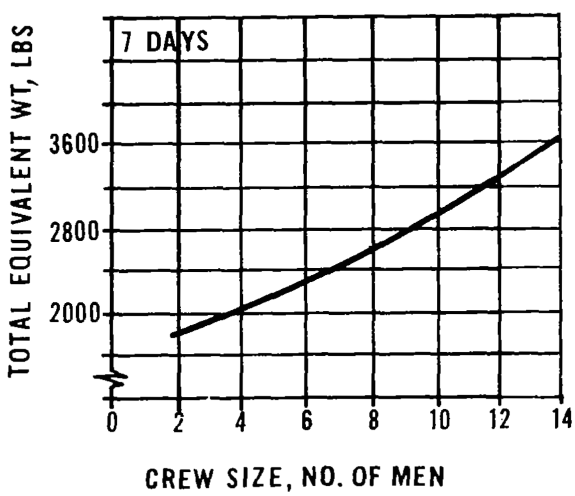
Nonrecurring - 2.0

Total - 1.6

Crew Time (hrs)

Scheduled — 1.17

Ground Refurbishment — 1.67



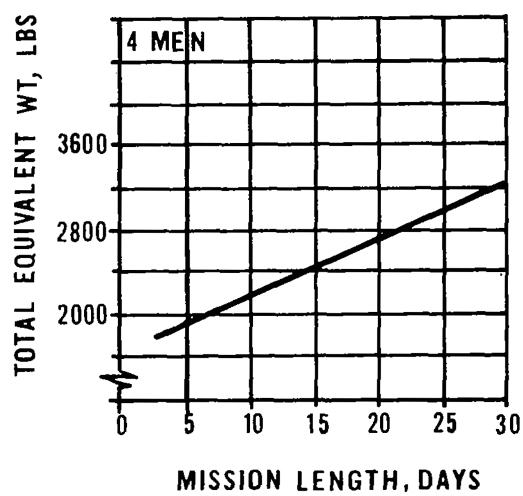


Figure 28. (Page 1 of 2)

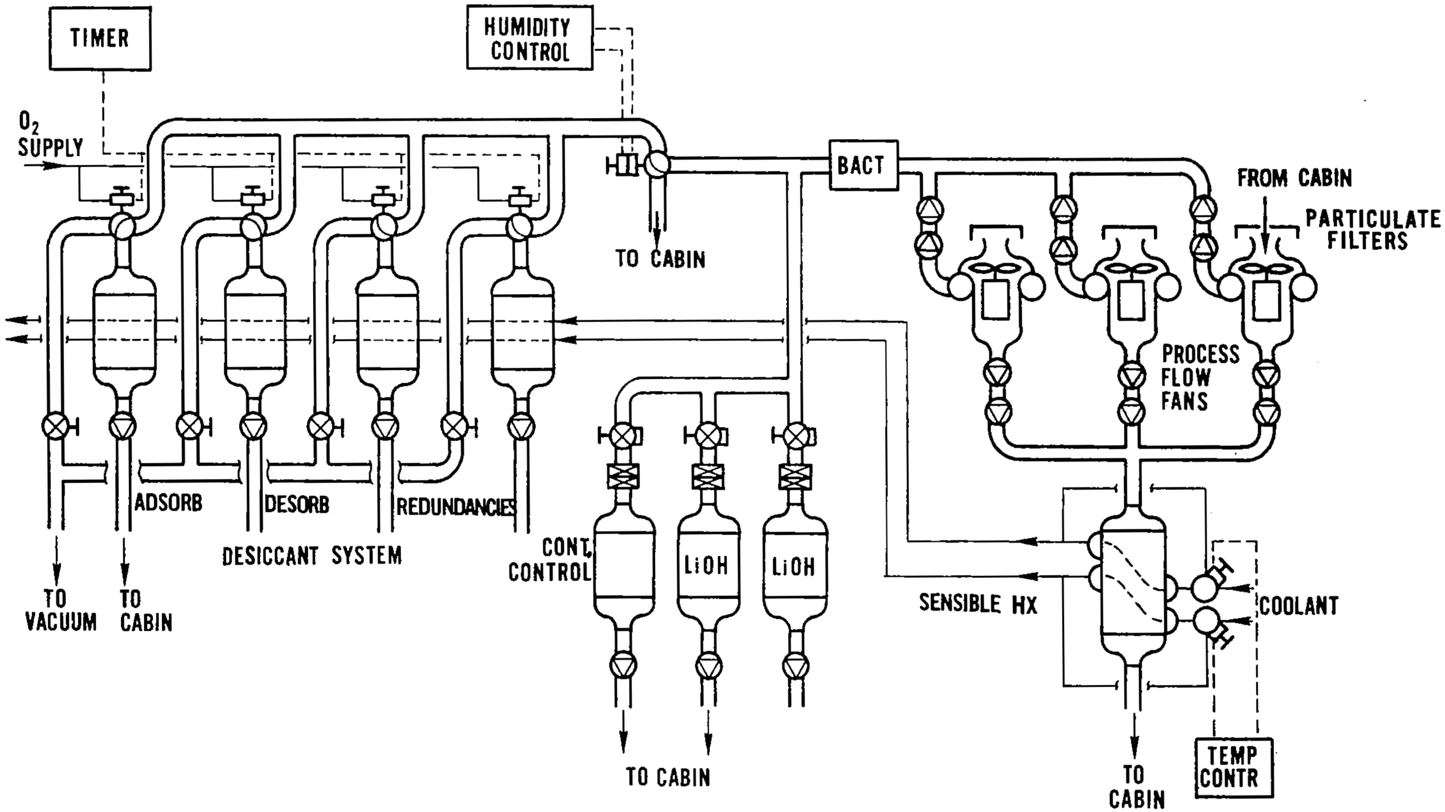


FIGURE 28. LITHIUM HYDROXIDE/DESICCANT CONCEPT (PAGE 2 OF 2)

The desiccant portion of the subsystem includes four canisters each containing approximately 2.0 pounds of silica gel. One canister absorbs water from the cabin air while a second desorbs water to vacuum. The remaining two canisters provide the necessary redundancy to meet the fail operational-fail safe requirement. Each canister is cycled by a pneumatically actuated three-position valve that permits cabin air to flow through the silica gel bed during the adsorb portion of the cycle, exposes the silica gel to vacuum during the desorb portion of the cycle and isolates the silica gel from cabin and vacuum when on standby. A check valve at the canister outlet prevents cabin air from flowing into the canister during desorption. A manual shutoff valve is provided in each vacuum line for failure isolation.

An electronic timer cycles the operating beds every 15 minutes. An electronic humidity controller senses cabin humidity and varies the humidity control air flow to control cabin humidity during periods of varying latent loads. As with the previous concept, adequate flow is circulated by the EC/LSS to satisfy ventilation requirements and supplementary ventilation fans are not required.

Desiccant selection. - A preliminary study was conducted to determine the best method of operation for the desiccant. The study considered cooled isothermal, non-cooled isothermal and thermal swing methods. Schematics of these three methods of operation are shown in figures 28, 29, and 30. Silica gel was selected as the desiccant material because of its high capacity for moisture at high relative humidities.

In the cooled isothermal method (figure 28), coolant flows through the desiccant beds, after leaving the cabin heat exchanger. No valving is required as the flow is never switched or modulated. As the heat of adsorption is equal to the heat of desorption, there is no net heat gain or loss to the coolant system since the coolant flows through both the adsorbing and desorbing beds. Therefore, the desiccant performance is considered relatively isothermal. As the rate of desorption varies over the desorption cycle, there may be a slight change in coolant temperature leaving the system, but this is considered to be insignificant.

In the non-cooled isothermal method (figure 29), the desiccant is packed into both sides of the plate fin heat exchanger. The desiccant on one side of the heat exchanger adsorbs while the desiccant on the other side desorbs. In this manner, the heat of adsorption is transferred to the desorbing bed resulting in essentially isothermal operation. This method has no liquid interfaces and the same performance as the cooled isothermal system. The beds are lighter as there are no coolant lines in the beds. Due to the redundancy required for the fail operational-fail safe requirement, this subsystem requires one additional bed and vacuum valve and, as a result, is 30 pounds heavier than the cooled isothermal system.

In the thermal swing method (figure 30), hot coolant water is circulated through the desiccant bed during desorption and cold coolant water is circulated through the bed during adsorption. This method would result in smaller desiccant beds than

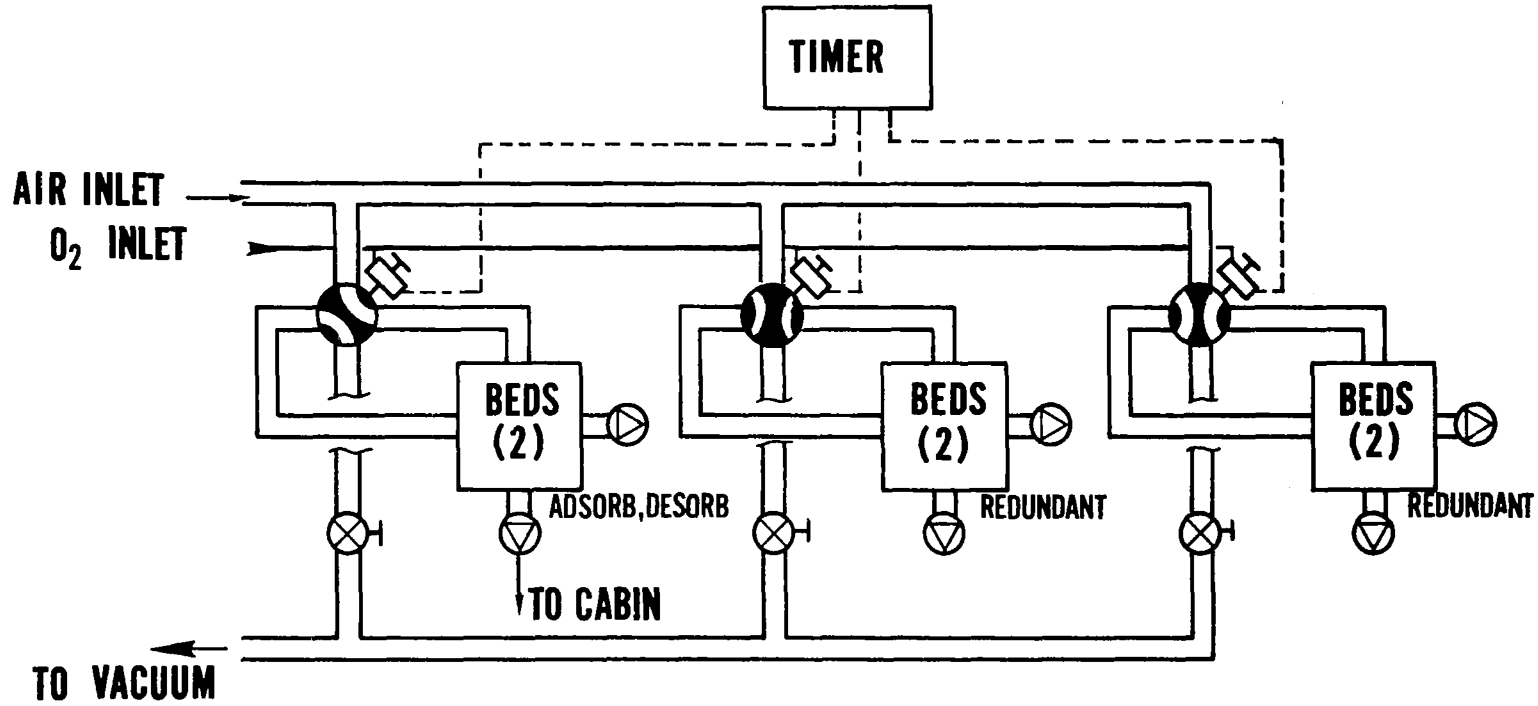


FIGURE 29. NON–COOLED ISOTHERMAL DESICCANT

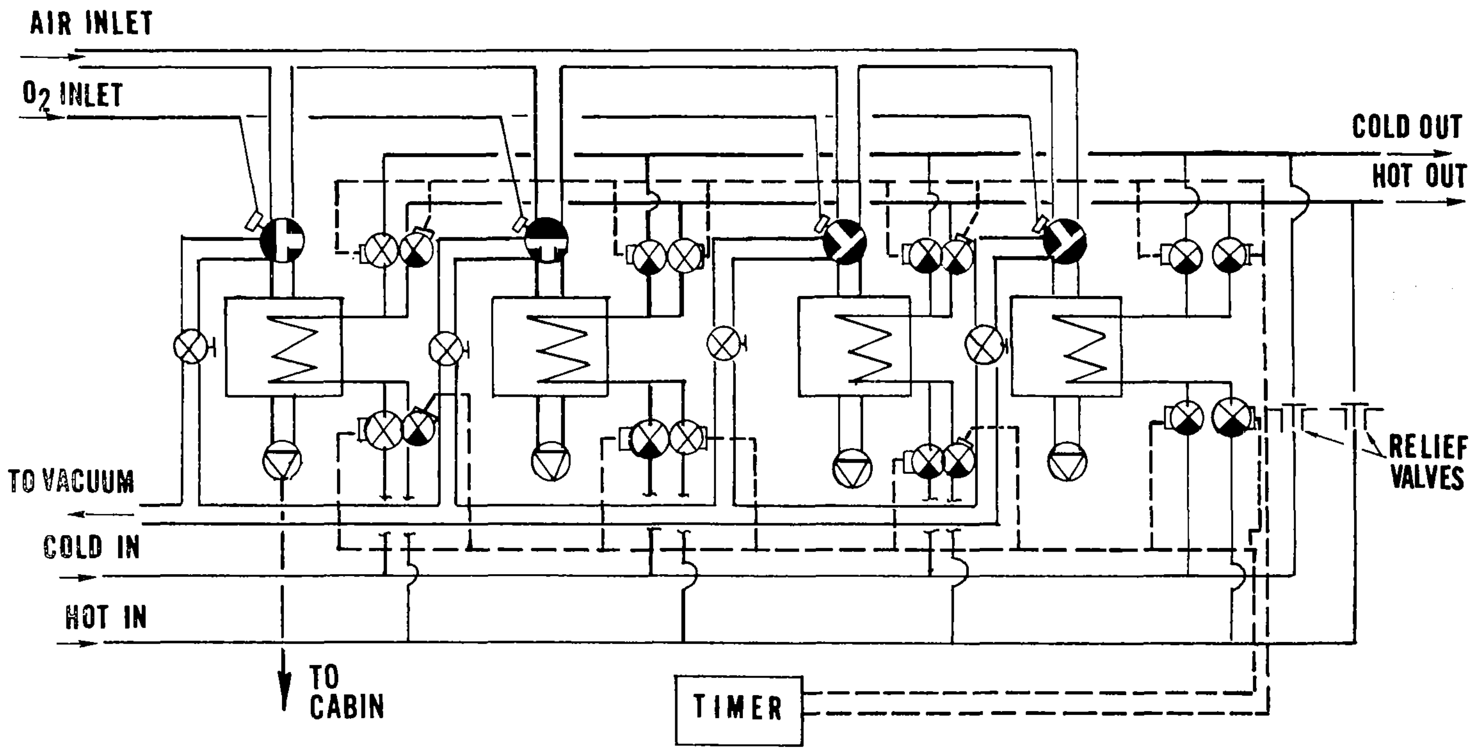


FIGURE 30. THERMAL SWING DESICCANT

in the isothermal methods, but adds the complexity of solenoid valves to the coolant loop for switching coolant from hot to cold. The additional improvement in "bed loading" with the active cooling and heating is small (approximately 10%) due to the fact that the beds are operated until they are almost fully loaded (approximately 70% average removal efficiency). This method requires many more components and is 16 pounds heavier than the cooled isothermal method. The thermal swing method being less reliable, less durable and more complex was dropped from further consideration.

As a result, the cooled isothermal desiccant method was selected because it is the lightest and least complex method considered.

Absolute criteria. - The design point flow chart for the LiOH/desiccant subsystem concept is shown in figure 31. Cabin temperature is 65°F and the cabin dew point is 43.8°F at nominal heat loads. If the cabin dew point exceeds 43.8°F, condensation will occur in the sensible heat exchanger. There is no latent heat load on the system as the water is removed by the desiccant. The heat rejection loop coolant flow rate is optimum at 1995 lbs/hr with a radiator outlet temperature of 42°F.

The basic componentry required for vacuum operation does not provide positive humidity control during the prelaunch, launch, reentry, and ferry phases of the mission. Therefore, the following provisions were considered:

- Prelaunch - humidity controller by GSE with flyaway connectors.
- Launch and reentry - these are short transients where some condensation will occur in the sensible heat exchanger, but the time is short enough that no free water enters the cabin.
- Ferry flight - a separate system must be added to handle humidity control for this mission phase.

The desiccant portion of the subsystem requires a vacuum line for desorption and normal precautions must be taken with the LiOH. This approach has twice as many components as the LiOH/condenser concept and is over three times as likely to fail. Reliability is greater than the LiOH/condenser concept as there is more redundancy, and is higher than the required reliability. Similar LiOH subsystems have been flight qualified. The desiccant portion is similar in technology to that developed for MOL and Skylab CO_2 removal systems.

Quantitative criteria. - This concept is one of the lighter concepts considered due to the radiator weight savings associated with the fact that the latent heat does not have to be removed from the atmosphere and does not show up in the coolant loop.

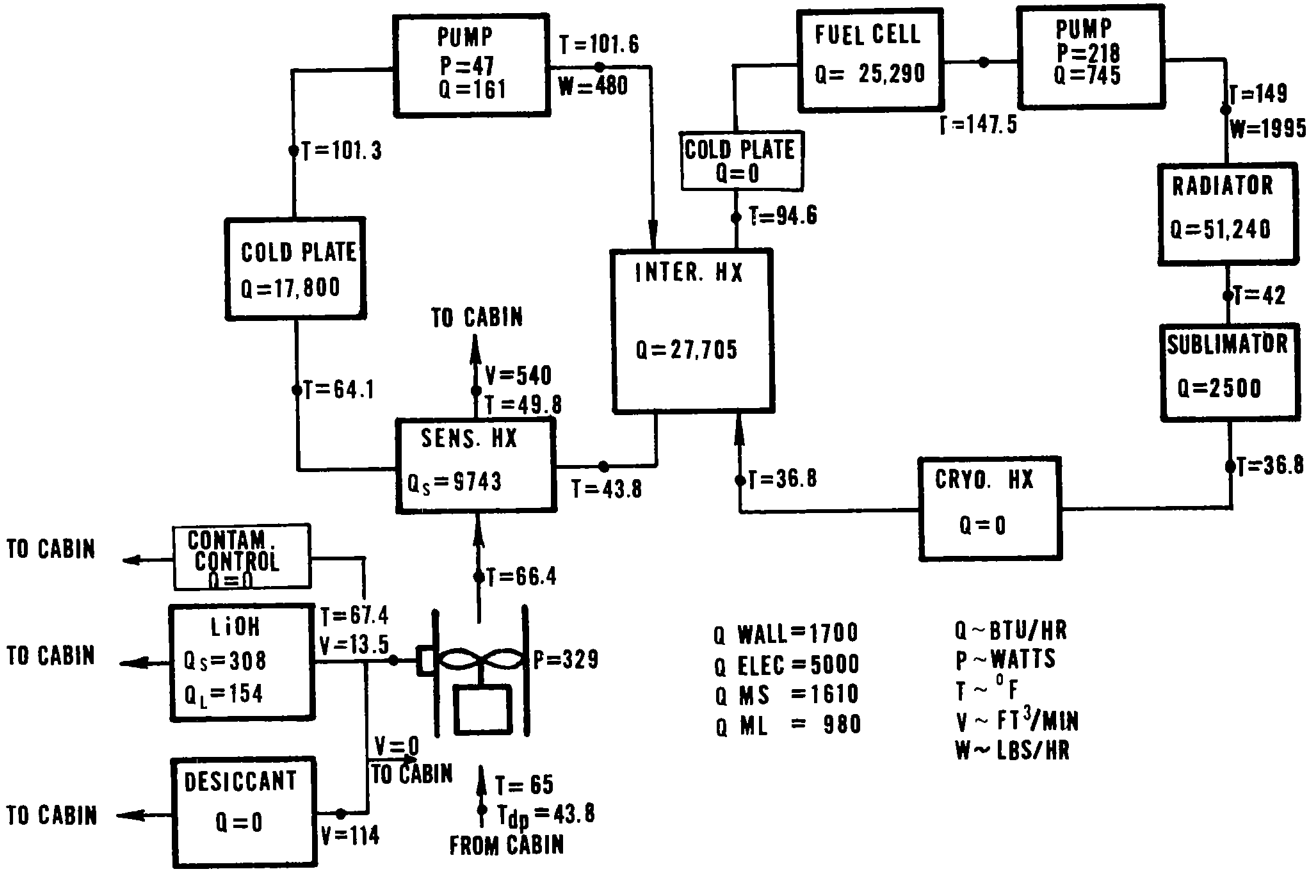


FIGURE 31. DESIGN POINT FLOW CHART, LiOH/DESICCANT CONCEPT

The total program cost is one of the highest due to the large number of components and the high usage of expendables. The volume is one of the lowest of the concepts considered.

Qualitative criteria. - The complexity is about average for the concepts considered. The concept is rather inflexible with respect to variations in crew size as the desiccant must be resized or additional canisters put on line. Total equivalent weight also increases rapidly with mission length due to high usage of expendables. The concept is not as sensitive to changes in radiator influxes, crew size, or air heat load as the condensing approach. Durability is not as good as the LiOH/condenser approach due to the larger numbers of moving components.

Refurbishment required is involved since the desiccant beds must be dried out with hot gas between missions and both charcoal and LiOH canisters, bacteria filters, and particulate filter, must be replaced. Checkout is simple but time consuming. Inflight maintenance is required as LiOH must be replaced on a daily basis.

Molecular Sieve/Condenser

This concept utilizes a regenerable molecular sieve for CO_2 removal and a condensing heat exchanger for humidity control. The condensed water is concentrated in a smaller air stream by an elbow collector and the mixture is ducted to the centrifugal separator for final liquid-air separation. A data sheet and a schematic of this approach including provisions for cabin ventilation and temperature control are shown in figure 32.

A set of high flow fans provides the flow for temperature and humidity control. A condensing heat exchanger cools and dehumidifies the air while air temperature is controlled by bypassing air around this condensing heat exchanger. A bacteria filter is placed in the heat exchanger bypass line to control airborne bacteria. Water separation and contaminant, temperature, and humidity control are identical to the LiOH/condenser concept explained earlier.

The molecular sieve portion of the subsystem draws flow from the outlet of the condenser utilizing its own set of fans. Placing the molecular sieve downstream of the condenser is necessary to minimize the size of the molecular sieve beds. Since the molecular sieve is easily poisoned by water, a desiccant bed is placed in each canister to dry the incoming air before it passes through the CO_2 removal bed. Locating the molecular sieve beds at the minimum water vapor level (at the condensing heat exchanger outlet) permits the smallest desiccant beds to be used. The desiccant bed consists of 13X molecular sieve material. It was selected for its relatively high capacity for water vapor at low dew points and good vacuum desorbing characteristics. The CO_2 removal material, 5A molecular sieve, was selected for its high adsorption rate for CO_2 when water is not present.

SUBSYSTEM: CO_2, HUMIDITY & TEMPERATURE CONTROL

CONCEPT: MOLECULAR SIEVE/CONDENSER

FLIGHT AVAILABILITY: 1975

Mission Phase Application

Launch X Orbit X Reentry X Cruise ____

RELIABILITY: 0.999643 MTBF: 11,908

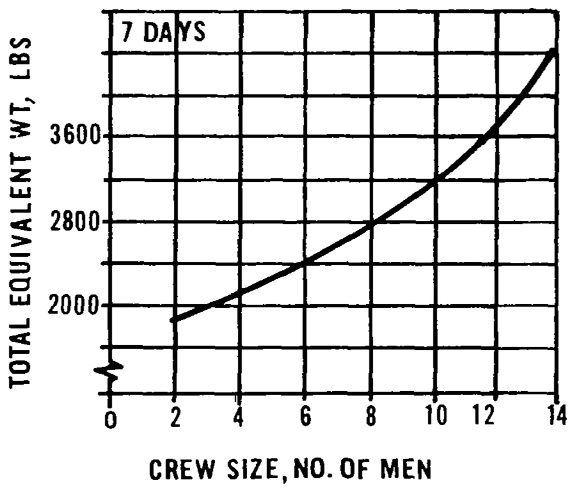
4 Men - 7 Days Plus 48 Hours Contingency

	Total Equivalent Wt. (lb)	Volume (ft^3)	Power (watts)
Installed Unit*	1668	44	713
Expendables	172	11	—
Power Equiv. Wt.	319	—	—
Totals*	2159	55	713

*Includes 958 pounds radiator penalty

Cost Factor	
Recurring -	1.1
Nonrecurring -	2.0
Total -	1.1

Crew Time (hrs)	
Scheduled —	0
Ground Refurbishment —	1.0



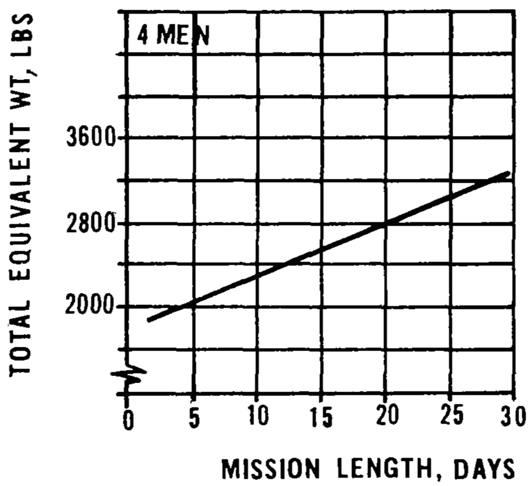


Figure 32. (Page 1 of 2)

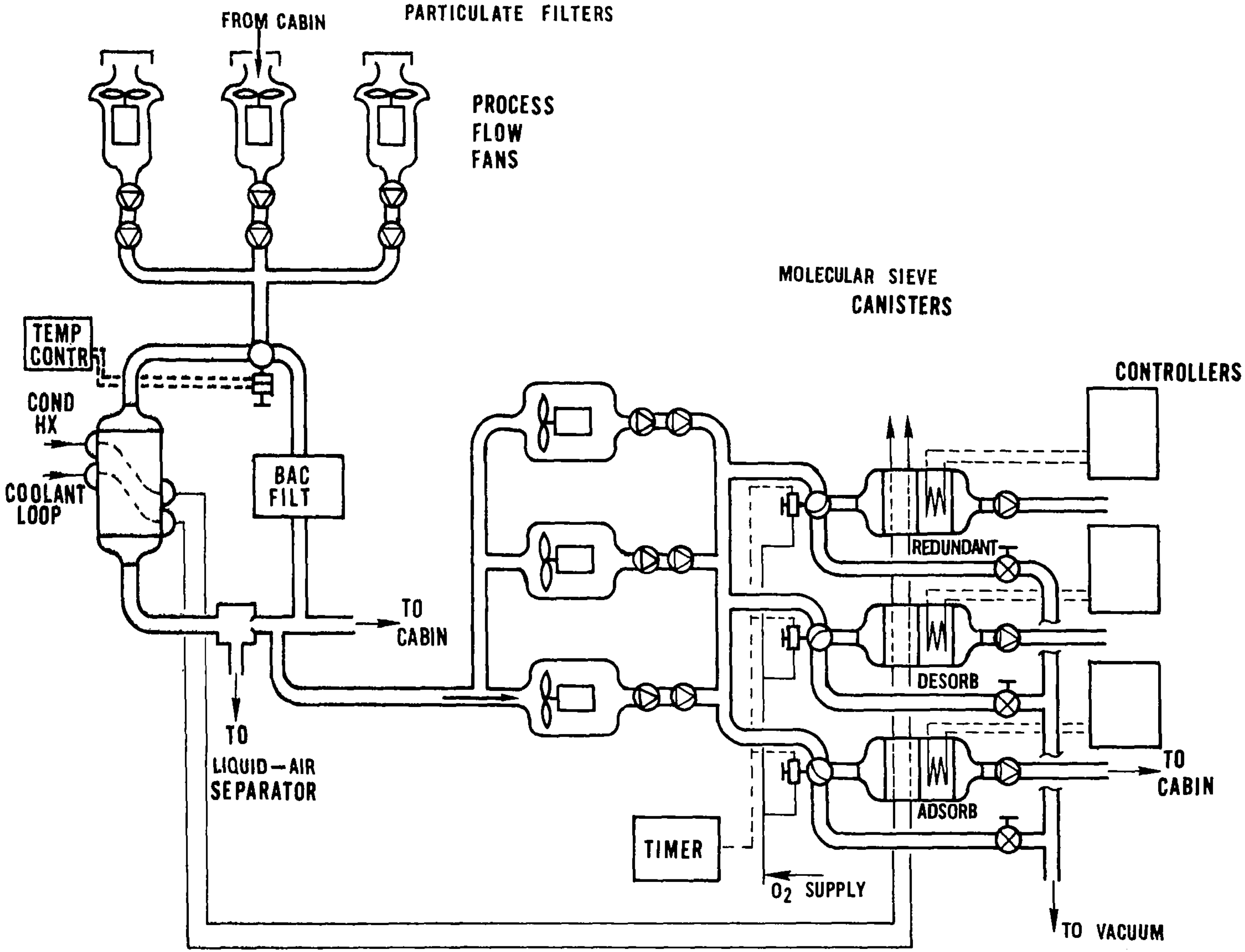


FIGURE 32. MOLECULAR SIEVE/CONDENSER CONCEPT (PAGE 2 OF 2)

The molecular sieve portion of the subsystem includes three canisters each containing 5.0 pounds of desiccant and 7.5 pounds of CO_2 removal material. One canister adsorbs CO_2 from the cabin air while a second desorbs to vacuum. The remaining canister provides fail operational redundancy. A fourth canister is not required for a fail safe condition, since the operation of a single canister will provide an acceptable degraded mode of performance following a second failure. In this degraded mode, the cabin CO_2 partial pressure would rise from 5 mm Hg to 10 mm Hg. Such a level is acceptable for the 48-hour emergency fail safe period. An electric heater is provided in the CO_2 removal section of each canister for regeneration in the event the bed is poisoned by water. The valving and controls for the molecular sieve are similar to those provided for the desiccant concept described earlier.

Molecular sieve concept selection. - Three methods of operation the molecular sieve assembly were considered: thermal swing, isothermal-cooled, and adiabatic. The isothermal-cooled molecular sieve without an ullage-save compressor was selected for integration into the CO_2, humidity, and temperature control subsystem because of its light weight and lower cost.

The thermal swing approach uses heating and cooling fluid in the water removal (desiccant) bed (13X) only, since the small gain in performance that would result from thermal cycling of the CO_2 bed does not justify the addition of heating and cooling circuits. A schematic of this concept would be similar to that previously shown for the thermal swing desiccant subsystem (figure 30).

The isothermal-cooled unit has a redundant coolant loop flowing through the desiccant portion of each canister. The adiabatic subsystem has no coolant flowing through either bed, and is similar to the Skylab subsystem or the MOL CO_2 removal subsystem. The thermal swing approach was dropped from further consideration due to the large number of cycling components (18 valves) that are required for operation.

The weight tradeoff study was made comparing the adiabatic and isothermal approaches. The results of the study are shown in figure 33. The isothermal subsystem is approximately 35 pounds lighter for the four-man, seven-day baseline mission. As the mission length increases, this difference increases to 425 pounds for a 4-man, 30-day mission. The isothermal subsystem was selected because of this weight advantage.

As 46% of the subsystem weight is ullage (adsorbed O_2 and N_2 and free O_2 and N_2), an investigation was conducted to see if the system weight would be reduced if the canisters are pumped to low pressure before being vented to vacuum. A comparison of the adiabatic and isothermal concepts with ullage-save compressors shows the isothermal subsystem to be 19 pounds lighter at seven days and 105 pounds lighter at 30 days, as shown in figure 34.

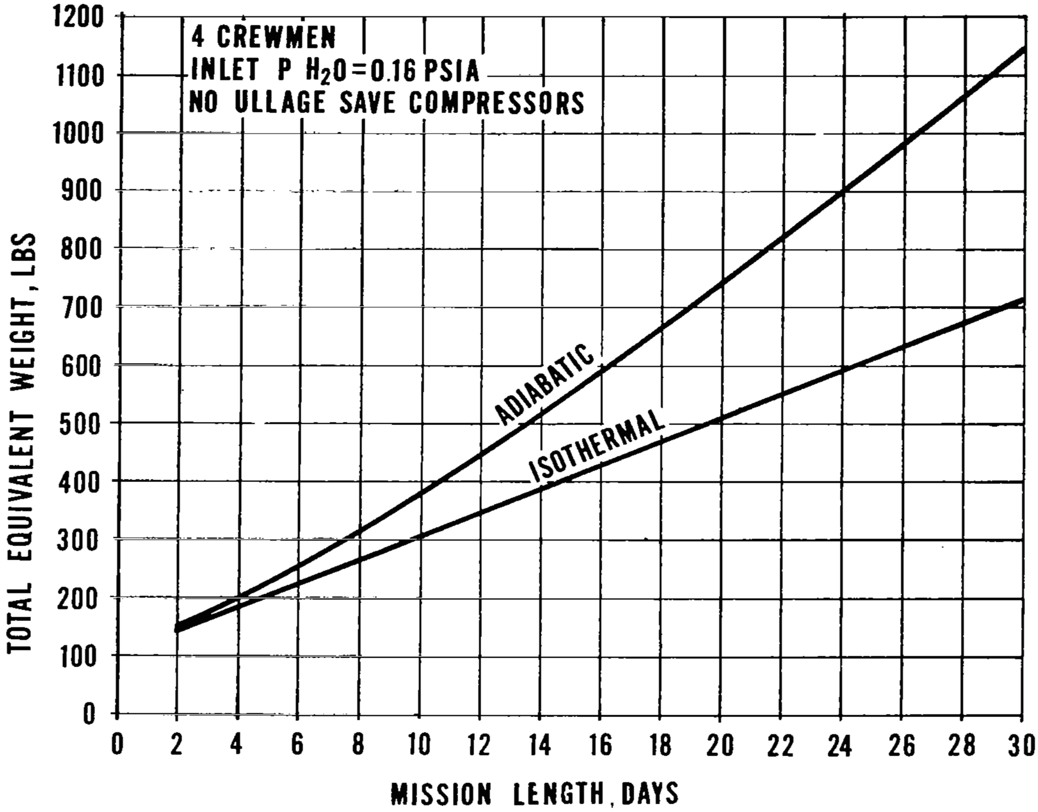


FIGURE 33. ADIABATIC VERSUS ISOTHERMAL MOLECULAR SIEVE, WITHOUT ULLAGE SAVE COMPRESSORS

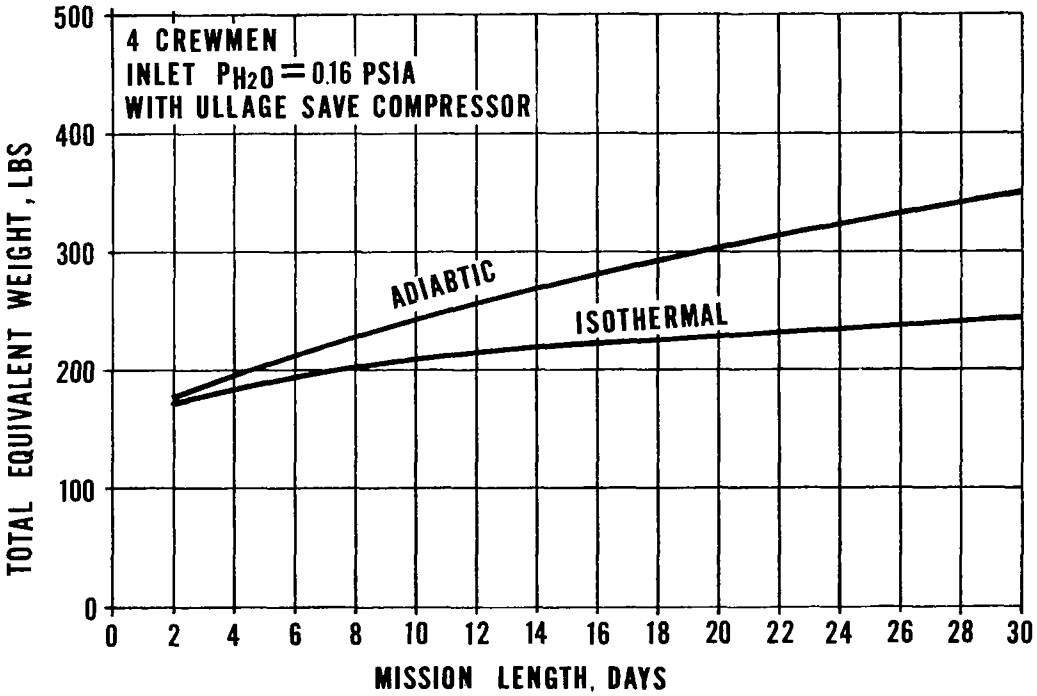


FIGURE 34. ADIABATIC VERSUS ISOTHERMAL MOLECULAR SIEVE, WITH ULLAGE SAVE COMPRESSORS

Figure 35 shows the weight of the isothermal subsystem with and without ullage save compressors versus mission length. At seven days, the compressors save 50 pounds of weight. The ROM cost of developing the compressors is extremely high. It was concluded that the weight savings of adding the ullage-save compressor was not justified because of the increased subsystem cost, increased complexity and decrease in durability. Therefore, the selected molecular sieve concept is an isothermal cooled molecular sieve without ullage-save compressors.

Absolute criteria. - A flow chart of system performance is shown in figure 36. The molecular sieve/condenser concept does not provide positive CO_2 control during launch and reentry. This is acceptable since the time periods involved are short and the CO_2 level remains within specification. A vacuum line is required for operation and is a potential leak to space. The approach has no special safety hazards and utilizes neither flammable nor toxic materials.

Considerable development efforts have been expended on this concept for space application. Consequently, confidence in flightworthy hardware is high. Prototypes, for example, have operated satisfactorily in the NASA Langley Integrated Life Support System chamber and in the McDonnell-Douglas 60-day test. Flight concepts are now being developed for the Skylab and the Space Station Prototype (SSP) for the NASA-MSC. System reliability is the lowest of the concepts evaluated, but the MTBF is only slightly lower than the LiOH/desiccant concept.

Quantitative criteria. - The total equivalent weight of this concept is one of the heaviest. The ROM cost for the total program is about 10% higher than the three least expensive approaches. Due to the sea level cabin pressure, the ullage loss is as high as the weight of LiOH that would be used for the same mission length. This approach is one of the larger volume concepts.

Qualitative criteria. - The molecular sieve/condenser concept is slightly more complex than the average system. It has two sets of fans and cycling valves. Flexibility of this concept is poor with regard to CO_2 control. New beds and fans will be required with increased crew sizes. As mission length increases, there is only a negligible weight savings over a LiOH system due to the high ullage penalty. At lower cabin total pressures, the system would be more competitive for longer missions as the ullage losses would decrease. A separate system would be required for CO_2 control during the ferry flight. Increases in radiator penalties, or air heat loads would make this approach less desirable than a desiccant-type subsystem.

Durability is low due to the number of moving parts. Refurbishment requires drying and cleaning of the molecular sieve beds with hot dry, CO_2 free gas between missions and replacement of bacteria and particulate filters. Checkout requires a functional check of the cycling valves. In-flight maintenance is not required.

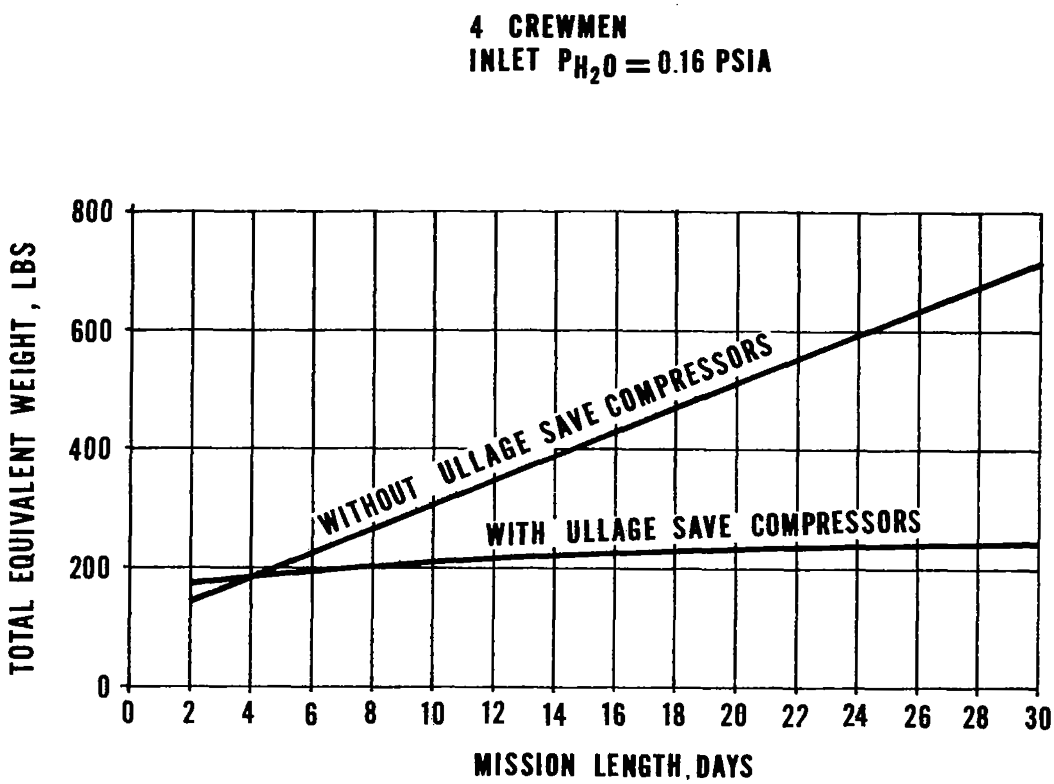


FIGURE 35. ISOTHERMAL MOLECULAR SIEVE, WITH AND WITHOUT ULLAGE SAVE COMPRESSORS

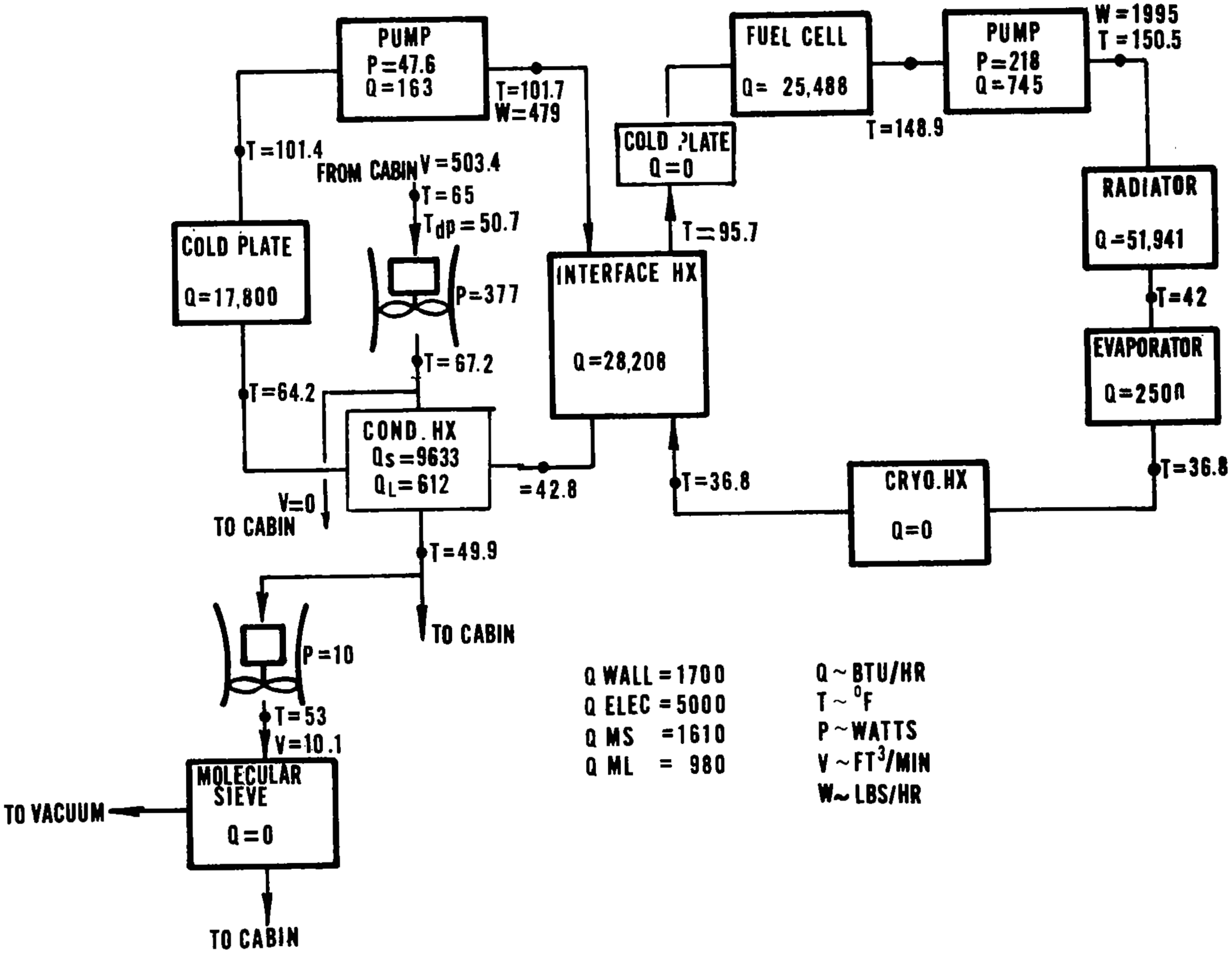


FIGURE 36. DESIGN POINT FLOW CHART, MOLECULAR SIEVE/CONDENSER CONCEPT

Molecular Sieve/Desiccant

This candidate utilizes a regenerable molecular sieve for CO_2 removal and a regenerable desiccant for humidity control. A data sheet and a schematic of this approach are shown in figure 37. A dual flow fan supplies air to the sensible heat exchanger from the low-pressure rise/high-flow side of the fan and to the humidity and contaminant control sections from the high-pressure rise/low-flow portion of the fan. A bacteria filter is placed in the low-flow portion of the system. A humidity controller diverts flow around the desiccant to control cabin humidity levels. A second set of fans supplies 20% of the air to the molecular sieve of the desiccant section from the discharge. This approach yeilds a significant weight advantage since only 10% of the flow through the low flow section of the fans is required for CO_2 control. In addition, it assures a constant flow through the CO_2 removal bed. A constant flow is required to prevent bed poisoning. Other methods to assure constant air flow to the CO_2 removal section were examined. The second set of fans was selected because it is the lightest method.

The desiccant portion of the subsystem is identical to that described for the LiOH/desiccant approach while the molecular sieve portion is identical to that described for the molecular sieve/condenser approach.

Absolute criteria. - The design point of this system is a 65°F cabin temperature with a 44°F cabin dew point at nominal heat loads. The cabin dew point is limited to 44°F to prevent condensation in the sensible heat exchanger. A flow chart of the optimum subsystem is shown in figure 38.

The molecular sieve/desiccant concept meets performance requirements. It, like all the concepts requiring vacuum desorption, does not provide positive CO_2 control during launch and reentry. The concept has no special safety hazards although it does contain two items which require a vacuum, the molecular sieve and desiccant beds. This concept has an average reliability, but because of the large number of components has the lowest MTBF (failure frequency). The MTBF is approximately one quarter that of the LiOH/condenser concept. This type of hardware is well developed and will be flown shortly on Skylab.

Quantitative criteria. - The total equivalent weight of this concept is slightly above the median of the concepts considered. In initial and total program cost it is one of the most expensive concepts. It has the highest volume of all the concepts considered.

Qualitative criteria. - This subsystem is the most complex of those considered and is also one of the most inflexible to changes in crew size and heat load. It is less sensitive to changes in air cooled electrical heat loads than the condensing concepts. Due to the large number of cycling valves and rotating fans, this subsystem

SUBSYSTEM: CO_2, HUMIDITY & TEMPERATURE CONTROL

CONCEPT: MOLECULAR SIEVE/DESICCANT

FLIGHT AVAILABILITY: 1975

Mission Phase Application

Launch X Orbit X Reentry X Cruise ___

RELIABILITY: 0.999742 MTBF: 7,068

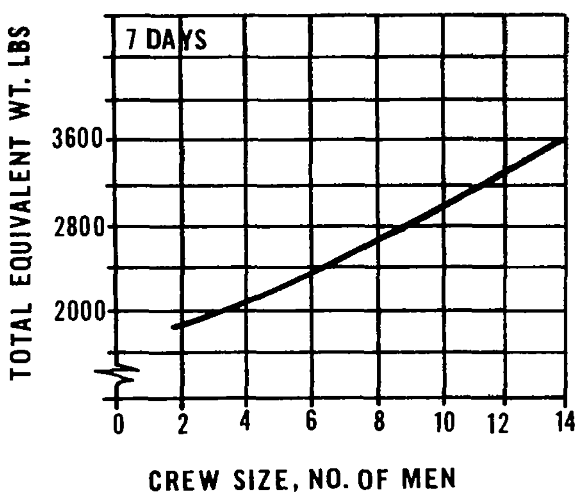
4 Men - 7 Days Plus 48 Hours Contingency

	Total Equivalent Wt. (lb)	Volume (ft^3)	Power (watts)
Installed Unit*	1679	46	565
Expendables	166	10	—
Power Equiv. Wt.	253	—	—
Totals*	2098	56	565

*Includes 951 pounds radiator penalty

Cost Factor	
Recurring -	1.5
Nonrecurring -	2.4
Total -	1.4

Crew Time (hrs)	
Scheduled —	0
Ground Refurbishment —	1.0



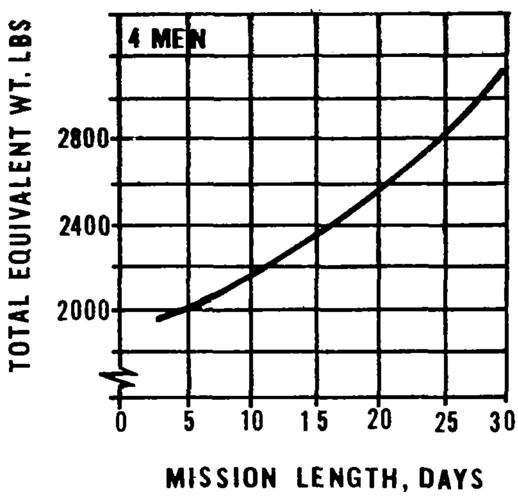


Figure 37. (Page 1 of 2)

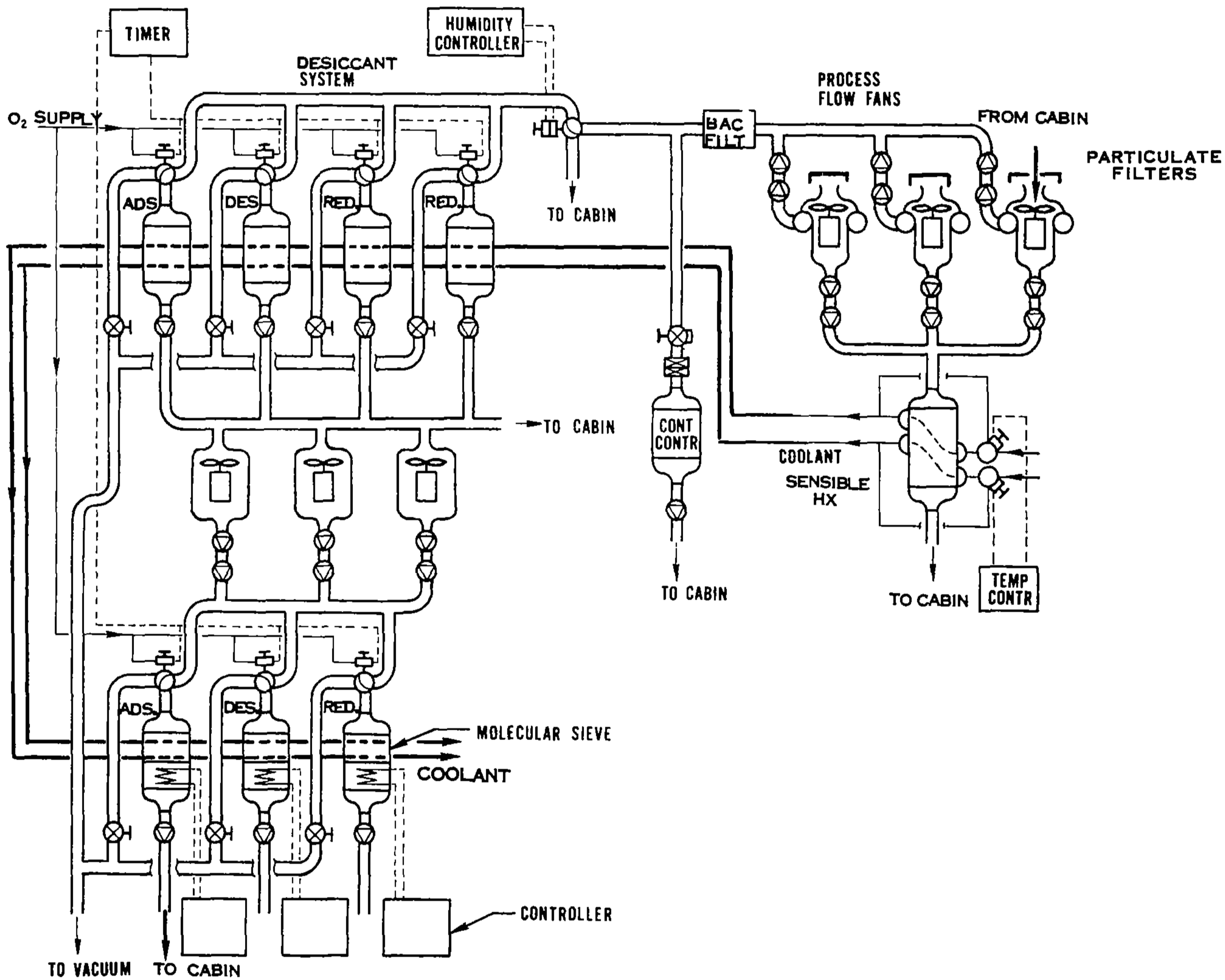


FIGURE 37. MOLECULAR SIEVE/DESICCANT CONCEPT (PAGE 2 OF 2)

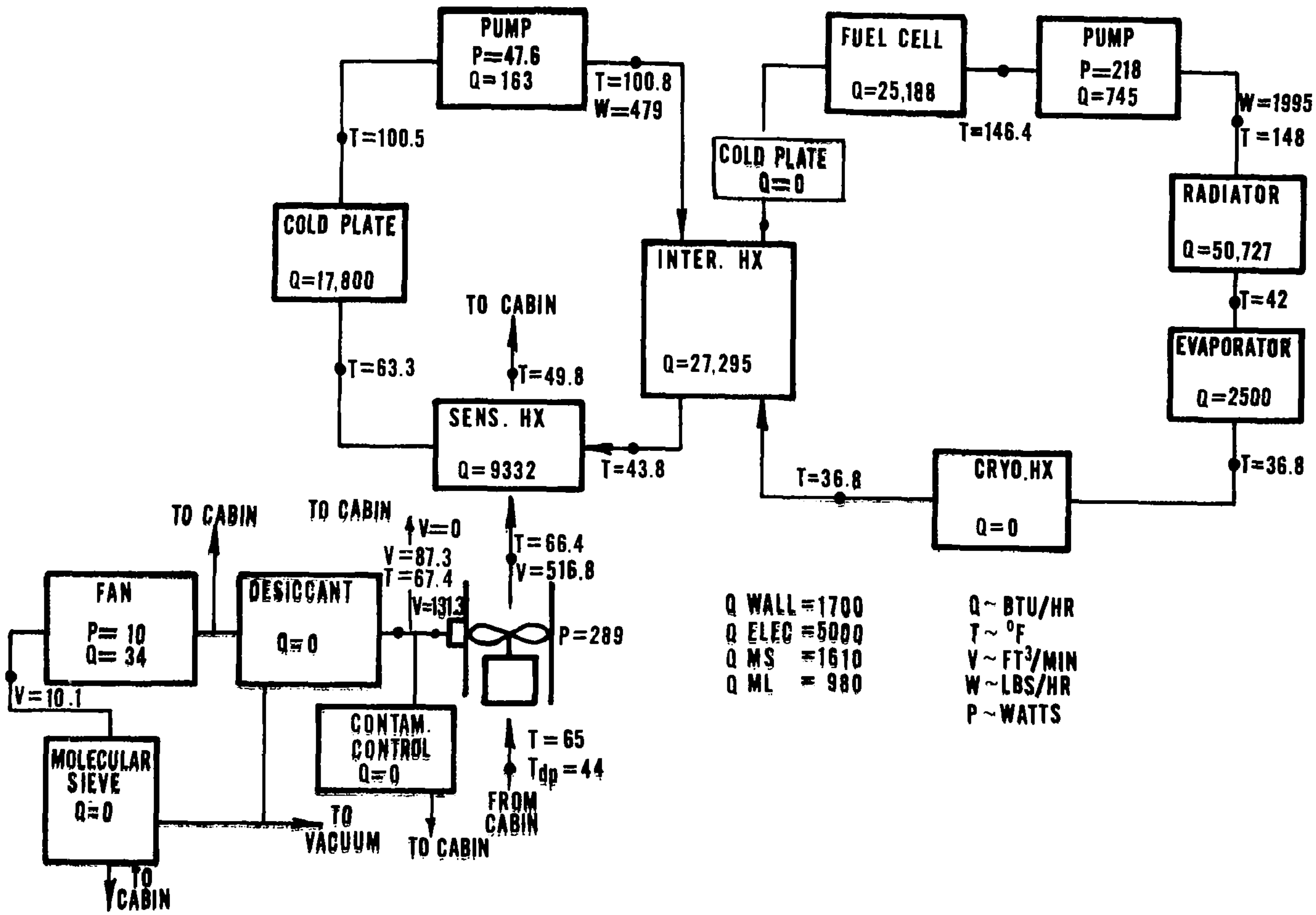


FIGURE 38, DESIGN POINT FLOW CHART, MOLECULAR SIEVE/DESICCANT CONCEPT is the least durable of those considered. Refurbishment consists of drydown and cleaning both the molecular sieve and the desiccant beds with hot dry, CO_2 free, gas and changing the charcoal canister, bacteria and particulate filters between each mission. This concept has the most equipment to checkout. It requires no in-flight maintenance.

Solid Amine (HS-C)

This candidate concept utilizes a proprietary Hamilton Standard vacuum regenerable solid amine (HS-C) for both CO_2 removal and humidity control. A characteristic of this solid amine is its strong affinity for CO_2 in the presence of water. In addition, the fact that water vapor desorbs more readily than CO_2 eliminates the possibility of water poisoning and precludes the requirement for a predryer.

A data sheet and a schematic of this approach are shown in figure 39. A single set of dual flow fans supplies the air for all of the required functions. The low pressure rise-high flow portion of the fan supplies air to the sensible heat exchanger. The high pressure rise-low flow section of the fan supplies air to the solid amine and contaminant control sections.

The solid amine portion of the concept is similar in operation to the desiccant portion of the LiOH/desiccant concept discussed previously. The major difference is that this concept is provided with double-ended desorption rather than single-ended desorption, as in the desiccant or molecular sieve approaches. This double ended desorption is used because lower pressure levels reduce the bed size.

Three methods of operation were considered:

- Cooled isothermal
- Non-cooled isothermal
- Thermal swing.

The cooled isothermal approach was selected based on similarity to the desiccant method of operation trade-off discussed earlier.

Absolute criteria. - The design point of the system is a 65°F cabin temperature with a 44°F cabin dew point at nominal heat loads. A flow chart of system performance is shown in figure 40. If the cabin dew point were to exceed 44°F, condensation would occur in the sensible heat exchanger. Solid amine, like the other vacuum desorbed concepts does not actively control CO_2 during launch and reentry. As discussed previously for the other concepts, this is acceptable. The concept

SUBSYSTEM: CO_2, HUMIDITY & TEMPERATURE CONTROL

CONCEPT: SOLID AMINE (HS-C)

FLIGHT AVAILABILITY: 1975

Mission Phase Application

Launch X Orbit X Reentry X Cruise ___

RELIABILITY: 0.999755 MTBF: 12,150

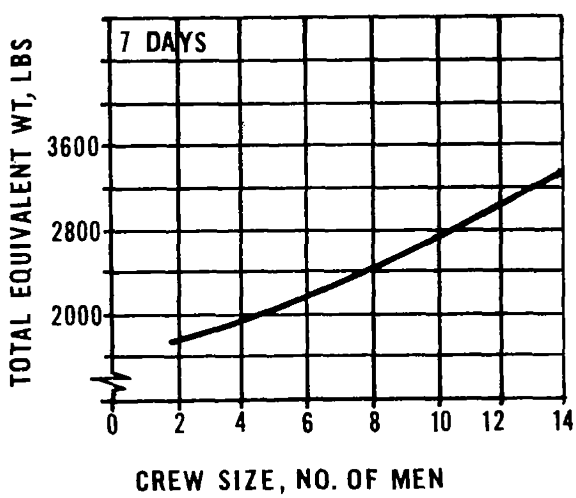
4 Men - 7 Days Plus 48 Hours Contingency

	Total Equivalent Wt. (lb)	Volume (ft^3)	Power (watts)
Installed Unit*	1654	45	567
Expendables	32	2	—
Power Equiv. Wt.	254	—	—
Totals*	1940	47	567

*Includes 936 pounds radiator penalty

Cost Factor	
Recurring -	1.2
Nonrecurring -	1.8
Total -	1.0

Crew Time (hrs)	
Scheduled -	0
Ground Refurbishment -	1.0



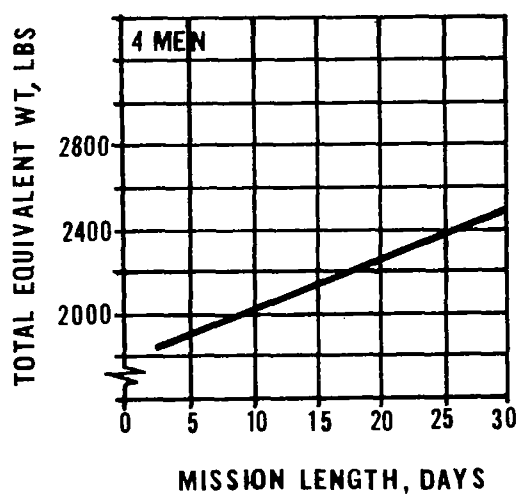


Figure 39. (Page 1 of 2)

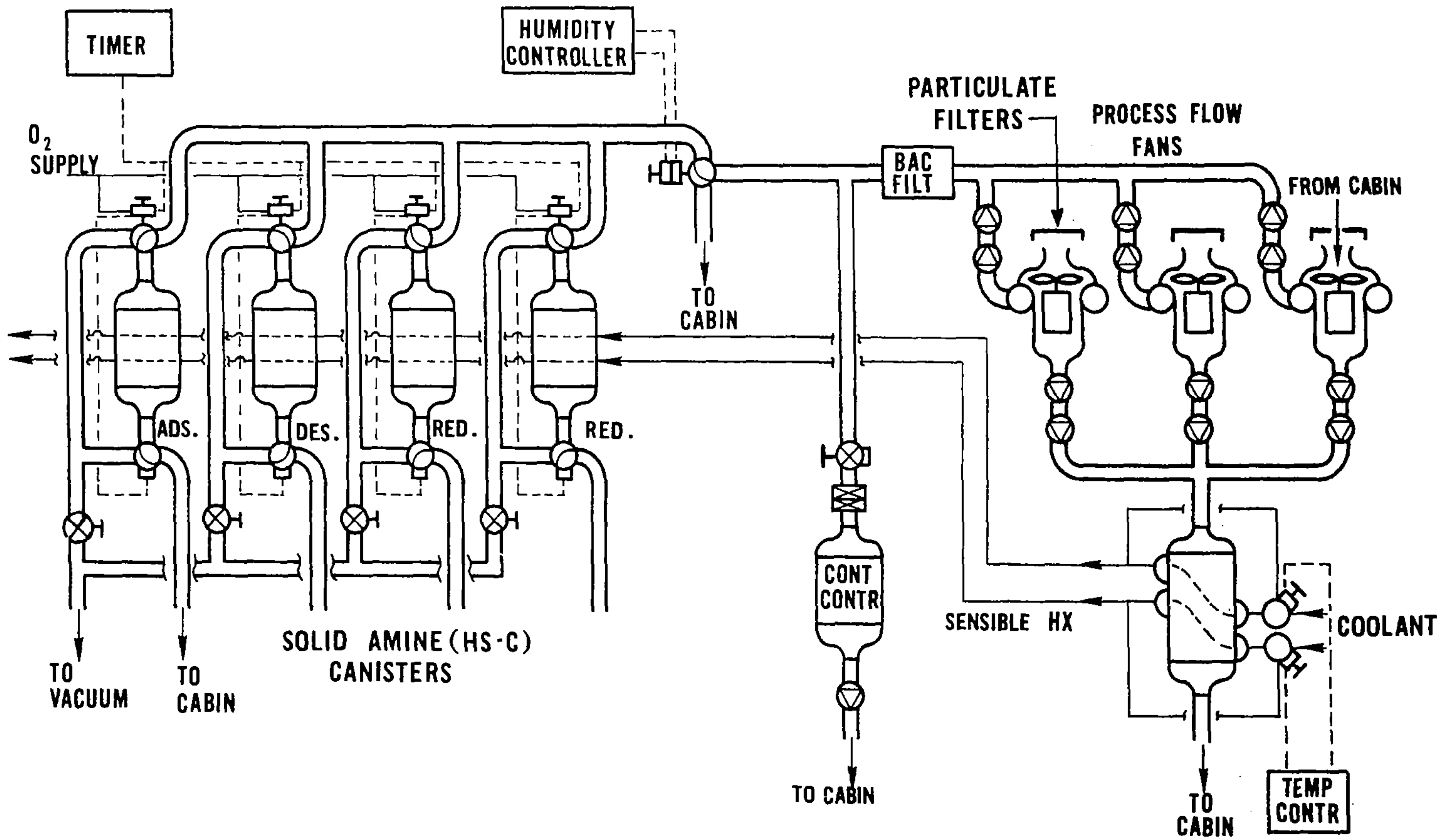


FIGURE 39. SOLID AMINE CONCEPT (PAGE 2 OF 2)

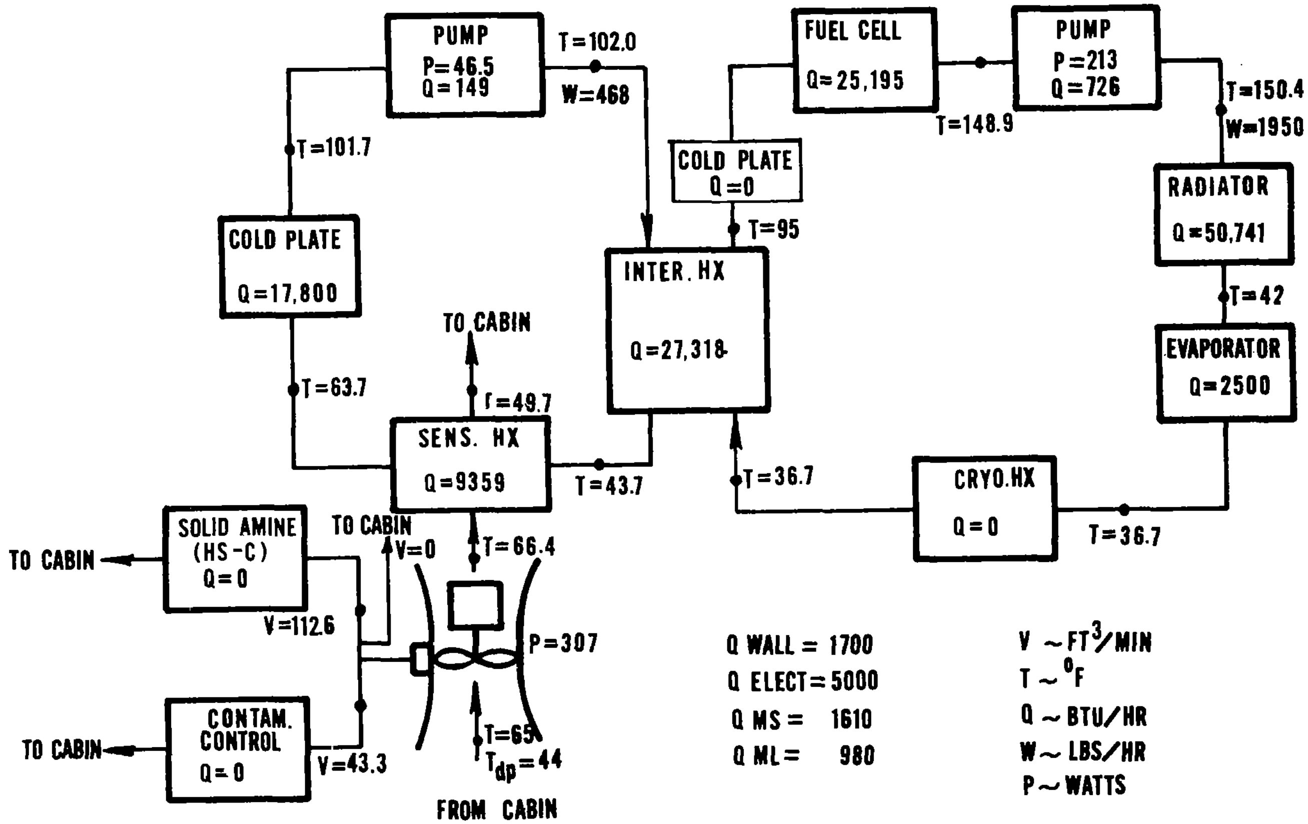


FIGURE 40. DESIGN POINT FLOW CHART, SOLID AMINE CONCEPT

requires a vacuum vent line. Reliability of this concept is the same as the LiOH/desiccant concept, but the MTBF is slightly lower due to the dual end desorption valves. The concept is in an earlier stage of development than the other candidates.

Quantitative criteria. - The solid amine concept is the lightest of all the concepts considered for crew sizes of 4 men or greater and mission lengths of 5 days or longer. The initial cost is the lowest of the regenerative concepts and total program cost is one of the lowest of the approaches considered. Its volume is above average.

Qualitative criteria. - The solid amine concept is the least complicated of the regenerative concepts, but it is still more complex than the LiOH/condenser approach. It is the least affected by increases in mission length. In addition, it is one of the most flexible with regard to increases in crew size, radiator influx, and air cooled electrical heat loads. Once the hardware is manufactured, the concept is rather inflexible to increases in latent load.

System durability is about average. Refurbishment requires dryout of the beds with either vacuum exposure or hot dry, CO_2 free, gas and replacement of the contaminant control canister and bacteria and particulate filters. Checkout is slightly better than average. No in-flight maintenance is required.

Hydrogen Depolarized Cell/Condenser

This candidate utilizes a hydrogen depolarized cell for CO_2 removal and a condenser for humidity control.

The hydrogen depolarized CO_2 concentrator is a fuel cell type device. The device consists of electrode pairs exposed on the cathode side to the cabin atmosphere and on the anode side to a hydrogen supply. A schematic of a basic cell showing the electrochemical reactions is shown in figure 41. The fuel cell reaction is used to establish a pH gradient between the electrodes. CO_2 is adsorbed at the cathode, due to the high hydroxyl concentration and rejected at the anode due to the low pH. Water is formed at the anode due to the fuel cell reaction and is evaporated into the air stream. Thus, CO_2 is concentrated at the anode and is vented overboard with any unreacted hydrogen and some water vapor.

The hydrogen depolarized cells are subject to dryout or flooding if the relative humidity of the inlet air flow falls outside of a relatively narrow band. Therefore, water sumps are added at the inlet of the subsystem to compensate for fluctuations in cabin relative humidity. The added weight of water storage sumps which permit operation over a wide range of inlet relative humidity, is compensated for by increased usage flexibility.

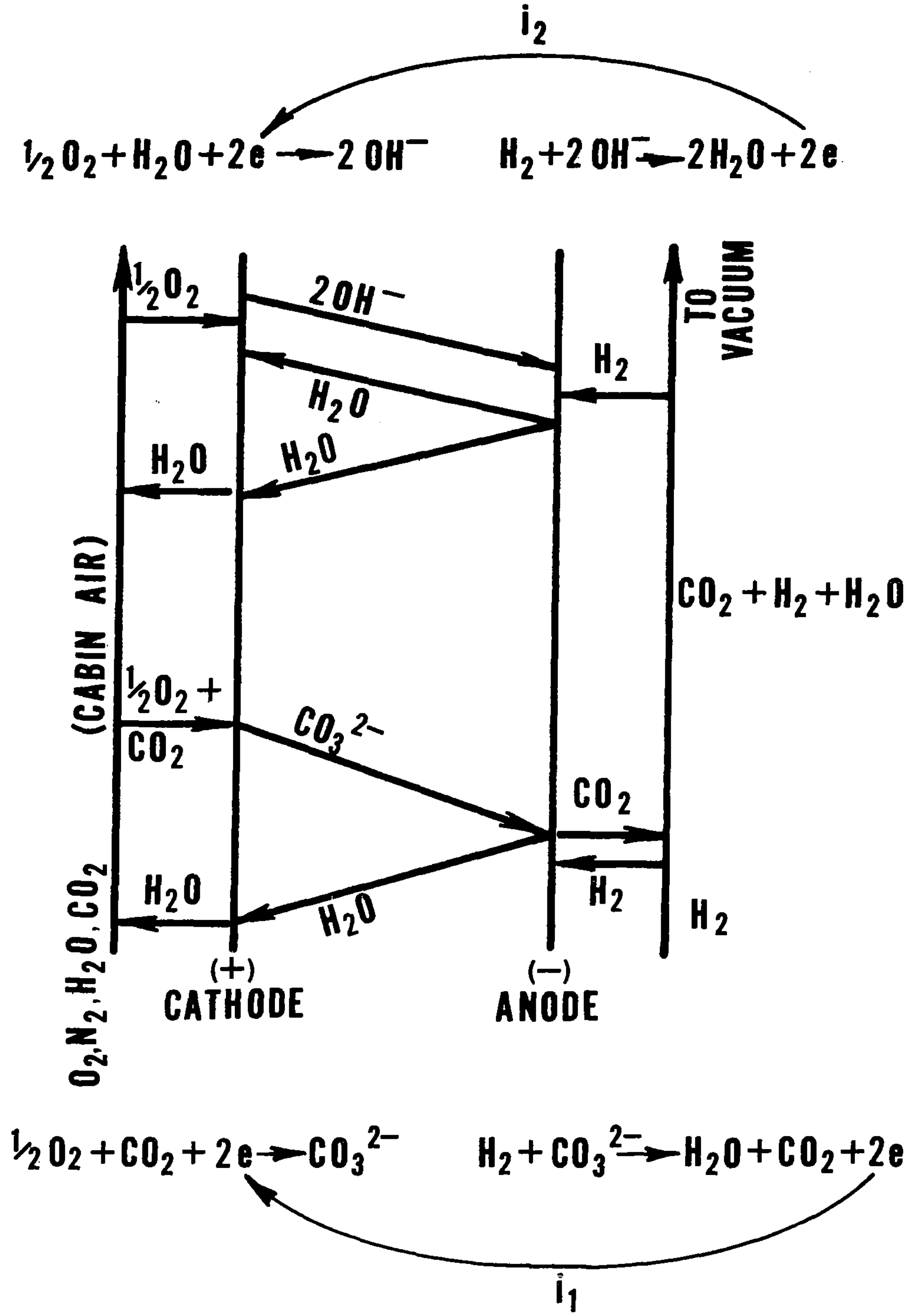


FIGURE 41. HYDROGEN DEPOLARIZED CELL REACTION

A data sheet and a schematic of this concept are shown in figure 42. To minimize fan power, a single set of fans provides flow for the condenser and hydrogen depolarized cell which are in parallel. The description of the condenser is similar to the other condenser concepts.

The hydrogen depolarized cell consists of five groups of cells, four of which are required to meet system performance. If an electrical failure occurs and a cell group becomes inoperative, it is shut down and performance is met utilizing the remaining cell groups. If a second failure occurs, a second cell group is shut down which will result in a rise in CO_2 partial pressure from 5 to 7 mm Hg,an acceptable fail safe condition. Because the fuel source is hydrogen, combustible detectors are placed with each group of cells to detect hydrogen leaks. Shutoff valves in the hydrogen supply lines permit isolation of the faulty cell group.

The hydrogen depolarized cell produces power (low voltage dc). No credit or penalty at this time has been assumed for the power produced by the cell (approximately 70 watts for 4 men), because it is not known if a low voltage - dc power requirement exists in the vehicle.

Pressure regulators are used to control the hydrogen inlet pressure upstream of an orifice so that a constant hydrogen inlet flow is maintained. The cell pressure is controlled by a group of pressure regulators. Triple redundancy is provided to meet the fail operational-fail safe requirement.

Absolute criteria. - A flow schematic of the optimized concept is shown in figure 43. This concept can meet all mission phase requirements, including ferry, and does not depend on system transients for CO_2 and humidity control. GSE is not required to condition the cabin atmosphere during prelaunch. The hydrogen fuel represents a potential explosion hazard. Electrical shutoff valves, combustible detectors, and alarms are required for safety. Reliability is about average while possessing the second highest MTBF. Development of this concept is now in progress and it is expected to be available by 1976.

Quantitative criteria. - This is the heaviest of the concepts evaluated. The large system impact on the latent load is a primary reason for this concept's high total equivalent weight. Initial cost is about average, but it has one of the lowest total program costs. Volume of this concept is about average.

Qualitative criteria. - This concept is simple, requiring one set of fans, a temperature control valve, and redundant hydrogen pressure regulators. It is fairly flexible from a fixed hardware standpoint. Alternate heat rejection concepts can be used for increased heat loads and crew size and additional modules can be placed in parallel for higher CO_2 removal rates. Subsystem weight increases very rapidly with increases in radiator penalty, heat loads, or crew size. Due to the small number of

SUBSYSTEM: CO_2, HUMIDITY & TEMPERATURE CONTROL

CONCEPT: HYDROGEN DEPOLARIZED CELL/CONDENSER

FLIGHT AVAILABILITY: 1976

Mission Phase Application

Launch X Orbit X Reentry X Cruise X

RELIABILITY: 0.999645 MTBF: 16,060

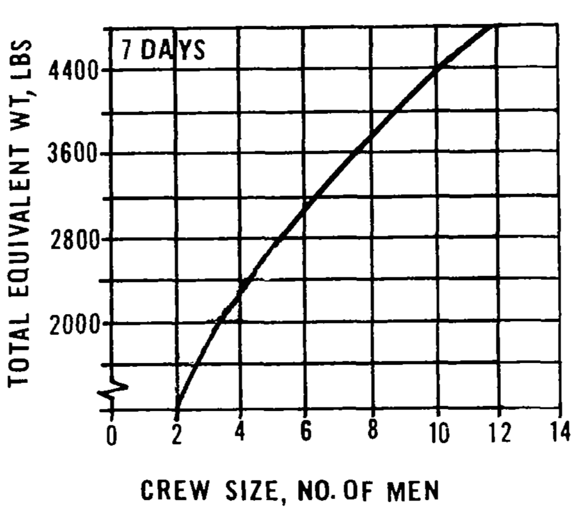
4 Men - 7 Days Plus 48 Hours Contingency

	Total Equivalent Wt. (lb)	Volume (ft^3)	Power (watts)
Installed Unit*	1804	43	723
Expendables	106	6	—
Power Equiv. Wt.	324	—	—
Totals*	2234	49	723

*Includes 1118 pounds radiator penalty

Cost Factor	
Recurring -	1.0
Nonrecurring -	2.0
Total -	1.0

Crew Time (hrs)	
Scheduled —	0
Ground Refurbishment —	0



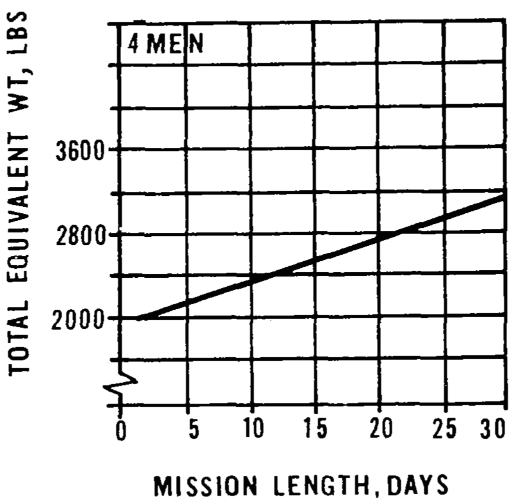


Figure 42. (Page 1 of 2)

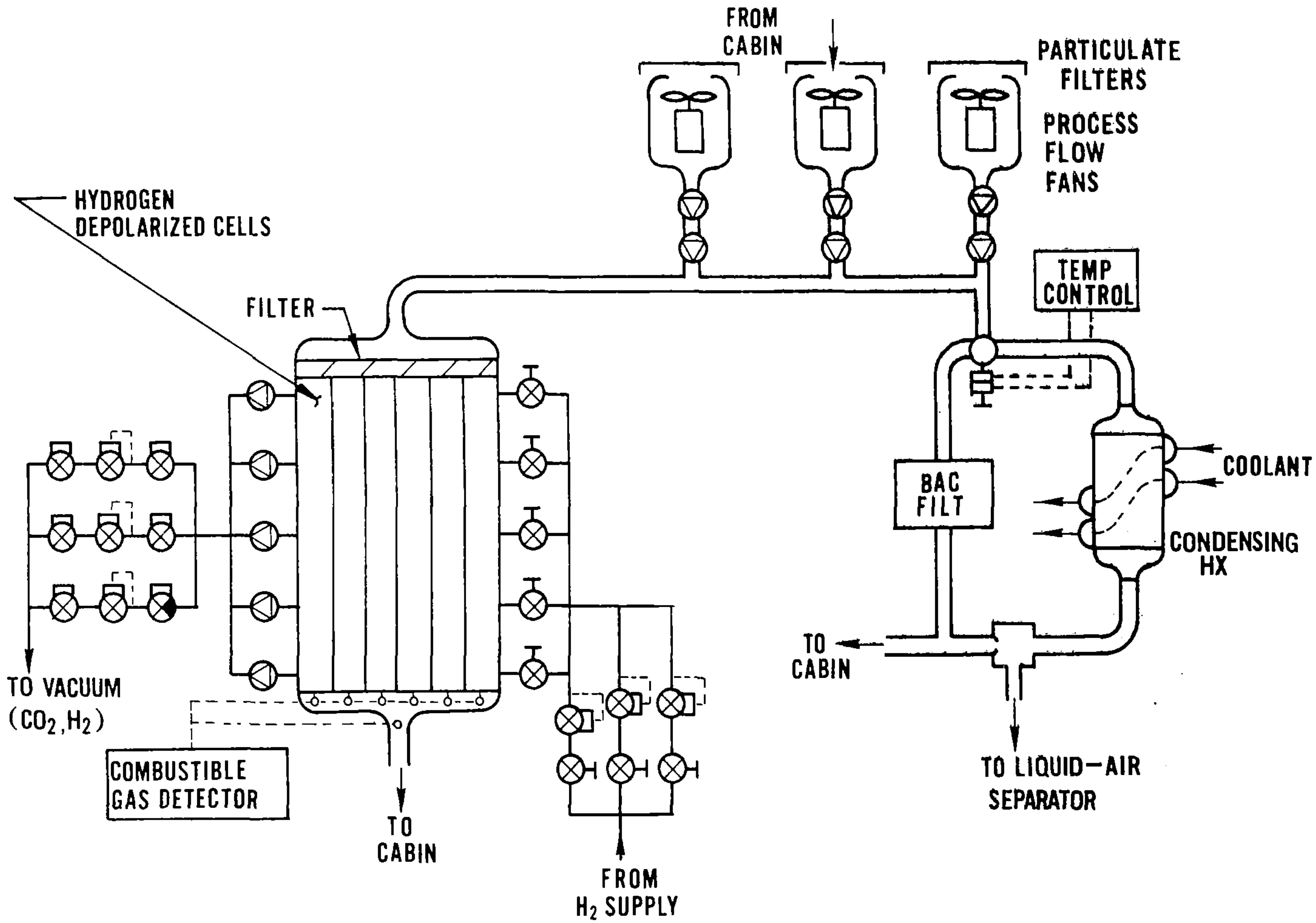


FIGURE 42. HYDROGEN DEPOLARIZED CELL/CONDENSER CONCEPT (PAGE 2 OF 2)

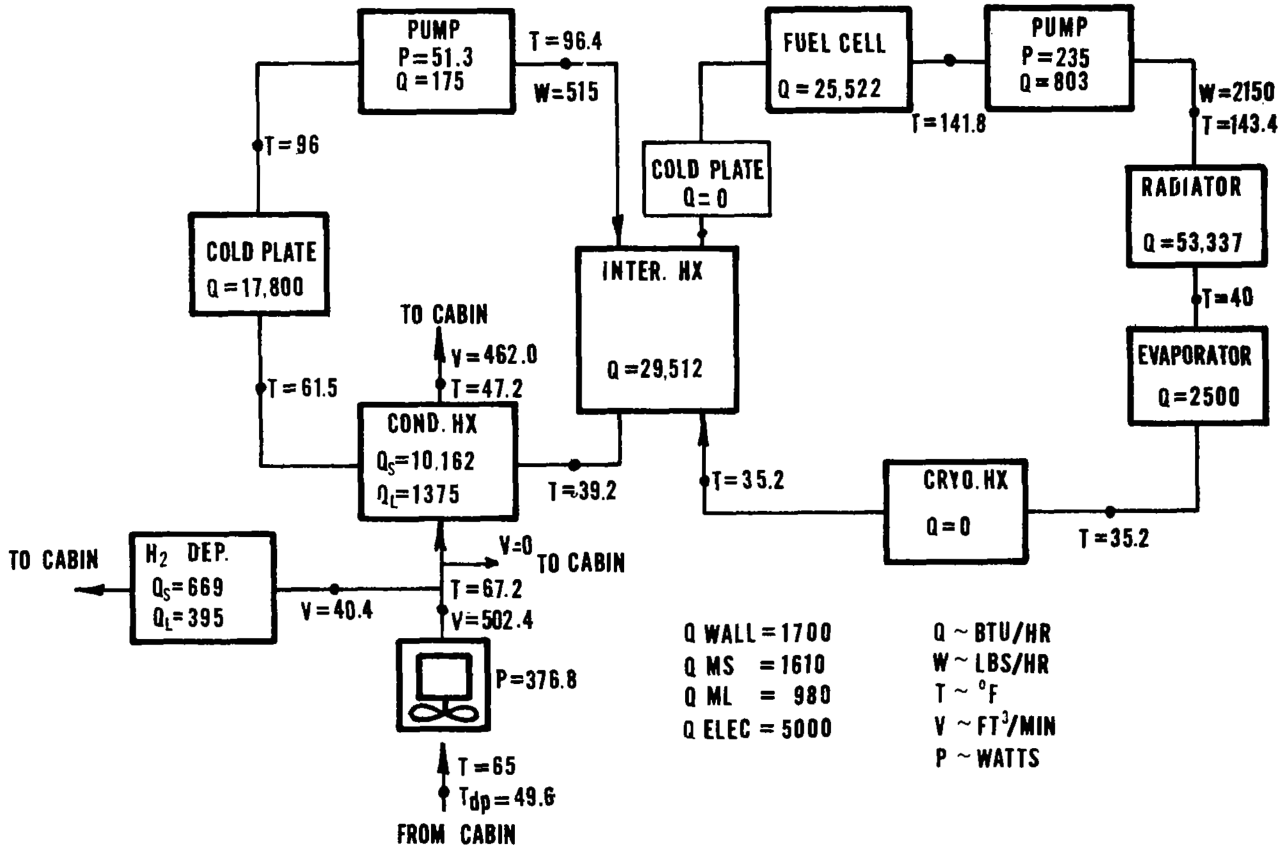


FIGURE 43. DESIGN POINT FLOW CHART, HYDROGEN DEPOLARIZED CELL/CONDENSER CONCEPT

components, the concept is very durable. Refurbishment requires changing the bacteria and particulate filters only. The expendable hydrogen is drawn from the "on board" tankage (OMS). The required amount of checkout is less than average and no in-flight maintenance is required.

Hydrogen Depolarized Cell/Desiccant

This candidate utilizes a hydrogen-depolarized cell for CO_2 removal and a regenerable desiccant (silica gel) for humidity control.

The description of the hydrogen-depolarized cell portion of this concept is identical to that of the hydrogen depolarized/condenser approach. The desiccant portion of the system is similar to the previously described desiccant approach. A single set of dual purpose fans supply air to the sensible heat exchanger, hydrogen depolarized cells, and the desiccant sections. The contaminant control canister is in series with the hydrogen depolarized cell section.

A data sheet and a schematic of this concept are shown in figure 44.

Absolute criteria. - A flow schematic of the optimized concept is shown in figure 45. This concept relies on system transients in order to control humidity during launch and reentry. GSE is needed to condition the atmosphere during prelaunch to control the humidity levels. The hydrogen fuel represents a potential explosion hazard. This concept has the highest reliability of those evaluated, but it also has one of the lowest MTBF. Development of this concept is now in progress and it is expected to be available by 1976.

Quantitative criteria. - This concept's total equivalent weight and volume is about average. It has the highest initial cost and the highest total program cost of the evaluated concepts.

Qualitative criteria. - This is one of the more complex approaches having temperature and humidity controllers and redundant hydrogen regulators. The desiccant portion of the system is inflexible once the hardware is sized. The hydrogen depolarized cell is more flexible in that the design is modular and can easily adapt to larger crew sizes by adding additional modules. Due to the heat and water vapor generated by the hydrogen depolarized cells, this concept is more sensitive to increased heat loads and crew size than the other desiccant concepts. The hydrogen depolarized cell approach uses less expendables than the LiOH or molecular sieve concepts, so the weight does not increase as rapidly with mission length. Due to the number of cycling valves, fans and pressure regulators, system durability is about average. The desiccant beds must be dryed out between missions with hot gas and the contaminant control canister and bacteria filter must be replaced. The required amount of checkout is about average and no in-flight maintenance is required.

SUBSYSTEM: CO_2, HUMIDITY & TEMPERATURE CONTROL

CONCEPT: HYDROGEN DEPOLARIZED CELL/DESICCANT

FLIGHT AVAILABILITY: 1976

Mission Phase Application

Launch X Orbit X Reentry X Cruise ___

RELIABILITY: 0.999782   MTBF: 8,404

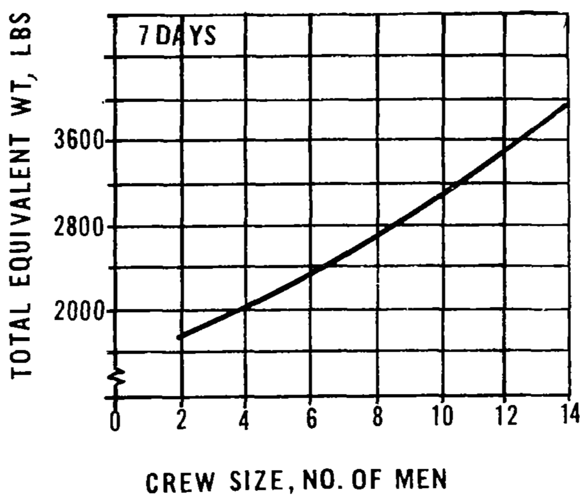
4 Men - 7 Days Plus 48 Hours Contingency

	Total Equivalent Wt. (lb)	Volume (ft^3)	Power (watts)
Installed Unit *	1666	44	610
Expendables	110	7	—
Power Equiv. Wt.	273	—	—
Totals*	2049	51	610

*Includes 881 pounds radiator penalty

Cost Factor	
Recurring -	1.7
Nonrecurring -	2.9
Total -	1.6

Crew Time (hrs)	
Scheduled -	0
Ground Refurbishment -	1.0



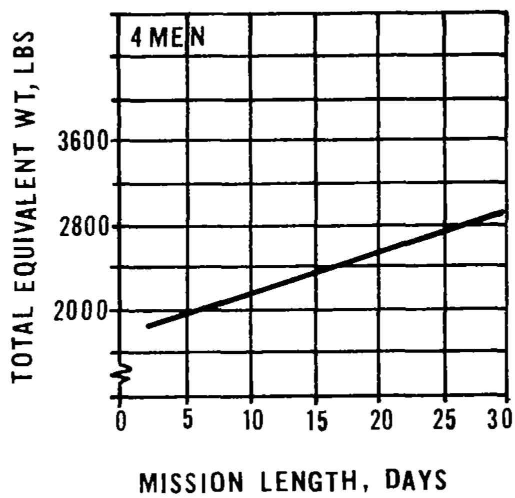


Figure 44. (Page 1 of 2)

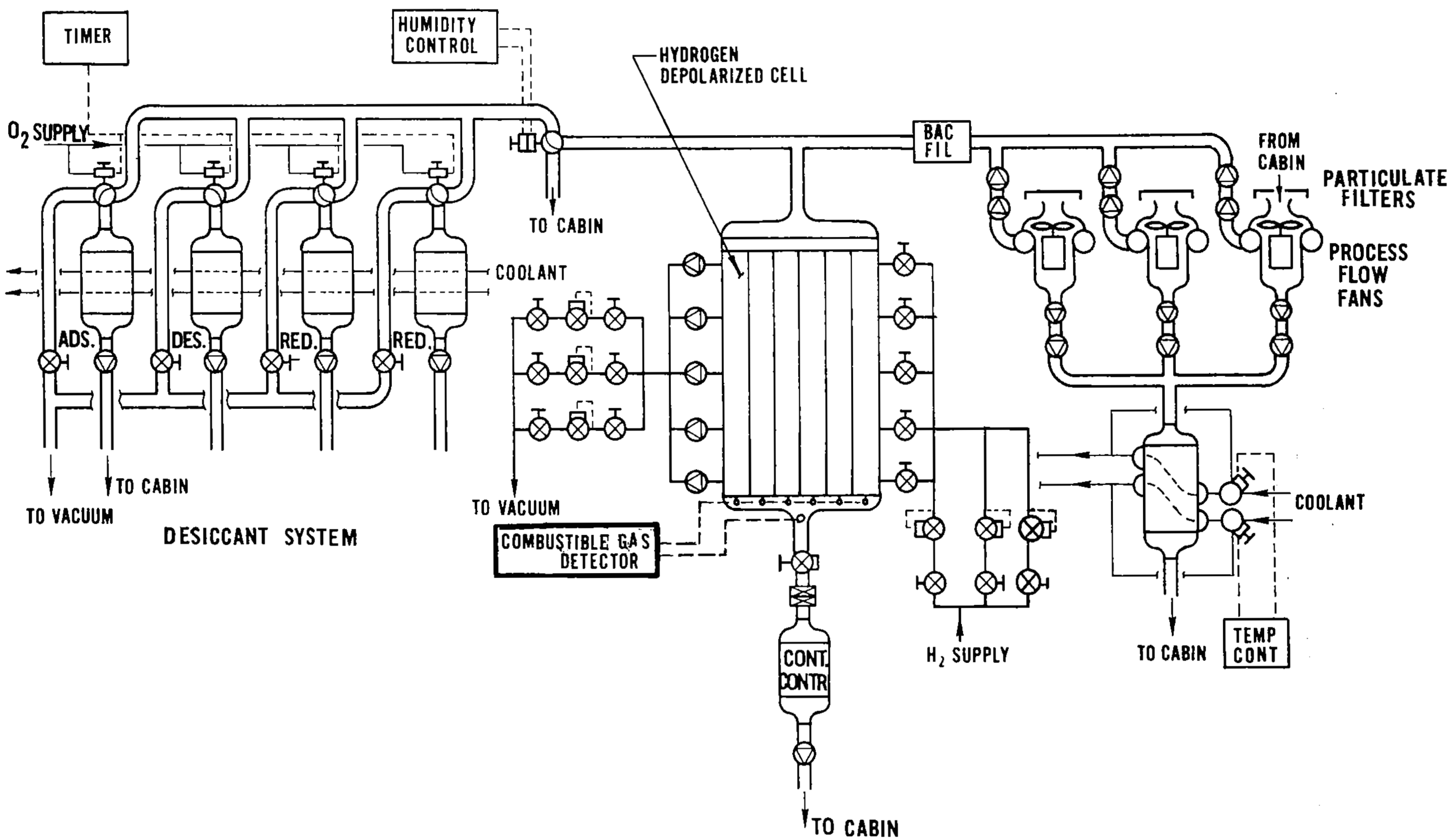


FIGURE 44. HYDROGEN DEPOLARIZED CELL/DESICCANT CONCEPT (PAGE 2 OF 2)

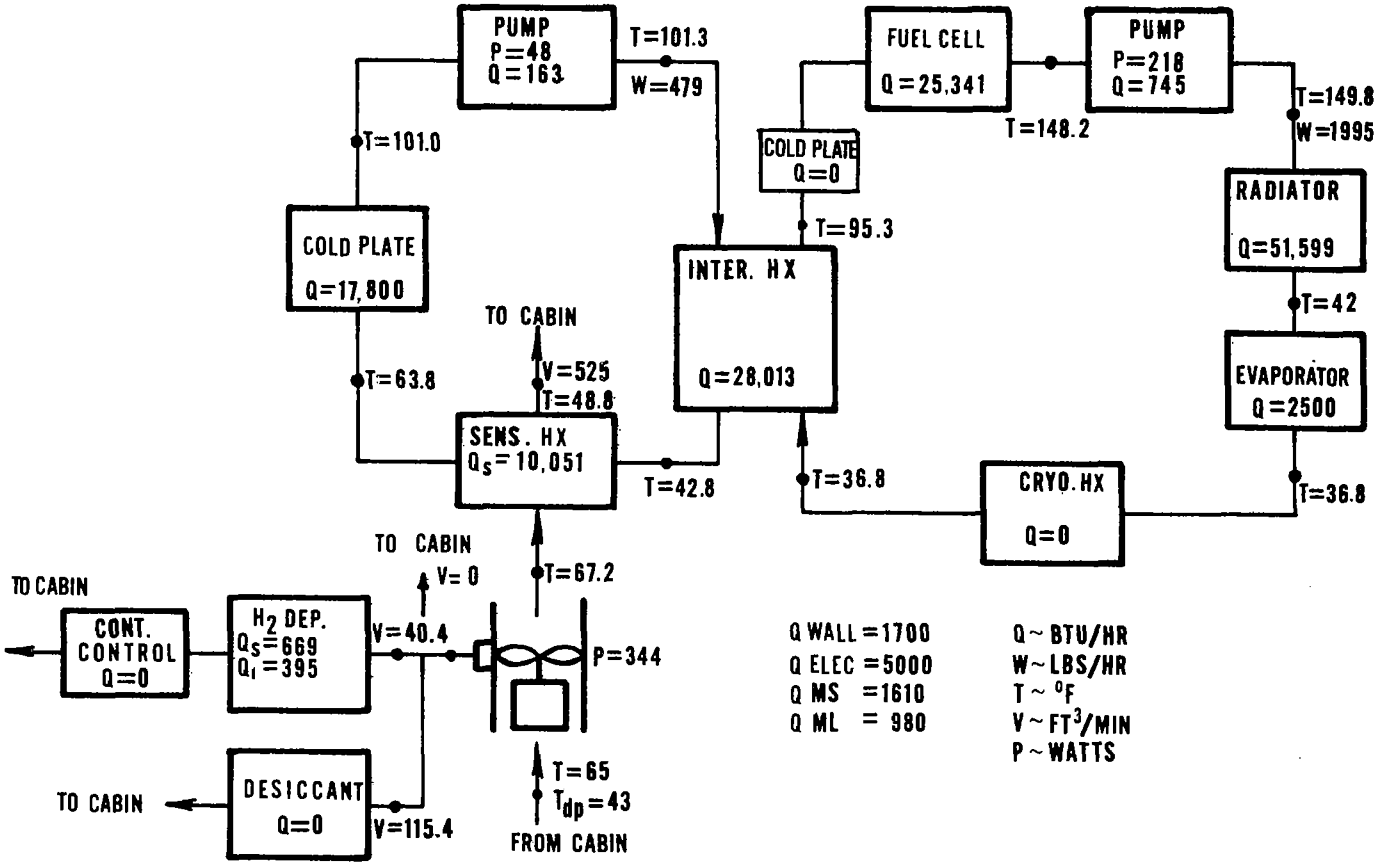


FIGURE 45. DESIGN POINT FLOW CHART, HYDROGEN DEPOLARIZED CELL/DESICCANT CONCEPT

Membrane Diffusion

Concentration by membrane permeation is a mass transfer process accomplished by a total pressure difference and selective diffusion. The degree of separation is dependent on the difference in transfer rates of the component gases across the membrane. Membranes have been developed that are highly permeable to CO_2. These membranes contain a CO_2 hydrolysis catalyst to increase permeability.

Inlet air drawn from the humidity control section is forced through the concentrator by a low pressure ratio fan. The air then passes through a heat exchanger which rejects the fan's heat. As the air passes through the stack, a portion of the flow permeates the walls. Because the membrane is more permeable to CO_2 than oxygen and nitrogen, the permeated gas has a higher CO_2 concentration. Air that does not permeate the walls is returned to the cabin. The permeated gas is pumped through a condenser separator and then overboard. A large quantity of water is delivered because of the membrane high water permeability. In fact, water permeability is 15 times greater than CO_2 permeability through the membranes. Calculations indicate that approximately 100 pounds of water vapor per day will be transferred through the membrane.

Absolute criteria. - The membrane diffusion concept considered has acceptable CO_2 control performance. However, when considering the significant impact on cabin humidity and the provisions required to resaturate the cabin atmosphere, the concept reduces to an unacceptable level. This is a complication not inherent in any of the other approaches considered. If the membranes should dry out, a potential fire hazard would exist. In addition, the cesium bicarbonate/sodium arsenate catalyst could poison the water condensate if extracted by the water vapor while passing through the membrane. However, since the water condensate is dumped overboard this is not critical. While these problems must be considered, they should be controllable.

The membrane diffusion concept, although now in the research phase, can be developed for a flight as early as 1978. Spectacular advances in membrane performance have occurred during the past few years and a two-man concentration unit has been integrated into a system designed for the F4C aircraft. However, this flight date is beyond that established for the space shuttle. Therefore, this concept is considered unacceptable and was not evaluated further.

EVALUATION AND SELECTION

A LiOH/condensing heat exchanger concept was selected for CO_2 removal and humidity control for the baseline EC/LSS for the orbital shuttle vehicle. This approach, has the smallest volume, lowest total program cost, the highest MTBF, is the least complex and the most durable. It also affords to the shuttle program the lowest cost through first flight. The LiOH/condenser concept, while not as flexible (in regard to weight) as the solid amine or LiOH/desiccant approaches, has the ability to adjust to mission requirements by utilizing more expendables. Longer missions would require additional LiOH cartridges. Larger crew sizes would require use of additional LiOH cartridges and a supplementary heat sink for the increased heat load. The solid amine (HS-C) concept had an almost equivalent quantitative evaluation including a lower weight difference of 149 lbs than the LiOH/condenser concept. It would be selected if mission requirements or heat loads increase as total program cost and weight would become much less than the selected LiOH concept.

The following sections compare the candidate concepts against the evaluation criteria for the four-man seven-day mission. An evaluation summary and data summary are presented in tables 16 and 17, respectively.

Absolute Criteria

Performance. - The membrane diffusion concept has marginal performance because it reduces the cabin humidity below acceptable levels, thereby requiring a humidifier to maintain an adequate cabin dew point.

All of the other concepts may, under low latent load conditions, allow the cabin dew point to decrease below 46°F. Otherwise, they all are equally as good from an on-orbit performance standpoint. During reentry, only LiOH/condenser and the H_2 depolarized/condenser concepts actively control the CO_2 and humidity levels while the other approaches rely on transient performance of the cabin or equipment. For this reason, LiOH/condenser and the hydrogen depolarized/condenser concepts are rated higher than the other approaches.

Safety. - The items considered in the safety criteria are: (1) fire hazard; (2) atmosphere contamination; (3) bacteriological build-up; and (4) direct leaks from cabin to vacuum. Each of the concepts contains one or more of the above problems. Both LiOH approaches can contaminate the cabin atmosphere. The solid amine, and molecular sieve and desiccant approaches can result in a leak to vacuum via the CO_2 removal and/or desiccant beds. Since each concept has one potential problem, all of these concepts are considered equal from a safety standpoint and are rated Good.

The presence of hydrogen and oxygen with the hydrogen depolarized concepts results in a potential fire or explosion hazard and, therefore, a Fair safety rating. A potential fire hazard with the membrane diffusion system is also present.

Reliability. - All candidate concepts had acceptable reliability. A summary of the reliability and failure rates for the seven approaches is shown in table 17.

TABLE 16

EVALUATION SUMMARY - CO_2, HUMIDITY, AND TEMPERATURE CONTROL

	Criteria	Candidate Concepts				
		LiOH/ Condenser	LiOH/ Desiccant	Molecular Sieve/ Condenser	Molecular Sieve/ Desiccant	Solid Amine (HS-C)
Absolute	Performance	Very Good	Good	Good	Good	Good
	Safety	Good	Good	Good	Good	Good
	Reliability	Very Good	Good	Good	Fair	Good
	Avail. /Conf.	Very Good	Good	Good	Good	Good
Quantitative	Total Equivalent Weight	Very Good	Very Good	Fair	Good	Very Good
	ROM Cost	Very Good	Fair	Good	Fair	Very Good
	Volume	Very Good	Very Good	Fair	Fair	Good
				Eliminated	Eliminated	
Qualitative	Complexity	Very Good	Good			Good
	Flexibility	Good	Fair			Very Good
	Durability	Very Good	Good			Good
	Refurbishment	Very Good	Fair			Good
	Checkout Capability	Very Good	Good			Good
	Maintainability	Good	Good			Very Good
		Selected	Eliminated			Eliminated

TABLE 16 (Concluded)

EVALUATION SUMMARY - CO_2, HUMIDITY, AND TEMPERATURE CONTROL

Criteria		Candidate Concepts				
		Hydrogen Depolarized Cell/Condenser	Hydrogen Depolarized Cell/Desiccant	Membrane Diffusion		
Absolute	Performance	Very Good	Good	Fair		
	Safety	Fair	Fair	Fair		
	Reliability	Good	Fair	Not Evaluated		
	Avail. /Conf.	Fair	Fair	Poor		
				Eliminated		
Quantitative	Total Equivalent Weight	Fair	Good			
	ROM Cost	Very Good	Fair			
	Volume	Good	Good			
		Eliminated	Eliminated			
Qualitative	Complexity					
	Flexibility					
	Durability					
	Refurbishment					
	Checkout Capability					
	Maintainability					

TABLE 17

DATA SUMMARY - CO_2, HUMIDITY AND TEMPERATURE CONTROL

Subsystem	MTBF Hrs	Fixed Weight lbs.	Power Watts	Total Equivalent Weight, lbs.	Cost Factors Through First Flight	Total Program	Volume, ft^3	Crew Time hrs.
LiOH/Condenser	41, 625	1577	722	2089	1.0	1.0	44	1.84
LiOH/Desiccant	12, 578	1547	595	2006	1.9	1.6	45	2.84
Molecular Sieve/ Condenser	11, 908	1668	713	2159	1.8	1.1	55	1.00
Molecular Sieve/ Desiccant	7, 068	1679	565	2098	2.2	1.4	56	1.00
Solid Amine (HS-C)	12, 150	1654	567	1940	1.6	1.0	47	1.00
Hydrogen Depolarized/ Cell/Condenser	16, 060	1804	690	2234	1.8	1.0	49	0.00
Hydrogen Depolarized Cell/Desiccant	8, 404	1666	610	2049	2.6	1.6	51	1.00

The LiOH/condenser has the highest MTBF because it is the simplest and has the fewest parts. The other concepts are more complex as indicated by their MTBF and are rated accordingly.

Availability/confidence. - The LiOH/condenser approach received the highest rating because it has flown on Mercury, Gemini and Apollo missions. The molecular sieve/condenser is rated Good because of its application for Skylab. The LiOH and molecular/sieve desiccant approaches and the solid amine concept are considered to be roughly equal to the molecular sieve/condenser concept and are rated Good. The hydrogen depolarized concepts are rated lowest since they are presently in an earlier state of development. The membrane diffusion concept will not be available by 1978, and, therefore, is considered unacceptable.

The result of the comparison is that the membrane diffusion concept is eliminated and all of the other approaches meet the absolute criteria with the LiOH/condenser except ranking higher than the others.

Quantitative Criteria

Total equivalent weight. - The effect of coolant flow, crew size, mission length on total equivalent weight are shown in figures 46, 47 and 48 respectively. As shown, the solid amine concept has the lowest total equivalent weight at the nominal design condition, for all crew sizes above four men, and for all missions in excess of five days. For missions shorter than five days, the LiOH/desiccant subsystem is the lightest and for crew sizes less than four men, the LiOH/condenser and the hydrogen depolarized/condenser subsystems are the lightest. The spread in total equivalent weight at the nominal design conditions is within 10% of the median subsystem concept weight.

ROM cost. - A relative cost factor comparison, based on total program cost and cost through first flight, presented in table 17. The total program cost includes the cost through first flight plus the hardware cost of five vehicles plus spares and expendables cost for 500 missions. The results indicate that the LiOH/condenser, solid amine, and the hydrogen depolarized/condenser concepts all have the same total program cost. The molecular sieve/condenser concept is 10% more costly and the desiccant version of the molecular sieve is 40% more costly. The LiOH/desiccant and hydrogen depolarized/desiccant concepts are both 60% more costly than the LiOH/condenser concept.

The cost through first flight is noted because it shows the cost relationship of an expendable (LiOH) versus a regenerative (all other competing concepts) subsystems. The expendable subsystem has the lowest initial cost while the regenerative subsystem cost appreciably more. This factor is considered significant for the shuttle.

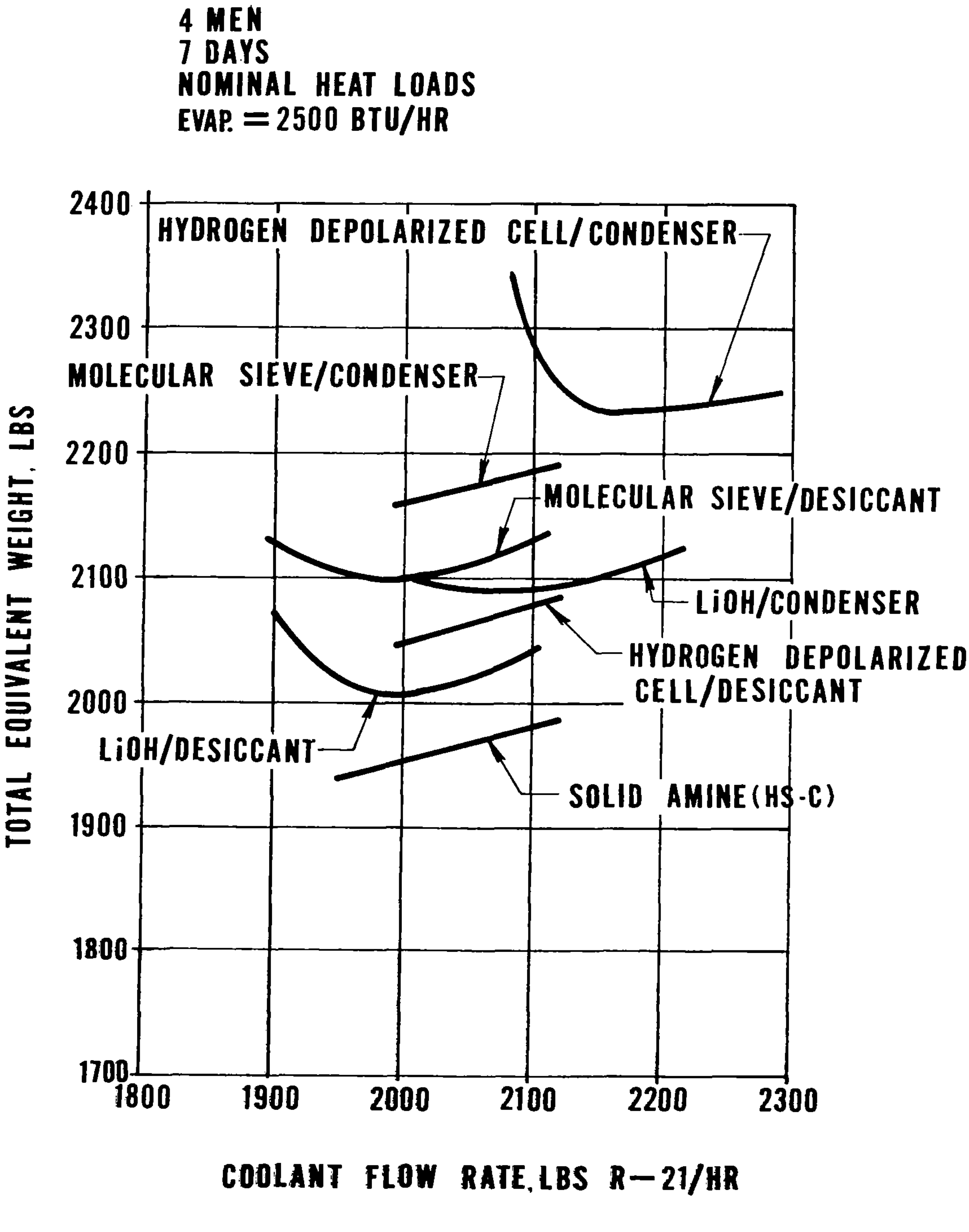


FIGURE 46. TOTAL EQUIVALENT WEIGHT VERSUS COOLANT FLOW RATE

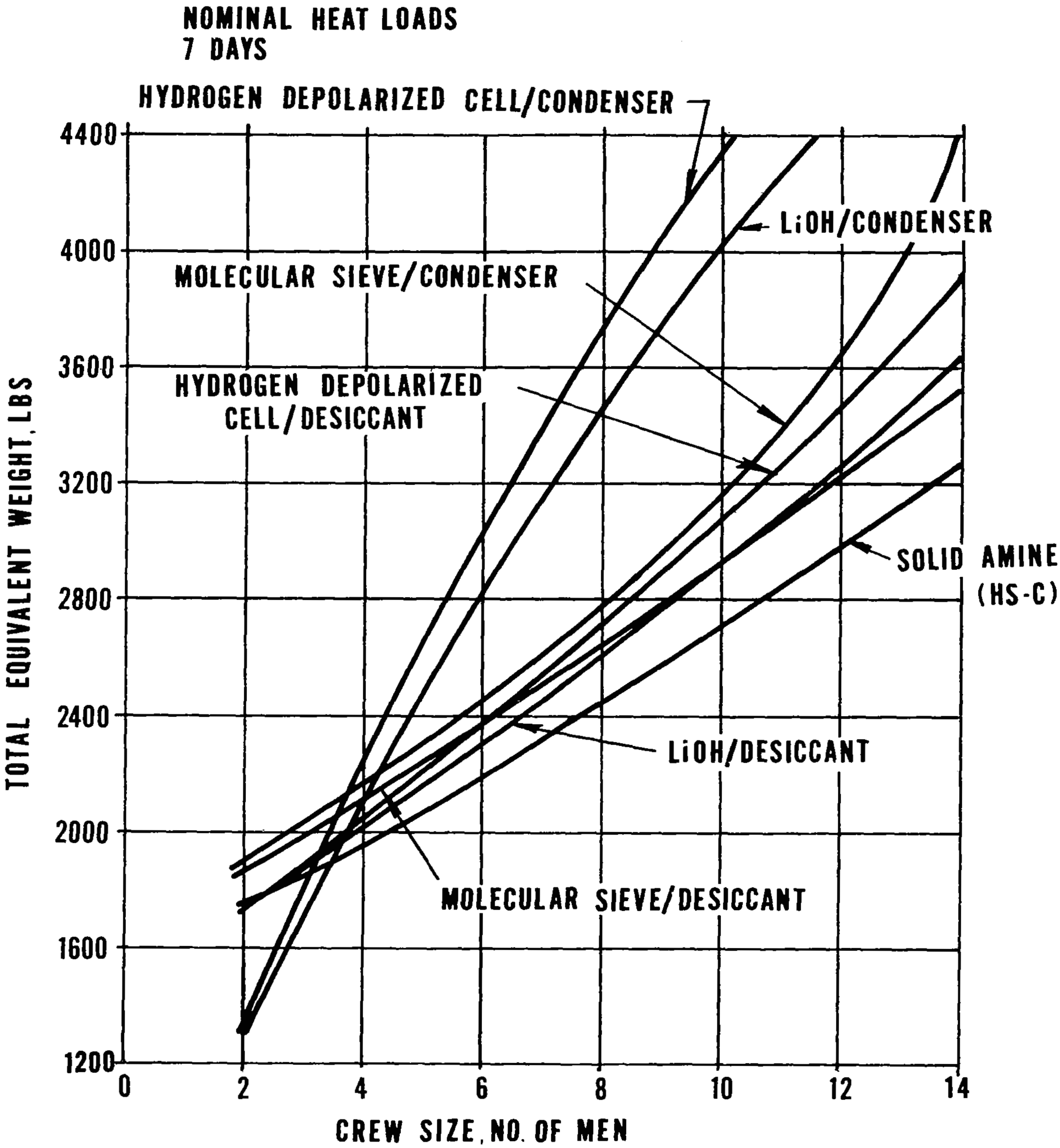


FIGURE 47. TOTAL EQUIVALENT WEIGHT VERSUS CREW SIZE

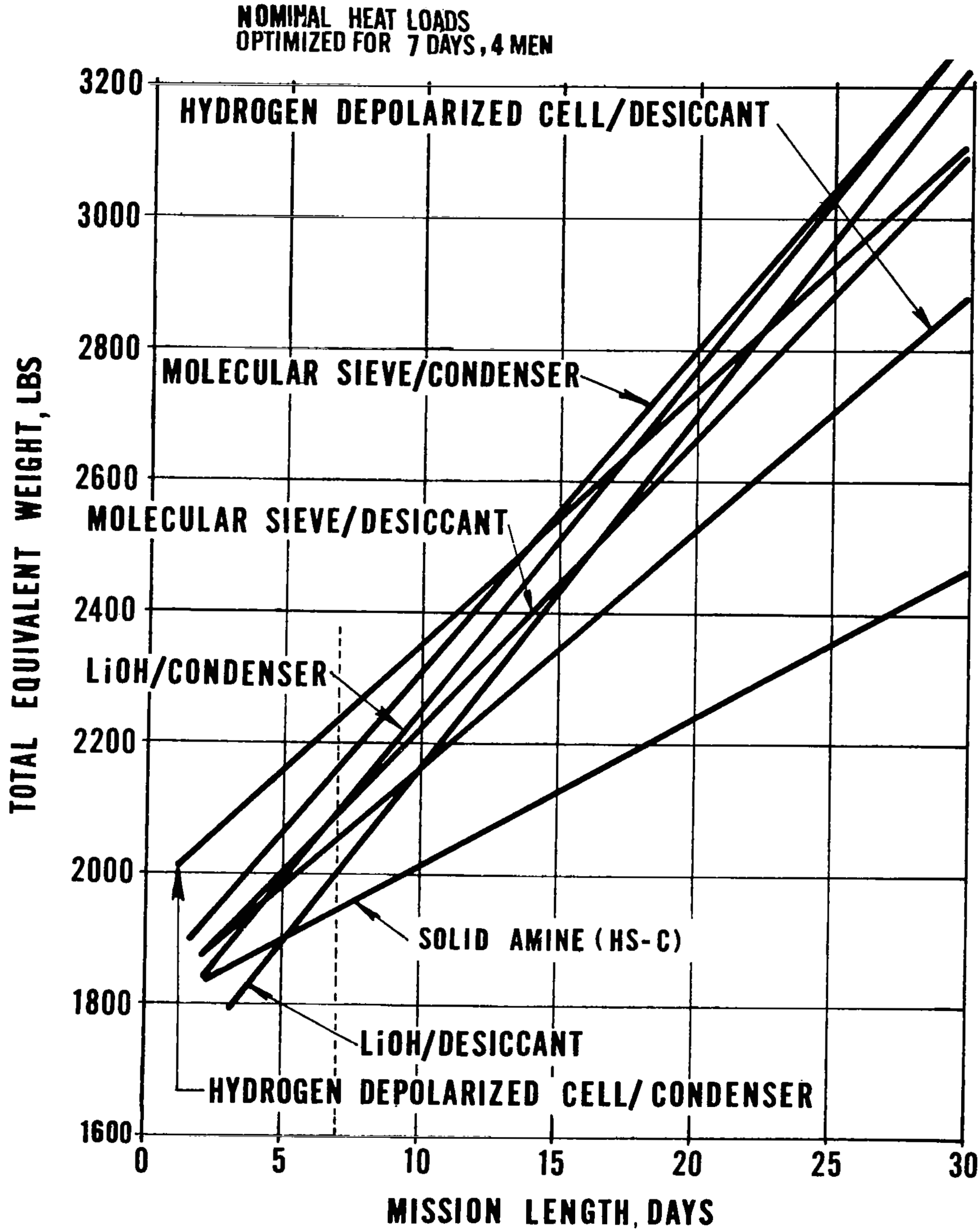


FIGURE 48. TOTAL EQUIVALENT WEIGHT VERSUS MISSION LENGTH

Volume. - A summary of the volume for each candidate concept is also shown in table 17. As shown, the LiOH approaches have the smallest volume. This is due to the fact the LiOH can be easily and densely packaged. The solid amine and the hydrogen depolarized concepts both have slightly larger volumes while the molecular sieve concepts have the largest volume. All of the concepts are within 15% of the median value.

After completing the quantative evaluation, both hydrogen depolarized concepts were dropped from further consideration. The hydrogen depolarized/condenser concept because of its high total equivalent weight and the hydrogen depolarized/desiccant concept because of its high cost. Both the molecular sieve concepts were also eliminated from further consideration as they had higher volumes and poorer overall ratings compared to the LiOH and solid amine concepts.

The three concepts remaining are carried through the Qualitative Criteria. These are LiOH/condenser and solid amine which are rated approximately equal and LiOH/desiccant which is rated lower.

Qualitative Criteria

Complexity. - The LiOH/condenser concept is rated Very Good because of fewer total components and fewer dynamic components. The other approaches are more complicated and are rated Good.

Flexibility. - For increases in crew size, cabin air heat loads and radiator influx, and decreases in the amount of water available for supplementary heat rejection, the solid amine and LiOH/desiccant concepts increase less in weight than the LiOH/condenser concept. For increases in mission length, the solid amine concept has by far the lowest increase in total equivalent weight.

For a fixed size subsystem, increases in crew size or heat loads would have a major effect on all of the concepts. To increase the CO_2 removal capacity, all of the approaches would require larger fans. In addition, the LiOH concept would require extra cartridges. The solid amine concept performance could improve somewhat if the adsorb/desorb cycles were changed; at the expense of ullage. For humidity control under these conditions, it is possible to use a supplimentary expendable heat sink to obtain a colder coolant temperature for additional water removal with a condenser concept. For the desiccant and solid amine concepts, the air flow must be increased and the cycle time shortened.

The solid amine concept is rated Good because of its ability to handle longer mission lengths and provide flexibility to changes in requirements. The LiOH/ condenser approach is rated Good because of its ability to handle increased crew sizes with increased expendables. The LiOH/ desiccant approach is rated Fair.

Durability. - The LiOH/condenser concept is rated Very Good due to the low amount of rotating equipment, cycling valves and electronic controllers required. The LiOH/desiccant and solid amine concepts contain more cycling valves and electronic controllers and are rated Good.

Refurbishment. - The LiOH/condenser concept requires refurbishment of the particulate and bacteria filters and LiOH cartridges, and dryout of the beds after every mission. The solid amine requires replacement of the charcoal canister. The LiOH/desiccant requires replacement of all three items plus purging of the desiccant beds.

Checkout capability. - The LiOH condenser concept has the least amount of equipment to check out prior to launch and is rated Very Good. The LiOH/desiccant and solid amine concepts with more equipment are rated Good. All of the approaches have at least one component that cannot be checked out prior to launch, such as; LiOH, desiccant beds, charcoal canisters, etc.. These items are installed or regenerated during refurbishment and are sealed until launch.

Maintainability. - The solid amine concept requires no in-flight maintenance and is, therefore, rated Very Good. The LiOH concepts require changing LiOH cartridges once per day and are rated Good.

Selection

A review of all the criteria of the three remaining candidate concepts shows that the LiOH/condenser has outstanding absolute and qualitative features and is Very Good on total program cost, volume and cost through first flight. For the above reasons, it LiOH/condenser approach is selected for the shuttle baseline mission. However, it should be pointed out that it is heavier than the solid amine (149 lb) or LiOH/ desiccant (83 lb) concepts.

The solid amine is slightly behind the selected approach in the absolute criteria, primarily because it is less developed than the other approaches at this time. It is expected that reasearch effort on solid amine will continue between now and the start of Phase C and at that time the knowledge accumulated on solid amine will be comparable to that accumulated on molecular sieve prior to the start of the design phase on the MOL and Skylab programs. If the requirements change to increase the amount of air cooled electronic equipment, increase the crew size, increase the radiator weight penalty or decrease the amount of fuel cell water available to evaporate, the solid amine concept would be selected. The solid amine concept, with its low weight and cost, good flexibility and growth potential should be considered as a good alternate concept.

IMPACT OF MISSION PARAMETERS

The impact of the following parameters on the concepts total equivalent weight was investigated.

- Crew Size
- Mission Length
- Cabin Air Cooled Electrical Heat Load
- Total Heat Load
- Radiator Influx

Effect of crew size and mission length are evaluated for all of the subsystems. The effect of cabin air cooled electrical heat load, total heat load, and radiator influx are shown for a typical condensing type concept and a typical desiccant type concept. The solid amine concept is also shown.

Crew Size

The effect of crew size on total equivalent weight is shown in figure 47. Total equivalent weight of the solid amine concept increases at a slightly slower rate than the rest of the concepts. The fastest rate of increase is in the LiOH/condenser and hydrogen depolarized/condenser condenser concepts. Concepts utilizing condensers result in a faster rate of weight increase due to the larger latent load that must be rejected by the radiator. In order to reject this latent load, a larger radiator, higher coolant flow rates and larger heat exchangers are required.

Mission Length

The effect of mission length on the total equivalent weight of the various concepts is shown in figure 48. Solid amine shows a marked advantage over the other approaches which are all about equal. For a 30-day mission, the solid amine approach is approximately 25 percent lighter than the other concepts. This is primarily due to the low ullage losses from the amine canisters since the amine does not adsorb nitrogen.

The molecular sieve concepts have about the same usage rate of expendables (ullage) as the LiOH approaches. The hydrogen depolarized concept is slightly lower in expendables (hydrogen) than either the LiOH or molecular sieve approaches, but much higher than the solid amine.

Cabin Air Cooled Electrical Heat Load

As the proportion of the electrical heat that is air cooled increases, the total equivalent weight of the subsystem also increases. To remove the heat at lower temperature levels the air flow rate must increase, heat exchangers become larger and coolant flow rates increase. The main difference between the concepts is that condensing approaches must remove and reject the latent heat load as well as the sensible heat load. As an example, a typical condensing concept (LiOH/condenser), desiccant concept (molecular sieve/desiccant) and the solid amine concept were compared with the air cooled electrical heat load varying from 2280 Btu/hr (approximately 10% of total) to 8300 Btu/hr (36% of total). The results are shown in figure 49. Over this range, the weight of the condensing approach varies 660 pounds while the desiccant and solid amine concepts vary 450 pounds and 610 pounds respectively. The solid amine concept is lighter over the whole heat range. The LiOH/condenser concept is lighter than the molecular sieve/desiccant concept at the low electrical air heat loads and heavier at the high values. Below the nominal heat load condition the minimum coolant flow rate is set by the restriction in fuel cell outlet temperature to a maximum of 150°F. At heat loads above the nominal condition, the coolant flow rate for the condensing concept is optimized at higher values (in order to remove the latent heat load) and results in heavier total equivalent weights than the desiccant and solid amine approaches.

Total Heat Load

The effect of total heat load on total equivalent weight as illustrated for the LiOH/condenser, molecular sieve/desiccant and solid amine concepts is shown in figure 50. As previously stated, the condensing concept weight increases at a faster rate than the desiccant and solid amine approaches. A major portion of the weight increase is attributed to heat rejection. The radiator area limitation of 900 square feet requires expendables to be used to handle the high heat loads. The majority of the difference in the total equivalent weight at the maximum heat load is the expendable required to suppement the radiator.

Radiator Influx

As the environmental heat influx to the radiator increases, the radiator must become larger to reject the required amount of heat from the EC/LSS. Figure 51 shows the variation in total equivalent weight versus the adiabatic sink temperature for the LiOH/condenser, molecular sieve/desiccant and solid amine concepts. If the adiabatic sink temperature increases above the nominal or the radiator weight penalty increases, subsystem selection would favor the solid amine concept.

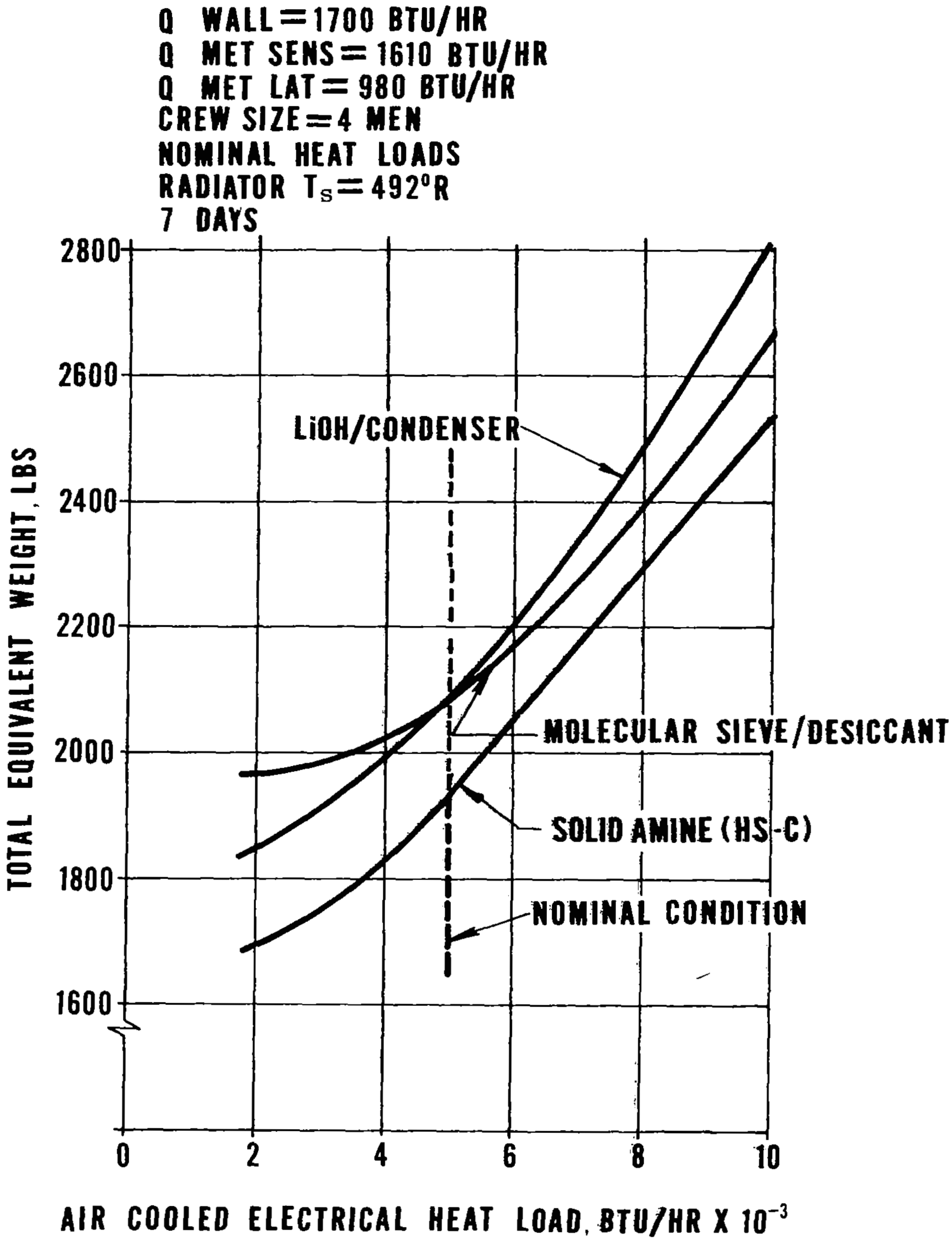


FIGURE 49. TOTAL EQUIVALENT WEIGHT VERSUS AIR COOLED ELECTRICAL HEAT LOAD

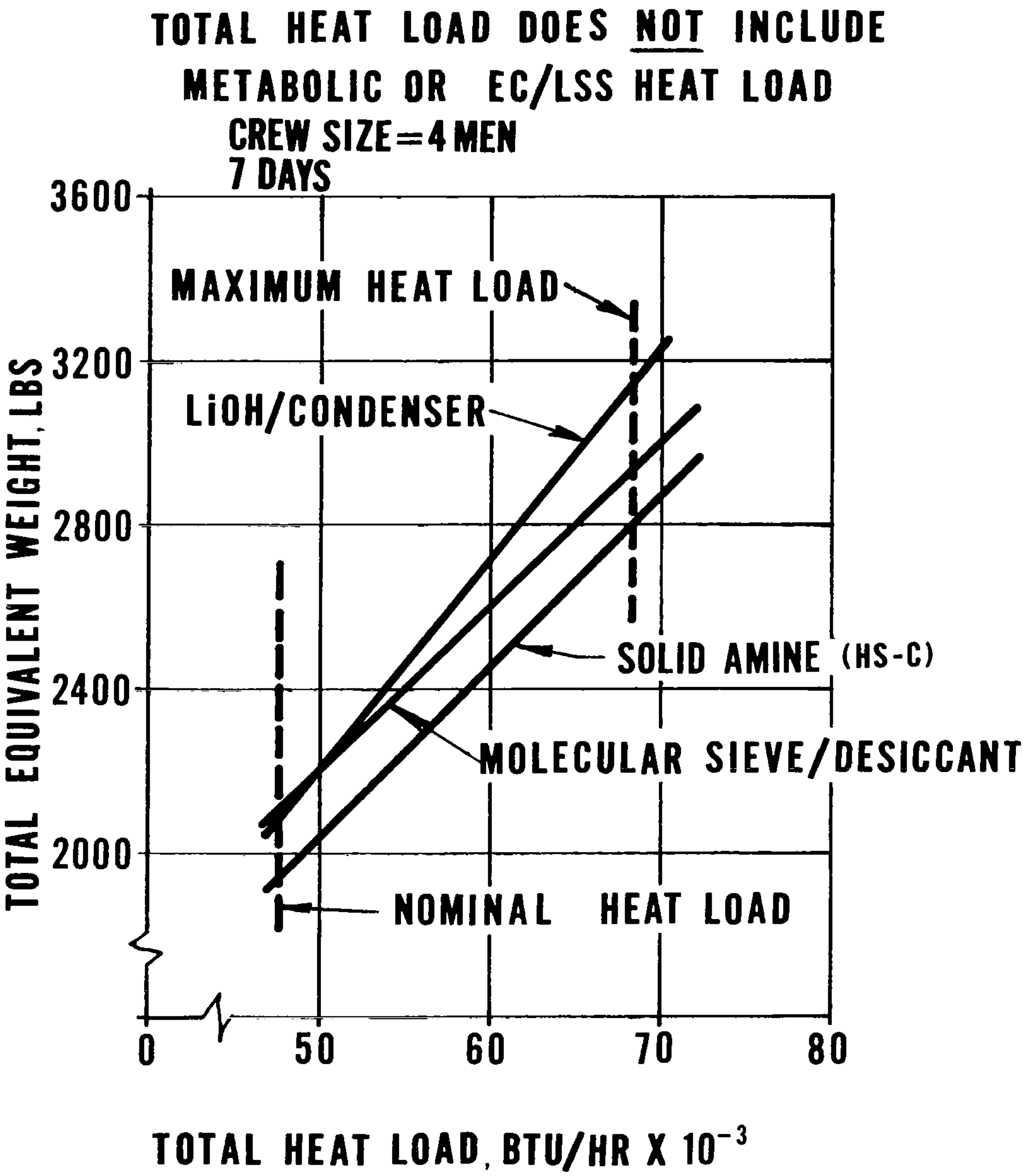


FIGURE 50. TOTAL EQUIVALENT WEIGHT VERSUS TOTAL HEAT LOAD

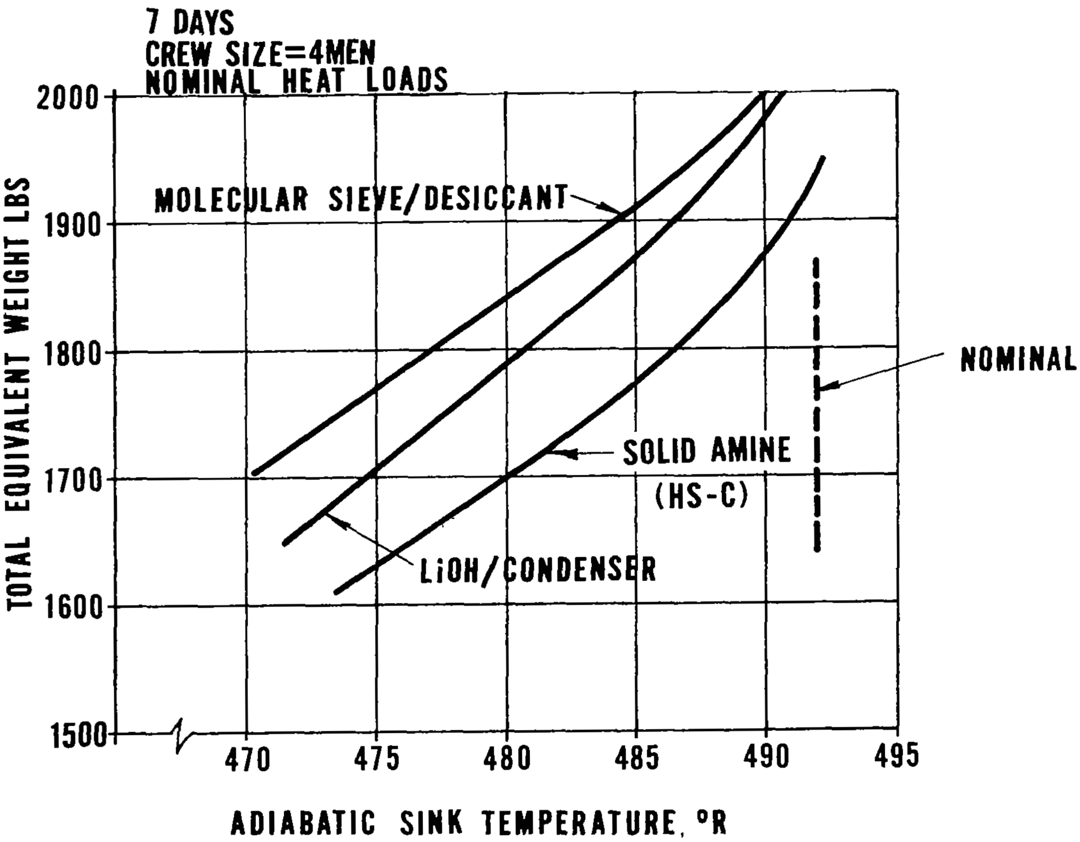


FIGURE 51. TOTAL EQUIVALENT WEIGHT VERSUS ADIABATIC SINK TEMPERATURE

For all the cases considered a water evaporator was used to evaporate the excess fuel cell water. Figure 52 shows the variation in total equivalent weight, for the LiOH/condenser, molecular sieve/desiccant and solid amine concepts, versus the evaporator heat load. If the evaporator were not used, the weight of the LiOH/condenser approach would increase 240 pounds, the molecular sieve/desiccant approach would increase 170 pounds and the solid amine approach would increase 180 pounds. These weights are based on average water usage rates and average radiator heat influxes. If water were used only during maximum heat load conditions, greater weight savings could be realized.

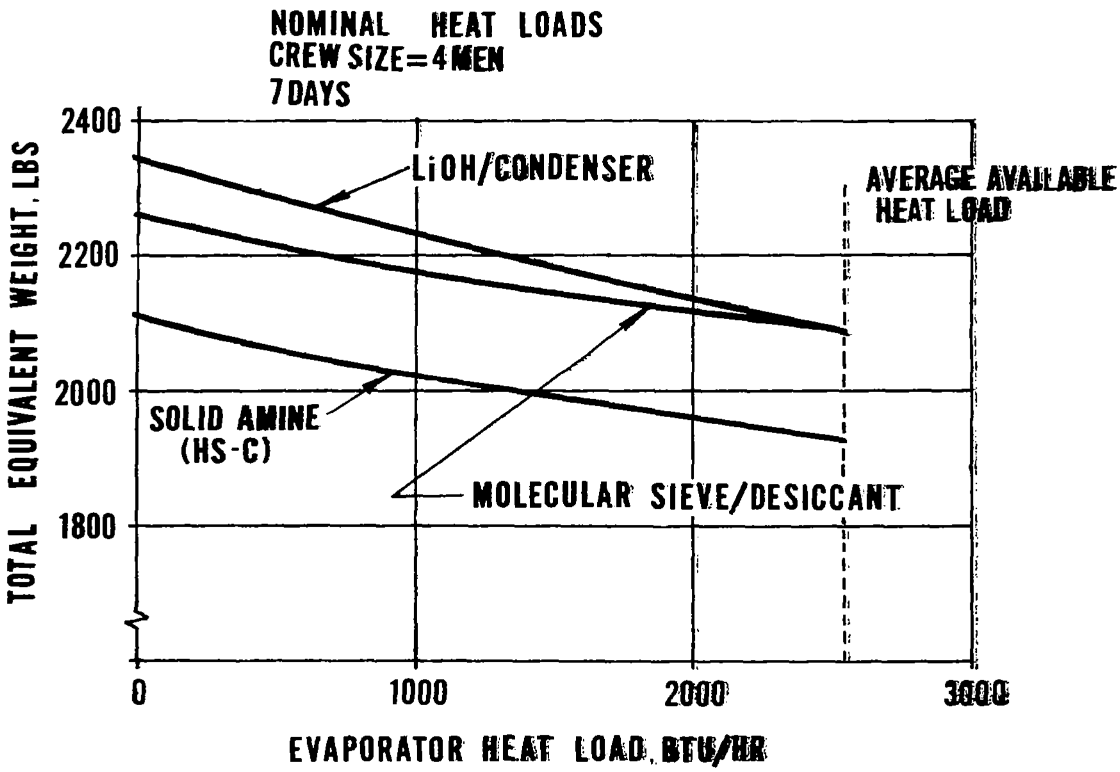


FIGURE 52. TOTAL EQUIVALENT WEIGHT VERSUS EVAPORATOR HEAT LOAD

ATMOSPHERIC CONTAMINANT CONTROL

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ATMOSPHERIC CONTAMINANT CONTROL

It is the function of the atmospheric contamination control subsystem to limit the atmospheric concentration of various contaminants to levels compatible with the health and comfort of the crew. Three types of contaminants are of concern; trace gases and odors, particulate material and microbiological material. These are discussed below, along with the subsystem selected for their control, and the impact of mission parameters on the selected subsystem.

TRACE GAS CONTROL

As with any closed environment, relatively long duration mission, the possible buildup of trace gas contaminants must be considered. These gases must be identified and their generation rates established in order to define adequate control methods. An adequate model for the shuttle is not available at the time of this study. The following paragraphs discuss the model synthesized for this study and the methods selected for control.

Contaminant Model

The contaminant generation rates are listed in the Requirements/Guidelines (appendix A). This list was generated by applying the approach used in the Basic Subsystem Module (BSM) study (reference in appendix B).

Generation rates for nonbiological contaminants were scaled up from Apollo test simulator values on the basis of equipment weight. Since the weight of the equipment in the shuttle cabin was estimated to be twice that for Apollo cabin equipment, a scale-up factor of two was used, and the resulting nonbiological rates were:

Acetone	1.02 grams/day
Methane	2.96
"Other"	1.02
Total	5.00 grams/day

"Other" contaminants are the same as those listed for the BSM and the Space Station Prototype (SSP) studies, except that the generation rates of each contaminant were:

Primary contaminants	0.02 grams/day
Secondary contaminants	0.002 grams/day

The generation of contaminants listed as primary is expected. Secondary contaminants are those that could occur and, therefore, should be given some consideration. Contaminants expected to be generated only by space station experiments are eliminated from the model.

Biological generation rates are those that were used in the BSM study with the exception of carbon monoxide. A generation rate of 0. 0162 grams/man-day was used rather than 0. 033 grams/man-day. This revised generation rate was based on the recent work completed at the Brooks Air Force Base by J. P. Conkle, et al, entitled, "Detailed Study of Contaminant Production In a Space Cabin Simulator at 258 mm Hg. ".

Actual Contaminant Concentrations

Assuming constant generation rates, the concentration of each contaminant tends to increase linearly with time. Cabin leakage reduces the rate of increase and limits the ultimate concentration to some maximum value. However, the leakage rate for the Shuttle Orbiter is generally unknown, and even the maximum allowable leakage rate cannot provide adequate control. Therefore, a more positive means of control is required.

If zero initial cabin air contamination is assumed, only eight of the contaminants for the baseline shuttle mission will exceed their maximum allowable concentrations. If the cabin air is passed through appropriate contaminant removal equipment with 100 percent removal efficiency, each contaminant will require a certain flow rate to limit its concentration to the maximum allowable level. Table 18 shows the eight contaminants requiring control for the baseline mission, their maximum allowable concentrations, elapsed time to reach maximum allowable concentrations (with zero and nominal leakage), and the process flow rates required to prevent them from exceeding their limit.

A variety of equipment is needed to keep the eight contaminants at acceptable concentrations. This equipment is discussed in the following sections. If initial contaminant concentrations were not zero, equipment flow rates would be the same, but equipment size and operating conditions would change. This will be discussed later.

Organic contaminants. - Six organic contaminants (acetone, acetaldehyde, acrolein, allyl alcohol, indole and methyl mercaptan) plus odors can be controlled effectively by activated charcoal. Six or more pounds of charcoal in one of the higher flow rate streams (for example the temperature and humidity control or waste management ventilation flow) should be adequate. Other methods considered for the removal of these six organic contaminants (pyruvic acid which is an organic will be considered separately) were lithium hydroxide, a catalytic oxidizer and Purafil; all of which were not completely adequate for the following reasons. If the lithium hydroxide proves less than 100 percent effective in removing methyl mercaptan and if the mercaptan is indeed generated at the rather conservative value listed, then charcoal would be required in

TABLE 18
CONTAMINANTS REQUIRING CONTROL

Contaminant	Maximum Allowable Concentration mg/m^3	Days to Reach Maximum Allowable Concentration		Process Flow Required for Control* CFM
		No Leakage	Nominal Leakage (3.5 lbs/day)	
Acetone	240.0	6.7	7.9	0.10
Acetaldehyde	36.0	5.1	5.8	0.14
Acrolein	0.25	3.5	3.9	0.20
Allyl alcohol	0.5	7.1	8.6	0.10
Indole	126.0	8.9	11.6	0.08
Methyl mercaptan	2.0	0.7	0.7	0.98
Ammonia	3.5	0.02	0.02	28.0
Pyruvic acid	0.9	0.02	0.02	41.0

addition to lithium hydroxide to insure that the maximum allowable concentration is not exceeded. If a catalytic oxidizer was used it would have to be protected from mercaptan poisoning. This protection could be achieved by preceding the catalytic oxidizer with 5.7 pounds of fine mesh charcoal. Purafil was not selected, because at this time, insufficient information is available on the adsorption properties of the material. A more detailed discussion of Purafil will be presented in a later section.

As a result of this evaluation, activated charcoal is selected for controlling the six organic trace contaminants because it is presently the most efficient method of control. It also is required to control odors effectively. A bed size of six (6) pounds of activated charcoal with a process flow rate of 45 cfm is adequate to control both odors and trace contaminants except for pyruvic acid and ammonia, which are discussed below.

Pyruvic acid. - Since pyruvic acid is completely soluble in water, control of this contaminant can inherently be accomplished by absorption by the condensed water in the cabin condensing heat exchanger. Alternate methods considered were catalytic oxidation, adsorption on charcoal, lithium hydroxide sorption and Purafil. Catalytic oxidation might be competitive on a very long mission, but for the shuttle mission, high pressure drop and elevated operating temperatures result in an excessive power penalty relative to other control methods. Charcoal adsorbs pyruvic acid moderately well, but its capacity is not nearly as great as that of lithium hydroxide. In addition, a thermal or contamination upset could cause rapid desorption of pyruvic acid from the charcoal, resulting in a toxic atmospheric condition. This possibility is precluded with the use of lithium hydroxide.

Lithium hydroxide not only absorbs pyruvic acid but also many other acidic contaminants. Therefore, the lithium hydroxide must be sized to have sufficient capacity for the pyruvic acid to prevent its displacement. The other acidic contaminants (or their oxidation products) include oxides of nitrogen, organic acids, sulfur containing compounds, and halogens. As a result, a relatively high flow rate (41 cfm) through a lithium hydroxide bed would be required. In operation, the lithium hydroxide will be rapidly converted to lithium carbonate by reaction with atmospheric carbon dioxide. Nevertheless, lithium carbonate formed in this manner has been shown to be effective in removing acid gases. Since the required flow rate is almost three times that required for carbon dioxide control (assuming lithium hydroxide is selected for this purpose) this would have an adverse impact on the total system flow.

Purafil, as noted before, apparently has the capability to sorb pyruvic acid, but further work is required in this area to demonstrate its effectiveness. As a result, it was concluded that the inherent capability of the condensed water in the condensing heat exchanger to sorb pyruvic acid is more than adequate for its control. This control is achieved with no additional equipment. The maximum cabin air flow required is 61 cfm which is well below the 200-500 cfm flow range of the condensing heat exchanger.

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*With no leakage.

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Ammonia. - The recommended method of ammonia control is absorption on a bed of copper sulfate ($CuSO_4$) on sorbeads. Alternate methods for controlling ammonia are catalytic decomposition and various other sorbents. Catalytic decomposition is an undesirable approach for three reasons. First, it consumes power for a heater to maintain the elevated temperature required. Second, pressure drop is usually high, resulting in significant fan power. Finally, hot spots can result in generation of nitrogen oxides, which are extremely toxic. Other sorbent materials considered include charcoal, phosphoric acid on charcoal and Purafil. Charcoal, even when specially activated, has a relatively low capacity for ammonia. Charcoal coated with phosphoric acid has a much higher capacity, but still less than half the capacity of copper sulfate on sorbeads, Another material which has ammonia sorption capability is Purafil. Purafil is a solid oxidant, consisting of approximately four percent potassium permanganate supported on alumina pellets. Its primary mode of action is adsorption of a gaseous contaminant followed by oxidation, after which the contaminant is permanently retained on the Purafil. Its capacity is affected little by either temperature or concentration, although absorption rate is strongly enhanced by increased temperature. It has the potential for replacing all elements of the trace contaminant control subsystem. It can control ammonia, pyruvic acid and carbon monoxide at the generation rates anticipated. However, at this time insufficient information is available on this material. It is, therefore, recommended that a test program be established to determine the suitability of Purafil for use on the Space Shuttle in view of its potential vehicle savings in terms of power, cost, weight and maintenance time.

It was concluded that sorbeads treated with copper sulfate is the safest, most efficient method for ammonia control. A bed size of 2.4 pounds and an air flow rate of 28 cfm is required.

PARTICULATE CONTAMINATION CONTROL

Particulate contaminants include both wet and dry debris consisting of droplets of water and other liquids, hair particles, skin flakes, lint, etc.. A particulate filter is used to remove these from the cabin atmosphere and to prevent them from entering the cabin air distribution ducting, process fans, and condensing heat exchangers. The particulate filter consists of a 100 mesh (149μ) teflon-coated screen designed for a bubble point exceeding the pressure drop so that it will not pass large drops of liquid. The filter is designed for a flow rate of 130 cfm and weighs about 1.4 pound. The filter is replaced after each mission.

BACTERIAL CONTAMINATION CONTROL

A 0.3-micron depth filter with a flow rate of 130 cfm is recommended for control of airborne bacteria. This design is based on an assumed reasonable bacteria concentration in the air and on an estimated generation rate. A bacterial concentration of less than 100 bacteria per cubic foot is sufficiently low to prevent any normal bacterial threat to the crew. Using this concentration level, and an average shedding rate of 3,000 bacteria per minute per man, a process flow rate of 130 cfm is required assuming a removal efficiency of 95 percent.

The type of filter used in a class 100,000 clean room is recommended. It consists of continuous sheets of binderless fiber mat folded and separated by a corrugated ceramic separator. This filter removes particles 0.3 micron and larger with a minimum efficiency of 95 percent. With a depth of one foot and a volume of 0.7 cubic feet, the end-of-mission pressure drop is estimated to be less than 0.4 inches of water. Weight is about 10 pounds. A filter could be used for several successive missions with very little additional pressure drop. Changing the filter each flight, however, is recommended because of possible colony bacteria growth on the filter between flights.

SELECTED SUBSYSTEM

Characteristics of the selected contaminant control methods are shown in table 19. These characteristics depend in part on an assumed configuration, which is shown in figure 53. Several features of the schematic deserve comment. First, the ammonia sorbent is placed in the same flow stream as the charcoal, as its flow rate requirement is about the same. This maximizes reliability and improves maintenance by combining the copper sulfate sorbeads and charcoal in a single canister serviced by a single fan. Quantitatively, there is no additional equivalent weight penalty for adopting this arrangement. Second, the particulate filter is placed upstream of the cabin fans and CO_2 humidity and temperature control loop to protect the fans, heat exchangers and water separator from debris, to facilitate maintenance, and to act as a muffler for the high flow air entering this subsystem. Third, two bacteria filters are used. One provides adequate microbiological control of the air entering the cabin from the waste management subsystem (WMS), and is on line at all times. The other is installed in the cabin temperature control loop. This filter will see a normal flow of approximately 200 cfm during most of the mission. Each filter is replaced upon completion of the mission. To facilitate maintenance and to keep the pressure losses to a minimum, the cabin bacteria filter is placed in parallel with the condensing heat exchanger.

TABLE 19
SELECTED ATMOSPHERIC CONTAMINATION CONTROL METHODS

BASELINE MISSION

Contaminant	Minimum Process Flow Required CFM	System Flow CFM	Control Method
Trace Contaminants			
Acetone	0.10	45	Activated Charcoal
Acetaldehyde	0.14		
Acrolein	0.20		
Allyl Alcohol	0.10		
Indole	0.08		
Methyl Mercaptan	0.98		
Ammonia	28	45	Copper Sulfate on Sorbeads
Pyruvic Acid	61	200-497.5	Condensing Heat Exchanger
Odors	30	45	Activated Charcoal
Particulate	130	511	100 mesh teflon screen
Microbiological	130	45-342.5	0.3μ bacteria filter (95% efficient)

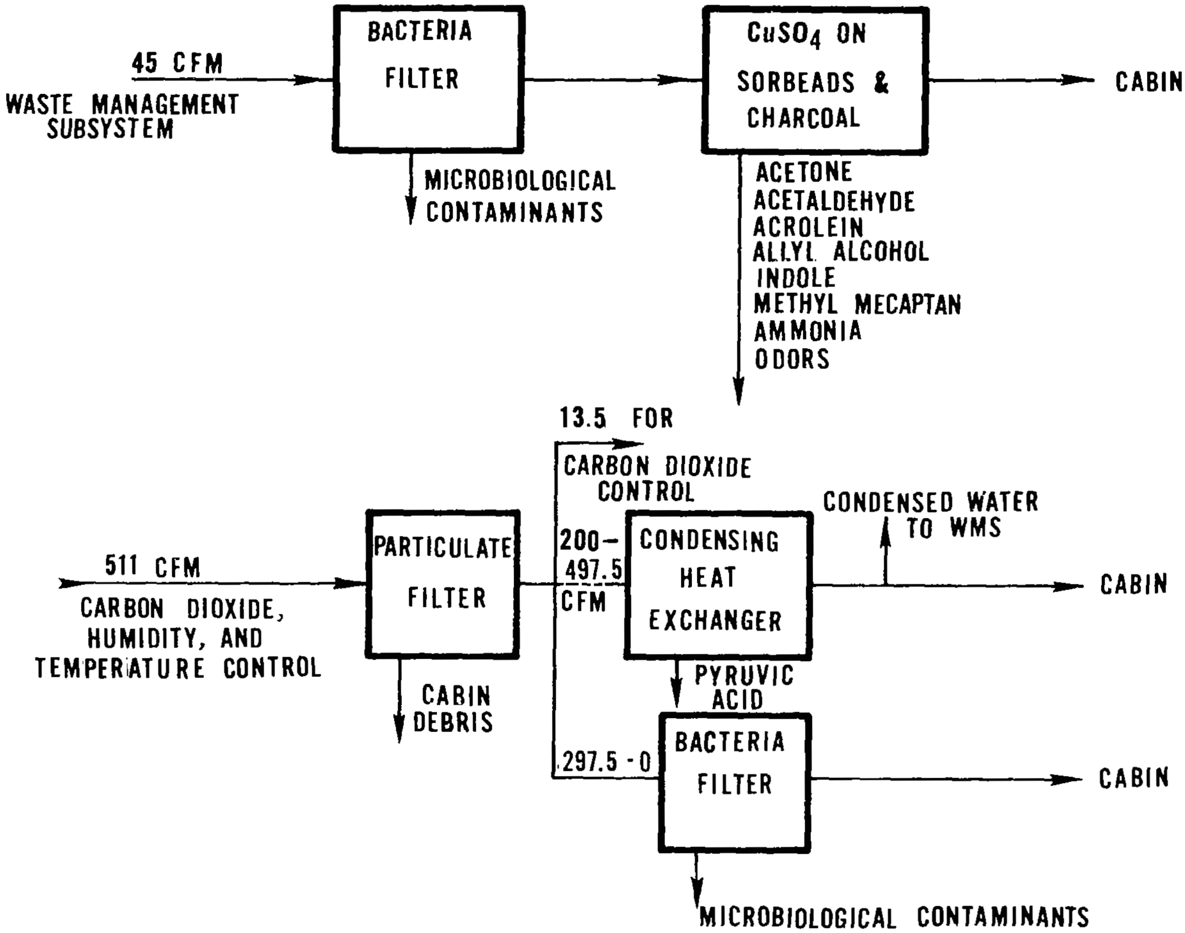

FIGURE 53. ATMOSPHERIC CONTAMINANT CONTROL FLOW SCHEMATIC

IMPACT OF MISSION PARAMETERS

The two parameters considered here are mission duration and crew size. In particular, two missions are of interest: the 30-day mission with a two-man crew and the two-day mission with four crewmen and 10 passengers aboard. Each of these missions has an additional contingency period of two days.

Mission Length

No matter how short the flight is, control of ammonia and pyruvic acid is required, so that copper sulfate on sorbeads and water absorption are always needed. For mission durations not exceeding three days, no other trace contaminant control is required except if desired for odor control. Control of acrolein becomes necessary for mission lengths exceeding four or five days.

A catalytic oxidizer is not required for the baseline mission because carbon monoxide (assuming zero initial concentration) will not reach its maximum allowable concentration in the seven-day period. However, oxidation of carbon monoxide is necessary for some alternative missions. Figure 54 shows how carbon monoxide concentration varies with time for various missions.

The 30-day mission, with a crew of two men, generally requires more expendables because of increased total man-hours. However, flow rate requirements are equal or lower, because of reduced total biological generation rates. Specifically, for ammonia control the quantity of copper sulfate sorbeads must be increased, but the four-man seven-day flow rate is twice the required rate. The same is true for removal of pyruvic acid. The charcoal for odor control tends to decrease because of reduced biological generation rates, but the overall effect is an increase in size because of the longer mission duration.

A catalytic oxidizer is required because the maximum allowable concentration for carbon monoxide is exceeded on the 16th day. In 32 days, methane, if not controlled, will build up to nearly three times its maximum allowable concentration. Therefore, a high temperature (580°F) catalytic oxidizer would be recommended to assure oxidation of all organic contaminants. The flow rate should be based on controlling acrolein rather than methane in order to fully utilize the catalytic oxidizer once the requirement has been established. Because of low reliability and safety, this high temperature design is not recommended unless a specific need for it arises. It should be noted that if the concentration of methane were significant instead of zero at launch, control of methane would be needed for mission lengths less than ten days.

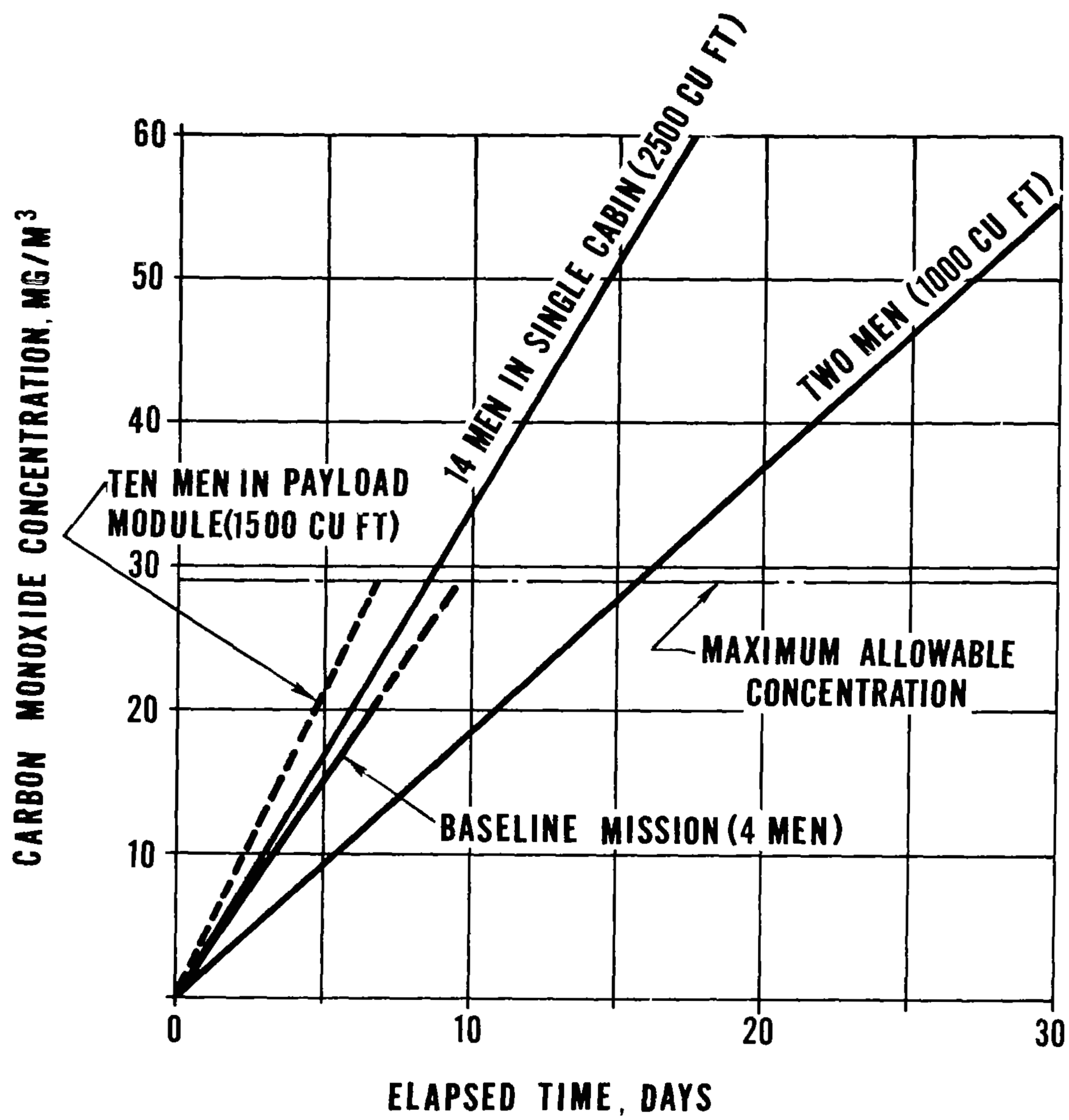

FIGURE 54. CO CONCENTRATION AS A FUNCTION OF TIME

Crew Size

In general, flow rate and bed size for the copper sulfate and charcoal are roughly proportional to crew size. The catalytic oxidizer is not required for a four-man crew (for the seven-day mission).

For a 14-man crew (two-day mission plus two-day contingency) in a single 2500-cubic foot cabin, a catalytic oxidizer is not required.

A design was evaluated for a payload module based on ten passengers and a two-day mission using nonbiological generation rates assumed to be the same as those for the main cabin. For this mission, the big change from the baseline (four men) design is in flow rates. Specifically, for ammonia and other trace contaminant control, the copper sulfate and charcoal bed size is somewhat increased, but the flow requirement more than doubles because of the number of men (10) aboard. For pyruvic acid control, the baseline subsystem size is more than adequate, but the required flow rate more than doubles because of the number of men aboard. Carbon monoxide concentration in the payload module does not exceed the maximum allowable limit and a catalytic oxidizer is not required assuming zero initial carbon monoxide concentration. The flow required for bacteria control would also increase to 325 cfm due to the number of men aboard.

In general, the net effect for the 10-man design relative to the four-man main cabin is increased fan power. To minimize this increase, the copper sulfate on sorbeads and charcoal would probably be contained in separate canisters with separate fans to reduce fan power.

If the mission for ten passengers exceeds seven days, a catalytic oxidizer is required because carbon monoxide exceeds the maximum allowable concentration (figure 54).

HEAT REJECTION

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HEAT REJECTION

The function of the heat rejection subsystem is to provide a means of rejecting the heat produced by the various vehicle systems including the EC/LSS.

Due to the variation in mission phases, no one heat sink is optimum for all of the mission phases. Table 20 shows the mission duration, the heat load, heat sinks available and the selected methods for each mission phase. To select the optimum heat rejection subsystem, each mission phase was examined and the optimum heat sink method chosen. The total subsystem was then examined to determine if some of the heat sinks could be made common with others. Lastly, the selected CO_2, humidity and temperature control subsystem was reexamined to determine if the optimum choice had been made when the impact of the selected heat sinks for the mission phases were considered. The various mission phases are discussed below, along with the subsystem selected and the impact of mission parameters on the selected subsystem.

BOOST

Due to the short time of the boost phase, the heat capacitance of the vehicle and EC/LS system was examined to determine if it could handle this mission phase. The following assumptions about the vehicle were made:

- Interior cabin surface is = 1600 ft^2
- Air film coefficient = 2.0 Btu/in-ft^2 $^\circ F$
- Cabin equipment and EC/LSS weight = 3000 lb.
- Average specific heat of equipment = 0.2 Btu/lb - $^\circ F$

With no active cooling, it is estimated that the equipment temperature will rise approximately $9^\circ F$ during the boost phase and that the air temperature will be $2^\circ F$ higher than the equipment temperature. Thus, if the air and equipment are precooled to $65^\circ F$ before launch the maximum air temperature at the end of the boost phase will be $76^\circ F$. If the vehicle is at the maximum air temperature of $75^\circ F$ before boost, the maximum air temperature at the end of the boost phase will be $86^\circ F$. However, the cabin air temperature during boost is expected to remain below the maximum limit of $75^\circ F$ for two reasons. First, the air temperature most likely will be maintained near the minimum level ($65^\circ F$) as thermal cooling of the vehicle is required during prelaunch. Second, the actual equipment temperature rise will be less than the conservatively

TABLE 20

HEAT SINK APPLICATION AS A FUNCTION OF MISSION PHASE

MISSION PHASE \ HEAT SINK	WATER	RADIATOR	RAM AIR	AIR CYCLE	AMMONIA	FREON 22	CRYOGENIC H_2	CRYOGENIC O_2	GSE	HEAT CAPACITANCE OF VEHICLE & EC/LS SYSTEM	HEAT LOAD (BTU/hr x 10^{-3})	MISSION DURATION (hrs)
Boost					X	X	X	X		S	53.4	0.1
Orbit	A	S			X	X	X	X			53.4	167.0
Reentry					X	X	S	X		X	60.2	0.3
Atmospheric Flight			X	X	X	X	S	X			60.2	0.5
Prelaunch			X	X	X	X	S	X	S		50	2.0
Post Landing				X	X	X	X	X	S		60.2	0.5
Ferry			X	X	X	X	S	X	X		30	4.0
Emergency (radiator loss, 12 hrs)	A				X	X	S	X			53.4	12.0
(With radiator, 48 hrs)		S			X	X	A	X			53.4	48.0

X - Applicable Concept
S - Selected Concept
A - Backup or supplementary concept

based value of 9°F. Should the air temperature exceed the upper limit, the time increment involved (approximately 5 minutes) is of such short duration that the condition is considered acceptable. For the above reasons, active cooling is not required during the boost phase of the mission.

ORBIT

The orbit phase of the mission lasts the longest and is the most critical of the mission phases. The heat sinks proposed to meet the requirements of this phase are:

- Radiator
- Expendables
  a. Water
  b. NH_3
  c. Freon 22
  d. Cryogenic H_2
  e. Cryogenic O_2

Table 21 shows the weight of the radiator and expendables required for the nominal mission (7 day) plus the 48-hour emergency period. The low weight of the radiator (one seventh the weight of the next lightest concept) results in its selection as the primary heat sink for the orbit phase of the mission. A curve of expendable weight versus mission length is shown in figure 55. It can be seen that a radiator is the lightest concept for missions greater than 1.5 days. Due to vehicle configuration considerations the radiator size and operating temperatures are limited. A size limitation of 900 ft^2 as a representative size of radiator area available to be deployed was established. For the orbit phase (53,400 Btu/hr) the radiator size is less than the maximum allowable (900 ft^2).

For transient periods of high heat load or high radiator heat influx, the utilization of an expendable heat sink will result in a lighter system. Either excess fuel cell water for an evaporator or low penalty cryogenic hydrogen from the OMS tankage are readily available. Under these conditions evaporation of water was selected for handling the high heat load transient periods as fuel cell water (62.4 lbs/day) is available at no penalty for supplementing the radiator.

Hydrogen, although available was not selected because there is not an excess of hydrogen and therefore a penalty must be assessed to the heat rejection concept.

TABLE 21

HEAT SINK WEIGHTS FOR THE ORBIT MISSION PHASE

Heat Sink	Weight, lbs
Radiator	996
Water	10,780
Ammonia	27,200
Freon 22	205,000
Cryogenic H_2 (Subcritical)	6,750
Cryogenic O_2 (Subcritical)	69,500

Mission length 215 hrs (includes 48 hours emergency)

Heat Load 53,400 BTU/hr

Weights do not include tankage, valves, heat exchangers and plumbing

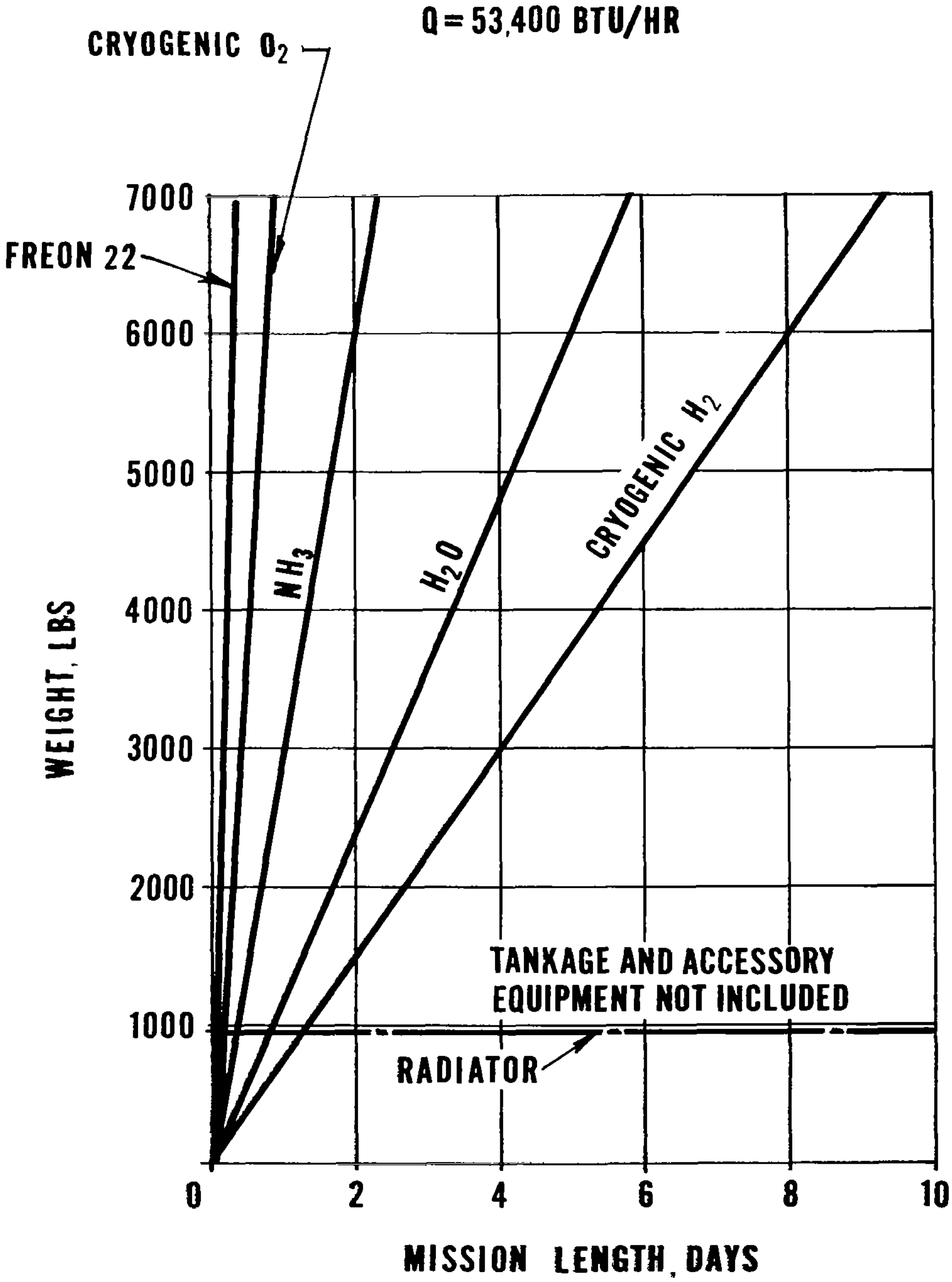


FIGURE 55 HEAT SINK EXPENDABLE WEIGHT AND RADIATOR WEIGHT VERSUS MISSION LENGTH, ORBIT PHASE

Subsystem optimization considering these factors will be necessary at a later date when vehicle heat load and orbital heat influx profiles are better known.

REENTRY AND ATMOSPHERIC FLIGHT

For the purpose of heat sink evaluation, the reentry and atmospheric flight phases are considered as one because the operating environment is essentially the same. The length of these phases (18 minutes and 30 minutes respectively) precludes the use of vehicle and EC/LSS capacitance as a heat sink. Applicable heat sinks investigated are:

- Ram Air
- Air Cycle
- Ammonia
- Freon 22
- Cryogenic H_2 (Subcritical)
- Cryogenic O_2 (Subcritical)

These concepts were examined below in detail because the selection of the best heat sink for these mission phases is not readily apparent.

Ram Air

In this concept ambient air is collected by a ram air scoop. The air is ducted through a coolant to air heat exchanger where the heat from the coolant loop is transferred to the air. The air is then dumped overboard. The air cannot be ducted into the cabin directly because its pressure is too low during atmospheric flight.

Absolute criteria. - A plot of ram air temperature versus altitude was calculated and is shown in figure 56. At altitudes below 15, 000 feet the cabin temperature is out-of-specification. At 25, 000 feet the electrical cooling temperature is out-of-specification. Therefore, the ram air concept was dropped from further consideration as it could not meet the performance criteria.

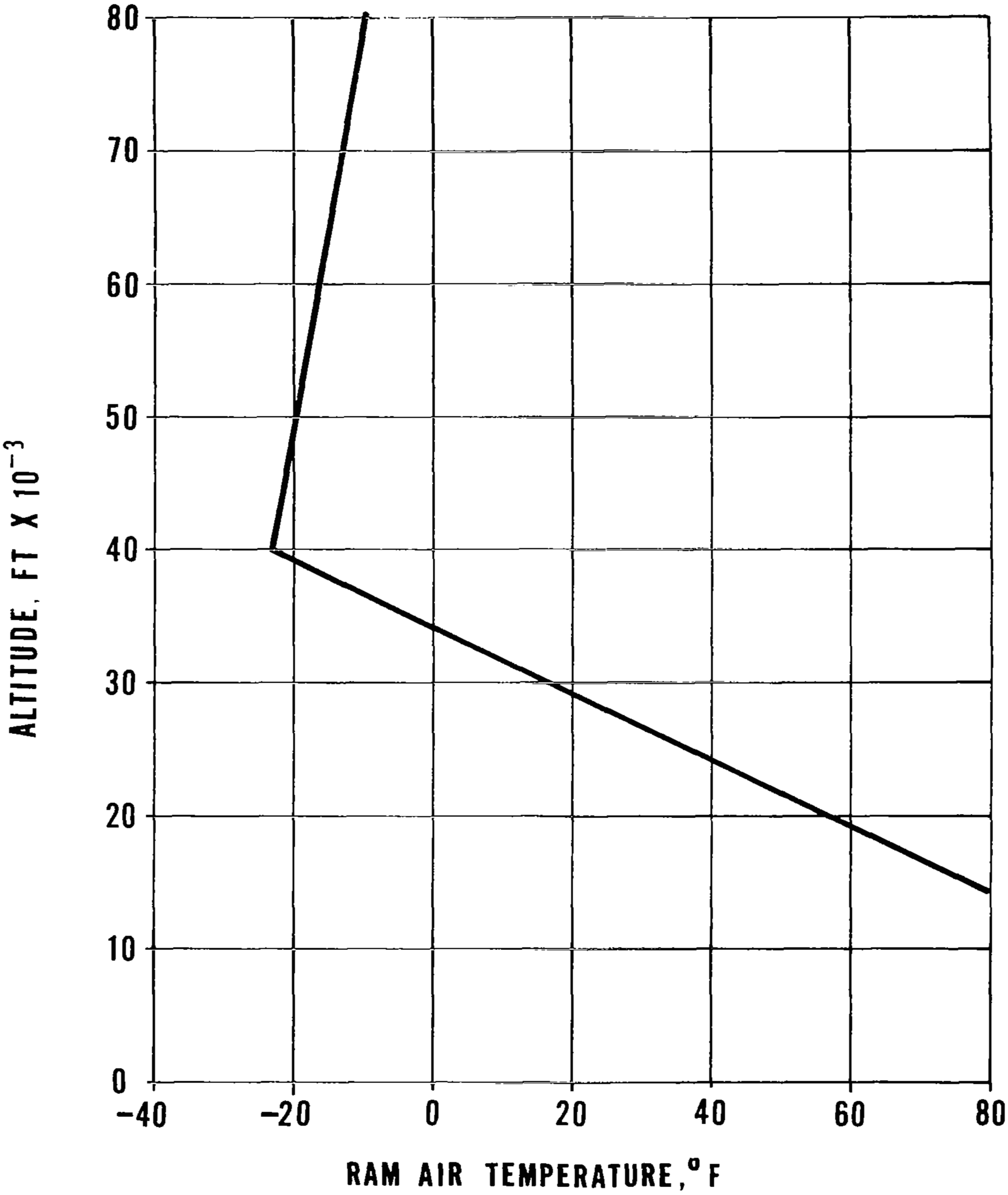


FIGURE 56. RAM AIR TEMPERATURE VERSUS ALTITUDE

Air Cycle

The air cycle approach that was selected for this evaluation is a "bootstrap" unit which is capable of providing ground cooling at engine idle conditions. For evaluation purposes, a design point for a Sea Level, M.51, hot day are used.

Engine bleed air, at high temperature and pressure, is initially cooled in a heat exchanger. The air is then compressed to a higher pressure raising the air temperature due to the heat of compression. A ram air (ambient air) heat exchanger is used to cool the air. The ram air is either forced through the heat exchanger by the ram pressure rise of the vehicle, (when flying) or by fan pressure rise (when on the ground). The cooled air is then expanded through a turbine to approximately cabin pressure and proceeds to a water separator. To prevent the air cycle water separator from freezing, the entering air (a portion of the turbine outlet flow) is mixed with a bleed off of compressor inlet air. A flow control orifice provides the cabin with constant flow. A second and independent bleed off of the compressor inlet is mixed with the water separator discharge flow to control cabin air temperature. The major portion of the turbine discharge air flow services a liquid loop-air heat exchanger. The heated air from the heat exchanger then proceeds to precool the engine bleed air prior to being dumped overboard. The turbine energy is utilized to power either the compressor and/or the ram air fan if required. To meet the fail operational-fail safe requirement three parallel assemblies would be required.

Absolute criteria. - A schematic and data sheet is shown in figure 57. This approach can meet the performance criteria during the atmospheric flight phase but cannot meet it for reentry. Either additional methods of heat rejection or reliance on vehicle transients would be required, or the degraded mode of performance during this phase of the mission accepted. The concept possesses the lowest MTBF of all the candidates under consideration. Availability/confidence is very high as various versions of the concept have have been successfully utilized in military and commercial aircraft.

Quantitative criteria. - Figure 58 shows the air cycle concept, at the nominal mission length (0.8 hours), to be approximately four times the total equivalent weight of the cryogenic approach. The air cycle curve on figure 58 does not include a penalty for the reentry phase (additional heat sinks or degraded performance) which would be required. Volume and cost are the largest of the concepts considered.

Qualitative criteria. - This concept is very complex yet fairly flexible and requires physical integration with the vehicle structure. It can handle varying heat loads at different altitudes and can adequately control CO_2 during the ferry phase of the mission. Increases in crew size would result in either higher cabin temperatures or would require a resizing of the concepts equipment to remain within specification. Durability is limited due to the large quantity of rotating equipment. Checkout capability is relatively simple and no in-flight or ground maintenance is required.

SUBSYSTEM: HEAT REJECTION - REENTRY AND ATMOSPHERIC FLIGHT

CONCEPT: AIR CYCLE

FLIGHT AVAILABILITY: 1975

Mission Phase Application

Launch ____ Orbit ____ Reentry ____ Cruise x

RELIABILITY: 0.999957   MTBF: 38,100

4 Men - 7 Days Plus 48 Hours Contingency

Total	Equivalent Wt. (lb)	Volume (ft^3)	Power (watts)
Installed Unit	288	18	0
Expendables	0	-	-
Power Equiv. Wt.	0	-	-
Totals	288	18	0

Cost Factor		Crew Time (hrs)	
Recurring -	2.4	Scheduled -	0
Nonrecurring -	2.1	Ground Refurbishment -	0
Total -	2.3		

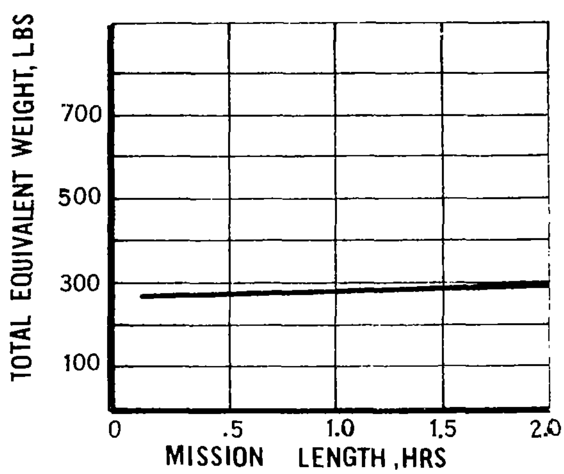


Figure 57 (Page 1 of 2)

SL M.51 HOT DAY

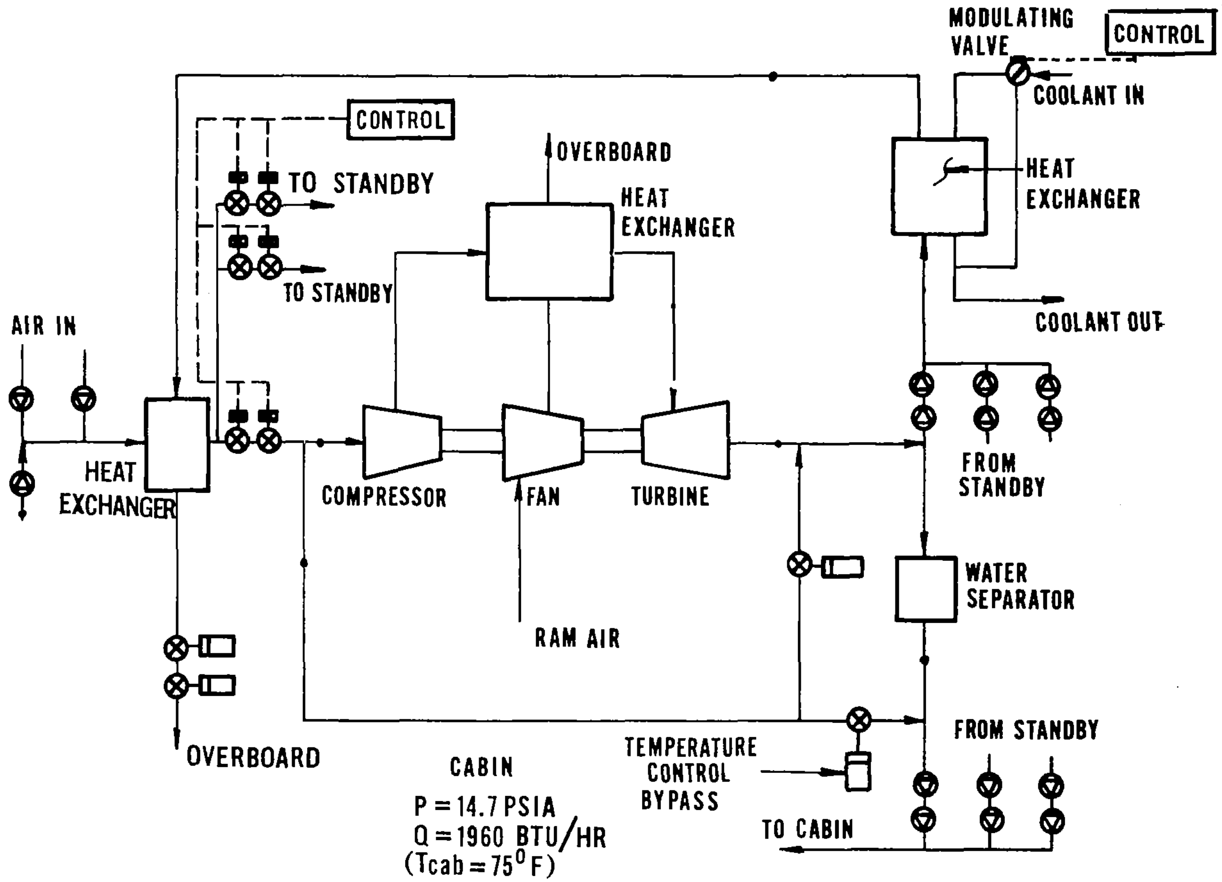


FIGURE 57. AIR CYCLE CONCEPT (PAGE 2 OF 2)

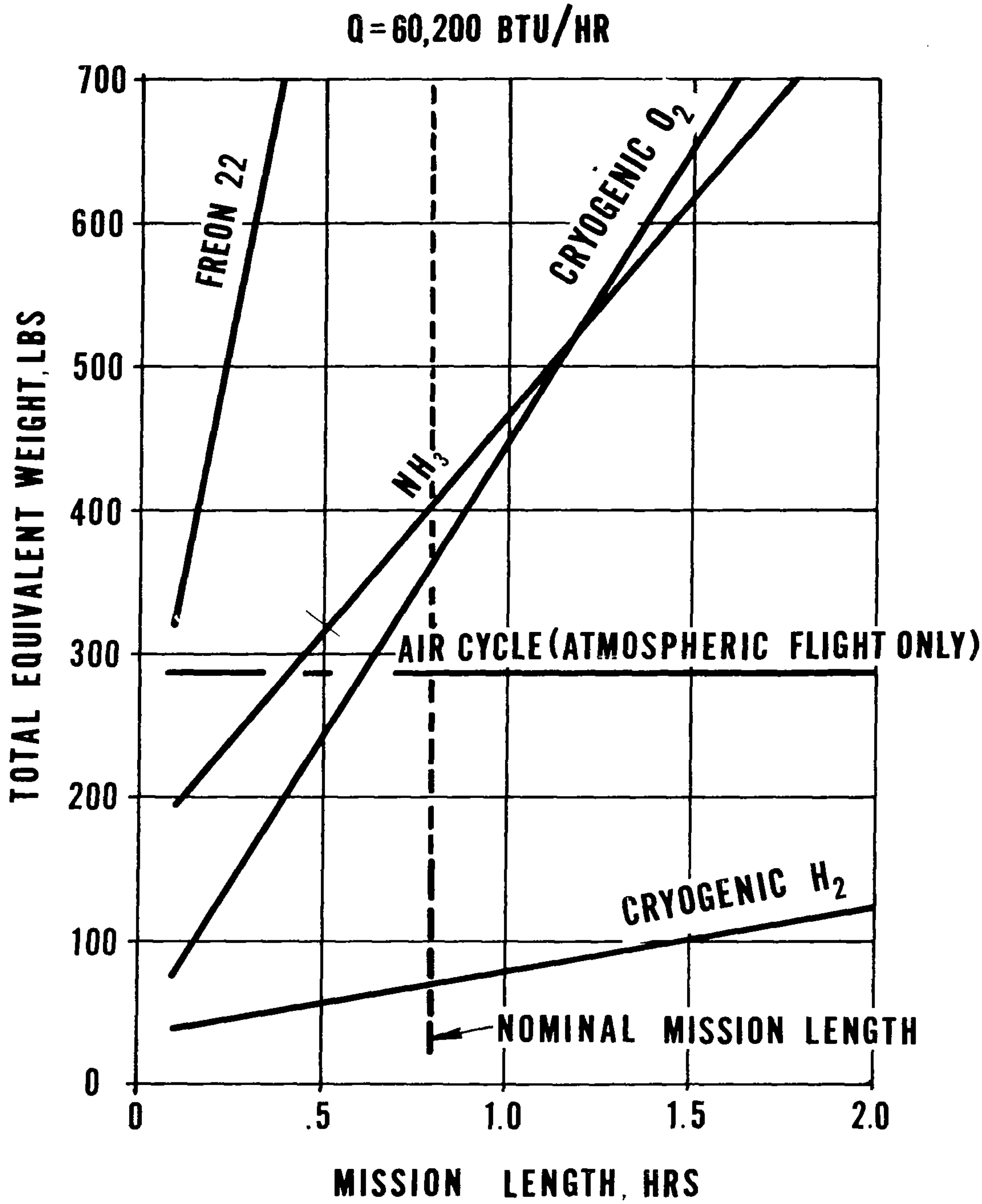


FIGURE 58. HEAT SINK TOTAL EQUIVALENT WEIGHT VERSUS MISSION LENGTH, REENTRY AND ATMOSPHERIC FLIGHT

Ammonia Expendable

Ammonia fluid evaporators utilize the latent heat of vaporization as a means of rejecting heat. For shuttle application, the ammonia is stored in three separate tanks, each containing 50% of the required amount for the mission phases. To maintain constant tank pressure while liquid is withdrawn, heaters are utilized to evaporate a small percentage of the liquid within the tank. A modulating valve controls evaporant flow rate and evaporant superheat. Evaporation temperature is controlled by regulating evaporation pressure (an absolute back pressure regulator is utilized). In addition to the two evaporators and heaters, triple redundant superheat controllers and back pressure regulators are required to satisfy the fail operational-fail safe requirement. Two independent evaporator loops were selected instead of a dual coolant loop evaporator because a failure of the refrigerant side of the heat exchanger in the latter approach would result in the loss of both coolant loops. A schematic and a data sheet are shown in figure 59.

Absolute criteria. - The large number of components required for this concept results in one of the lowest MTBF of the concepts under consideration. The concept meets performance and availability/confidence criteria, but does pose a safety hazard in ground servicing and ground operation in that ammonia is toxic.

Quantitative criteria. - The total equivalent weight of the competing concepts as a function of mission length is shown in figure 58. It can be seen that the total equivalent weight of the ammonia concept is approximately four (4) times that of the next lightest approach. The ROM cost for the total program is about 40% higher than the least expensive approach. This approach is also one of the larger volume concepts.

Qualitative criteria. - This concept like all expendable fluid evaporators, when compared to the cryogenic hydrogen heat sink, is very complex in that it requires controls for both evaporant flow rate and superheat. The concept is very flexible in that it can handle increased heat loads by utilizing additional expendables. Concept weight is a direct function of crew size and mission length and increases at a much faster rate than the cryogenic approaches. Cabin temperature is limited by the size of the evaporator. The result of increased crew size and mission length on a fixed evaporator size is an increase in cabin temperature. This concept is fairly durable in that it requires only a backpressure regulator and a modulating value. Refurbishment requires filling the expendable tanks between missions. Checkout is more complex than the cryogenic approach due to the additional dynamic equipment and a verification of expendable quantity is required. In-flight maintenance is not required.

Freon 22 Expendable

A Freon 22 fluid evaporator, like the ammonia concept, utilizes the latent heat of vaporization as a means of rejecting heat.

SUBSYSTEM:	HEAT REJECTION - REENTRY AND ATMOSPHERIC FLIGHT
CONCEPT:	NH_3

FLIGHT AVAILABILITY: 1975

Mission Phase Application

Launch*____ Orbit*____ Reentry x____ Cruise x____

*May be used, if required

RELIABILITY: 0.999936 MTBF: 41,700

4 Men - 7 Days Plus 48 Hours Contingency

	Total Equivalent Wt. (lb)	Volume (ft^3)	Power (watts)
Installed Unit	145.7	21	470
Expendables	185.0	-	-
Power Equiv. Wt.	74.0	-	-
Totals	404.7	21	470

Cost Factor	
Recurring -	1.3
Nonrecurring -	1.3
Total -	1.3

Crew Time (hrs)	
Scheduled -	0
Ground Refurbishment	- 1.0

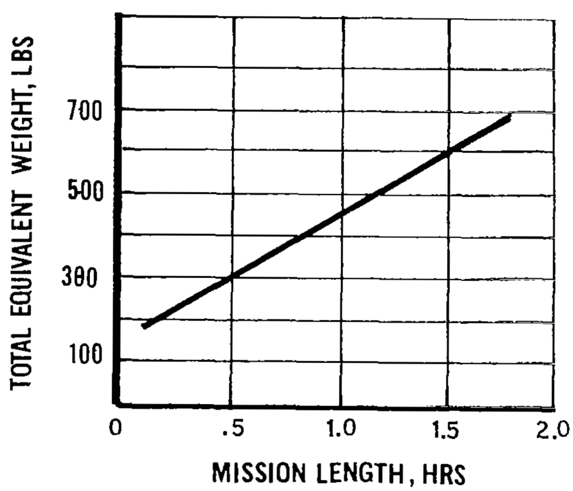


Figure 59 (Page 1 of 2)

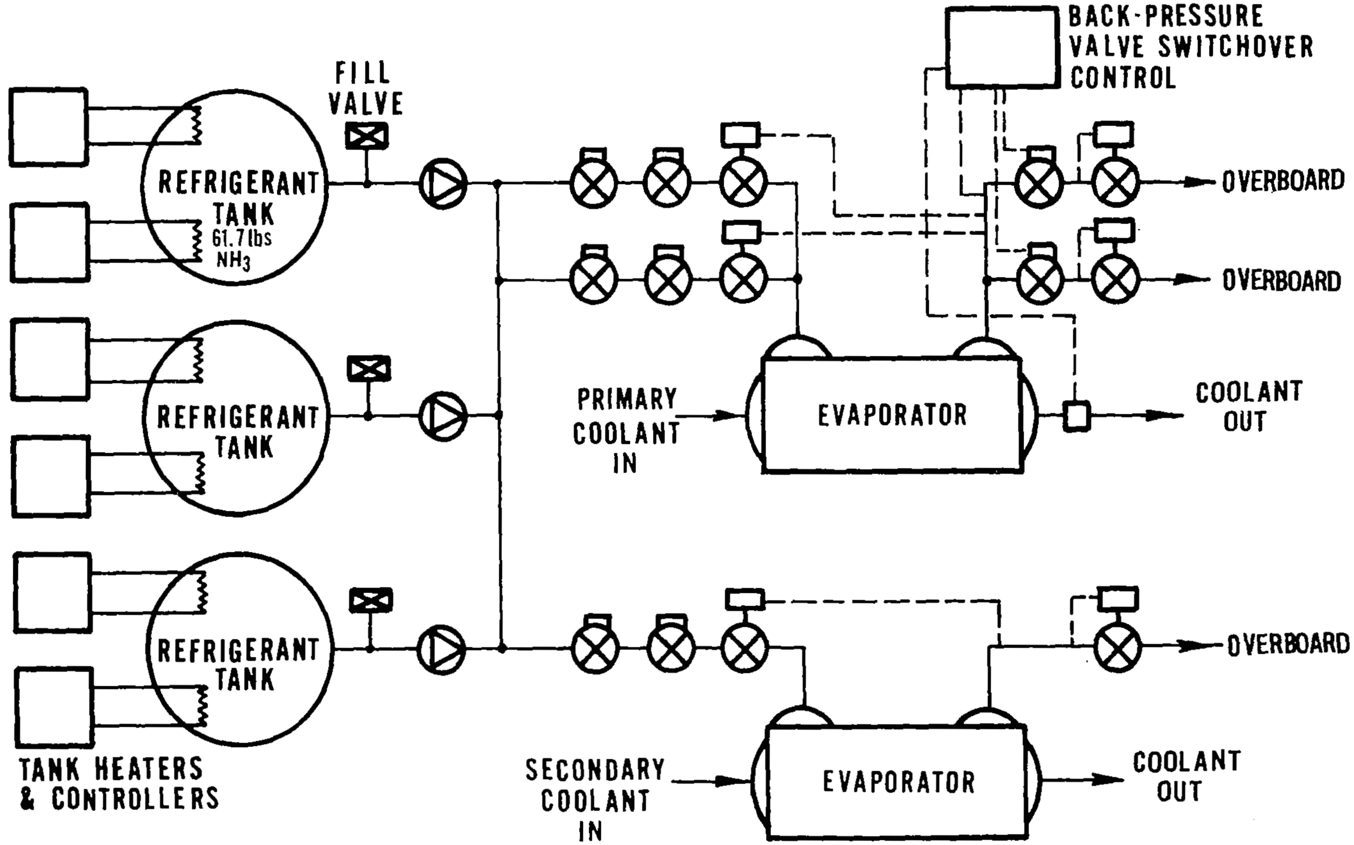


FIGURE 59. AMMONIA HEAT SINK CONCEPT (PAGE 2 OF 2)

Freon 22 was selected as a candidate because its vapor pressure at 30°F is above atmospheric pressure and it possesses the highest heat of vaporization of all of the Freons that meet this vapor pressure/temperature requirement. The saturation temperature at atmospheric pressure must be 30°F or less in order to obtain adequate ground cooling.

The schematic of this concept is the same as that for the ammonia approach shown in figure 59 and it operates in the same manner. Figure 60 is a summary of the concept's quantitative data. The variation of total equivalent weight versus mission length for reentry and the atmospheric flight phases is shown in figure 58.

Absolute criteria. - The Freon approach possesses one of the lowest MTBF of the concepts evaluated. The performance and availability/confidence of the concept are very good. The concept does not present any safety problems to the shuttle.

Quantitative criteria. - As shown in figure 58, the total equivalent weight at any point in time during the mission is much higher than any of the competing concepts. This concept has the largest volume and is one of the most expensive approaches under consideration.

Qualitative criteria. - This concept is identical to the ammonia approach previously discussed.

Cryogenic Hydrogen

This concept uses cryogenic liquid hydrogen at -423°F and heats it to 0°F before venting it overboard.

A schematic and a general data sheet of the cryogenic hydrogen concept are shown in figure 61. Two parallel shutoff valves admit hydrogen from the OMS tankage into the heat exchanger. In the event the inlet valves fail open, redundant shutoff valves are provided at the heat exchanger outlet. Parallel control valves vary the hydrogen flow rate to control the coolant loop temperature leaving the heat exchanger. A second heat exchanger is used for the secondary coolant loop to provide fail operational-fail safe capability. Two independent coolant loop heat exchangers are used, to prevent the situation where a failure on the hydrogen side of the heat exchanger would cause a failure of both coolant loops. In addition, there is the added danger (even though remote) of freezing the coolant loop. With a single heat exchanger, if the primary coolant loop freezes, the secondary loop also freezes.

Absolute criteria. - Due to the small number of components required, this concept possesses the highest MTBF and is one of the most reliable of the concepts evaluated. Cryogenic hydrogen heat exchangers have been successfully utilized on the Apollo program. Therefore, confidence is high that a lightweight design can be realized.

SUBSYSTEM: HEAT REJECTION - REENTRY AND ATMOSPHERIC FLIGHT

CONCEPT: FREON 22

FLIGHT AVAILABILITY: 1975

Mission Phase Application

Launch*____ Orbit*____ Reentry x Cruise x

*May be used, if required

RELIABILITY: 0.999936 MTBF: 41,700

4 Men - 7 Days Plus 48 Hours Contingency

	Equivalent Wt. (lb)	Volume (ft^3)	Power (watts)
Installed Unit	209	74	484
Expendables	980	-	-
Power Equiv. Wt.	77.5	-	-
Totals	1266.5	74	484

Cost Factor	
Recurring -	1.3
Nonrecurring -	1.3
Total -	1.3

Crew Time (hrs)	
Scheduled -	0
Ground Refurbishment -	0.5

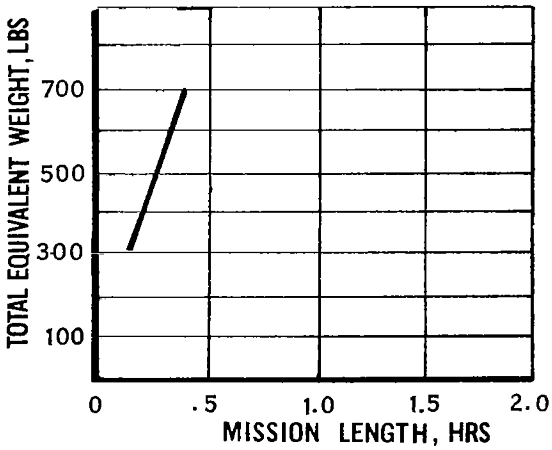


Figure 60 Freon 22 (Data Sheet)

SUBSYSTEM: HEAT REJECTION - REENTRY AND ATMOSPHERIC FLIGHT

CONCEPT: CRYOGENIC HYDROGEN

FLIGHT AVAILABILITY: 1975

Mission Phase Application

Launch*____ Orbit*____ Reentry _x_ Cruise _x_

*May be used, if required

RELIABILITY: 0.999942 MTBF: 137,500

4 Men - 7 Days Plus 48 Hours Contingency

	Equivalent Wt. (lb)	Volume (ft^3)	Power (watts)
Installed Unit	33.1	2.0	5
Expendables *	36.4	6.7	-
Power Equiv. Wt.	0.8	-	-
Totals	70.3	8.7	5

* Includes Tankage Penalty

Cost Factor

Recurring - 1.0

Nonrecurring - 1.0

Total - 1.0

Crew Time (hrs)

Scheduled - 0

Ground Refurbishment - 0

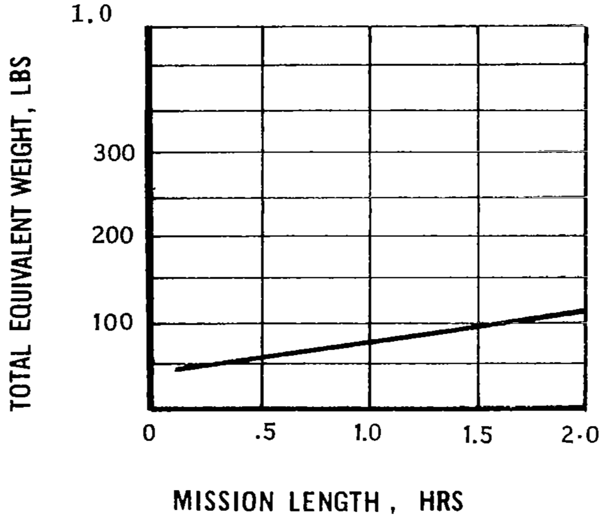


Figure 61 (Page 1 of 2)

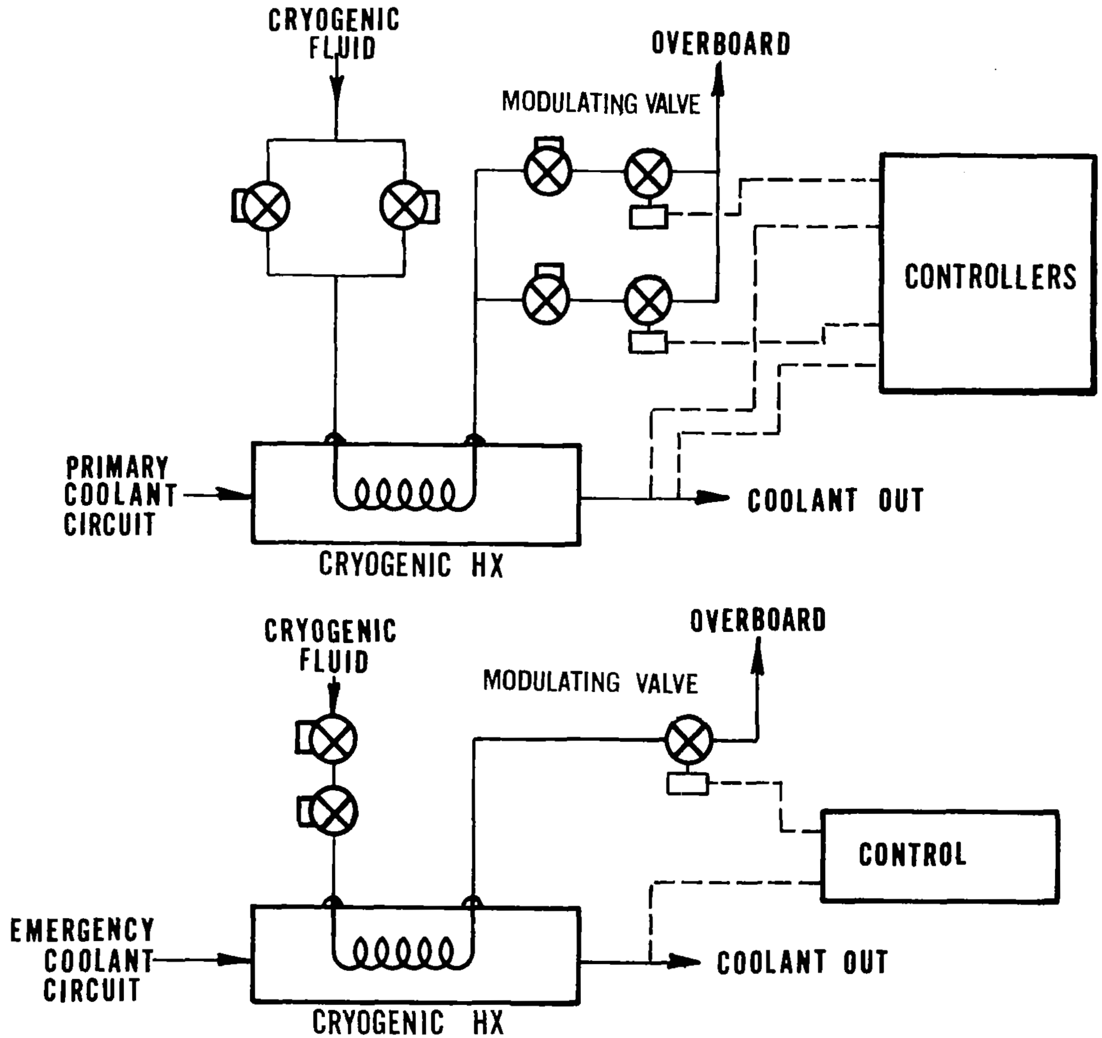


FIGURE 61. CRYOGENIC HYDROGEN (PAGE 2 OF 2)

Since hydrogen is combustible, a potential safety hazard can exist upon reentry. It is recommended therefore, that the hydrogen be vented to either the engine exhaust, APU exhaust or hydrogen tankage venting area.

Quantitative criteria. - This concept is by far the lightest of the candidates evaluated for the reentry and atmospheric flight phases of the mission. Volume and ROM costs are low.

Qualitative criteria. - The concept is adaptable to all mission phases and can also complement the radiator for heat rejection during the orbit phase. The concept is simple (few moving parts) and flexible. The large temperature gradients across some of the components and the equipment temperature cycling may result in the concept's durability being hindered. Refurbishment consists of purging the subsystem with inert gas in order to replace any of the components. Checkout is simple. No in-flight maintenance is required.

Cryogenic Oxygen

This concept is identical in operation to the previously discussed cryogenic hydrogen approach (see figure 61).

Absolute criteria. - The cryogenic oxygen concept possesses essentially the same absolute characteristics as the previously discussed cryogenic hydrogen approach. Furthermore, this concept possesses the additional requirement of developing a control for two-phase flow. The control problem results from the fact that more than one flow rate can exist at a specific ΔP of the control valve and heat exchanger, depending on the quality of the entering fluid. A general data sheet is shown in figure 62.

Quantitatiave criteria. - This concept is much heavier than the cryogenic hydrogen approach because the thermal capacitance of oxygen is much lower than that of hydrogen. Volume and ROM costs are low as is the cryogenic hydrogen approach.

Qualitative criteria. - This concept is adaptable to all mission phases and can also complement the radiator for heat rejection during the orbit phase. The concept requires a more complex control scheme than the cryogenic hydrogen approach. The effect of increased crew size and mission length is more severe than either the cryogenic hydrogen or ammonia approaches because the available heat capacitance is lower. Due to the control method for two-phase flow the durability is lower than the cryogenic hydrogen concept. Refurbishment consists of purging the subsystem with inert gas in order to replace any of the components. Checkout requires a verification of the operational status of the control scheme. No in-flight maintenance is required.

SUBSYSTEM: HEAT REJECTION - REENTRY AND ATMOSPHERIC FLIGHT

CONCEPT: CRYOGENIC OXYGEN

FLIGHT AVAILABILITY: 1975

Mission Phase Application

Launch*____ Orbit*____ Reentry x Cruise x

*May be used, if required

RELIABILITY: .0.999942

MTBF: 137,500

4 Men - 7 Days Plus 48 Hours Contingency

	Equivalent Wt. (lb)	Volume (ft^3)	Power (watts)
Installed Unit	38.4	2.0	5
Expendables	326.4	4.6	-
Power Equiv. Wt.	0.8	-	-
Totals	365.6	6.6	5

Cost Factor

Recurring - 1.0

Nonrecurring - 1.0

Total - 1.0

Crew Time (hrs)

Scheduled - 0

Ground Refurbishment - 0

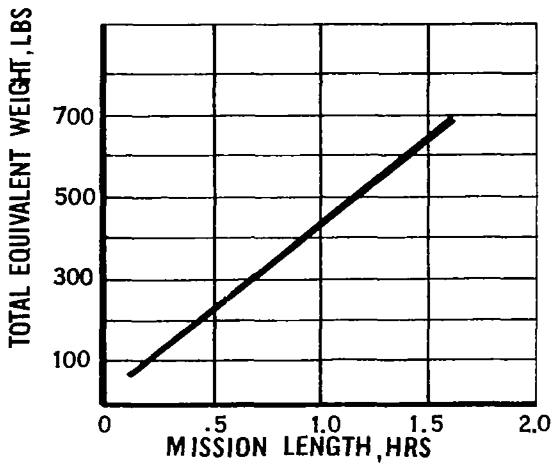


Figure 62 Cryogenic Oxygen (Data Sheet)

Evaluation and Selection

A cryogenic hydrogen heat sink is selected for the reentry and atmospheric flight phases based on the selection criteria. It has the lowest weight, equals the cryogenic oxygen concept for lowest cost, and is only slightly greater than the cryogenic oxygen concept in volume. If the cryogenics used are excess, and no weight or volume penalty is required for their use (OMS tank ullage), the selection between O_2 and H_2 must be made on the basis of availability. If there is both gas and liquid in the cryogenic tank, the H_2 concept will be lighter and lower in cost than the oxygen subsystem because a two-phase flow control requirement exists with oxygen. An evaluation summary is presented in table 22.

Absolute criteria. -

Performance: The ram air concept was dropped from further consideration as it did not meet the performance requirements. The air cycle concept was rated Fair because of the additional heat sink required and marginal performance during the reentry phase of the mission. All of the expendable concepts were equally good in performance.

Safety: All of the remaining candidate concepts were rated Good from the safety standpoint except the ammonia approach, which was rated slightly lower due to its toxic nature.

Reliability: The reliability of each approach (except the ram air concept which was not carried past the performance criteria) is presented in their respective data sheets. The cryogenic approaches have the highest MTBF and are rated Very Good. The air cycle, expendable ammonia and Freon concepts have approximately the same MTBF and are rated slightly lower. All of the concepts have acceptable reliability.

Availability: The air cycle concept because of its successful application in most military and commercial aircraft, the ammonia concept for its application in the B70 aircraft and Freon for its utilization in the common place refrigerator and its utilization for ground cooling of the Apollo program's Lunar Module (LM) are all rated equally high. The cryogenic approaches were rated slightly lower due to the two-phase control scheme required for the oxygen concept, plus the required development of a lightweight heat exchanger.

The result of the comparison is that the ram air concept is eliminated because of unacceptable performance while all of the other approaches meet the absolute criteria.

Quantitative criteria. -

Total equivalent weight: figure 58 shows the effect of mission length on the total equivalent weight of the candidate concepts. For all mission lengths, the cryogenic hydrogen has the lowest total equivalent weight. The difference between the cryogenic

TABLE 22

EVALUATION SUMMARY - HEAT REJECTION - REENTRY AND ATMOSPHERIC FLIGHT

Criteria		Ram Air	Ammonia	Air Cycle	Freon 22	Cryogenic H_2
Absolute	Performance	Poor	Very Good	Fair	Very Good	Very Good
	Safety	Fair	Fair	Good	Good	Good
	Reliability	Good	Good	Good	Good	Very Good
	Avail. /Conf.	Very Good	Very Good	Very Good	Very Good	Good
		Eliminated				
Quantitative	Total Equiv. Weight		Fair	Fair	Poor	Very Good
	ROM Cost		Good	Poor	Good	Very Good
	Volume		Good	Good	Poor	Very Good
			Eliminated	Eliminated	Eliminated	
Qualitative	Complexity					Very Good
	Flexibility					Very Good
	Durability					Good
	Refurbishment					Fair
	Checkout Capability					Very Good
	Maintainability					Very Good
						Selected

TABLE 22 (Concluded)

EVALUATION SUMMARY - HEAT REJECTION - REENTRY AND ATMOSPHERIC FLIGHT (Concluded)

Criteria		Candidate Concepts				
		Cryogenic O_2				
Absolute	Performance	Very Good				
	Safety	Good				
	Reliability	Very Good				
	Avail./Conf.	Good				
Quantitative	Total Equiv. Weight	Fair				
	ROM Cost	Very Good				
	Volume	Very Good				
		Eliminated				
Qualitative	Complexity					
	Flexibility					
	Durability					
	Refurbishment					
	Checkout Capability					
	Maintainability					

hydrogen approach and the nearest competitor at the design condition (0.8 hour) is approximately 400%. In actuality, this spread would be even greater because the total equivalent weight of the air cycle does not include the weight penalty assessed for additional heat rejection during the reentry phase and the additional weight of ram scoops and ducting.

The air cycle, ammonia and cryogenic oxygen concepts are rated Fair while the Freon approach, because of its low heat of vaporization, results in an excessive total equivalent weight and a Poor rating.

ROM cost: The relative cost of each concept based on total program cost is presented in table 23. The cryogenic concepts have the lowest cost and are rated Very Good. The ammonia and Freon concepts were rated slightly lower as the costs are each approximately 30% higher. The air cycle, which possesses the highest cost, is rated Poor.

Volume: A summary of the volume for the candidate concepts is also shown in table 23. As shown, the cryogenic oxygen concepts have the lowest volume. The cryogenic hydrogen was rated equal to the cryogenic oxygen approach as the difference between them is relatively small. The ammonia and air cycle concepts were rated slightly lower. The Freon approach has the largest volume and was rated Poor.

Upon completing the quantitative evaluation, the Freon concept was dropped from further consideration because of its excessive total equivalent weight and volume. The ammonia and air cycle concepts were also eliminated from further consideration. The ammonia concept because of high total equivalent weight and the air cycle concept because of high cost and total equivalent weight. The cryogenic oxygen approach was also eliminated from further consideration because of its high total equivalent weight. Therefore, the cryogenic hydrogen concept is selected as the heat sink for the reentry and atmospheric flight phases of the mission. This concept has the lightest weight, lowest cost, and highest MTBF of all the concepts.

As a matter of study methodology, the selected cryogenic hydrogen approach was carried through the qualitative criteria.

<u>Qualitative criteria.</u> -

Complexity and flexibility: The cryogenic heat exchanger can be used for all mission phases and can also be used to complement the radiator during orbit. It has few moving parts and is rated Very Good for both complexity and flexibility.

Durability: Due to the large temperature gradients across some of the components and the temperature cycling of the equipment, the cryogenic hydrogen concept is only rated Good for durability.

TABLE 23

QUANTITATIVE SUMMARY-HEAT REJECTION, REENTRY AND ATMOSPHERIC FLIGHT PHASES

Concept	MTBF (Hrs)	Fixed Weight (lbs)	Power (Watts)	Total Equivalent Weight (lbs)	Total Program Cost Factor	Volume (ft^3)	Crew Time (Hrs)
Air Cycle	38, 100	288.0	0	288.0	2.3	18.0	0
Ammonia	41, 700	145.7	470	404.7	1.3	21.0	1.0
Freon 22	41, 700	209.0	484	1266.5	1.3	74.0	0.5
Cryogenic Hydrogen	137, 500	33.1	5	70.3	1.0	8.7	0
Cryogenic Oxygen	137, 500	38.4	5	365.6	1.0	6.6	0

Refurbishment: Refurbishment is rated Fair as the subsystem must be purged with inert gas in order to replace any of the components. This is not a major problem, but it does complicate ground refurbishment.

Checkout and maintainability: Checkout capability and maintainability are rated Very Good. The subsystem is completely automatic and requires no maintenance. Due to its automatic operation it can easily be checked out by the onboard computer.

PRELAUNCH AND POST LANDING

For prelaunch and post landing mission phases the main methods of removing the thermal heat load are expendables and Ground Support Equipment (GSE).

Continuous topping of the vehicle cryogenic tanks during prelaunch permits the installed cryogenic heat exchanger to be used with no system penalty. However, it is anticipated that GSE cooling will be required for the booster during prelaunch and, therefore, will be available for vehicle cooling if so desired. The choice of whether to use the cryogenic or GSE heat exchanger for prelaunch does not effect the concept or vehicle weight, but depends on an operations analysis of the mission phase.

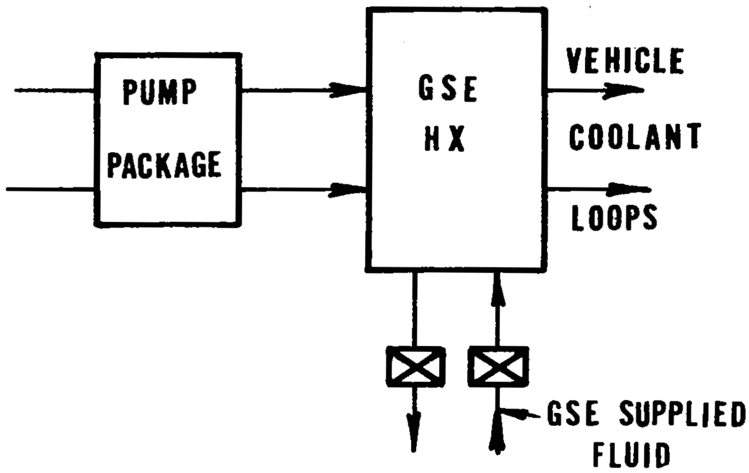
It has been assumed for this study that GSE will be available to supply cooling fluid where the vehicle lands. For post landing, the amount of cryogenics available is presently unknown. It is, therefore, recommended that GSE be used for cooling during the post landing phase.

The two basic types of GSE cooling are (figure 63):

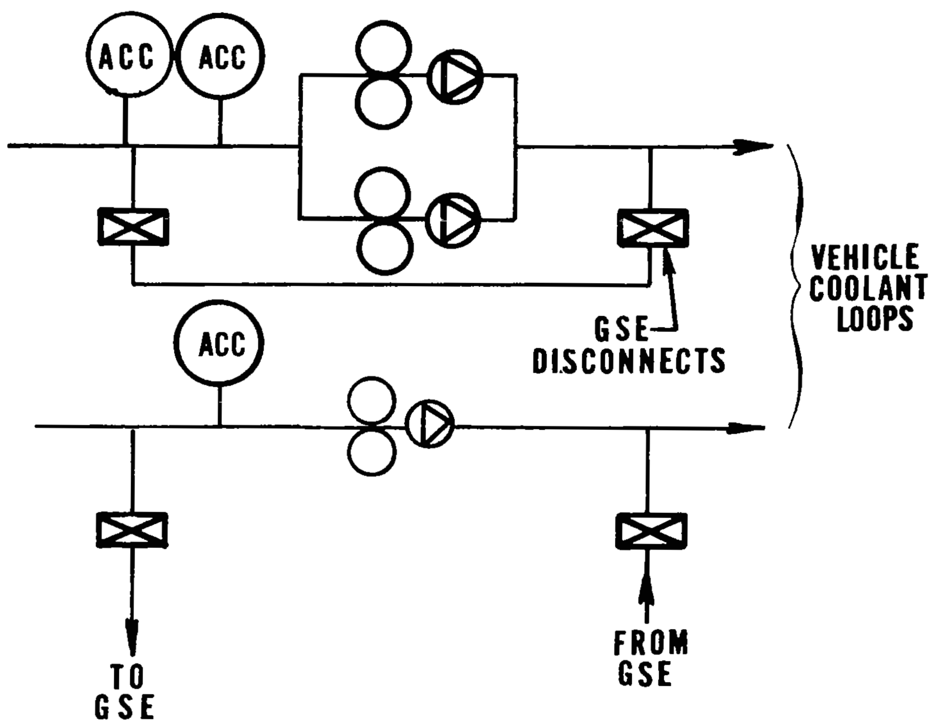
- A heat exchanger in the vehicle with cooling fluid supplied to the heat exchanger by the GSE

- Disconnects around the vehicle pump with cooling fluid pumped through the vehicle heat rejection loop by the GSE.

With an installed heat exchanger, the vehicle heat rejection loop is intact and the vehicle pumps operate when cooling is desired. It is estimated that this approach will be approximately 14 pounds heavier than the concept which supplies coolant fluid direct into the vehicle heat rejection loop. The major advantages of the installed heat exchanger are that potential contamination and air inclusion into the vehicle heat rejection loop from the GSE is precluded and that subsystem integrity is maintained. These reasons are considered enough to offset the 14 pound weight difference. Therefore, the installed GSE heat exchanger is selected.



CONCEPT A



CONCEPT B

FIGURE 63. GSE HEAT REJECTION SCHEMATIC

In conclusion, the selected methods of heat rejection for the prelaunch and post landing phases result in no additional internal vehicle equipment being required. This weight savings is a result of utilizing a cryogenic heat exchanger for thermal control during the reentry phase and a GSE heat exchanger as the heat sink during ground verification and checkout prior to the prelaunch phase.

FERRY FLIGHT

For this mission phase, weight and power are of secondary concern. The overriding criteria are cost and basic vehicle modifications required to accommodate this phase. It is undesirable to add equipment (to be carried throughout the remainder of the mission) in the cabin to provide a heat sink for this mission phase only.

The two basic methods available for cooling are:

- Air cycle
- Cryogenic heat exchanger

The other expendable concepts (Freon and ammonia) result in an excessive weight penalty (approximately 6200 pounds of ammonia versus approximately 1650 pounds of cryogenic hydrogen with Freon even a greater penalty) for the 4-hour ferry mission and, therefore, were not considered.

Cryogenics must be loaded to supply the Auxiliary Power Unit and the fuel cells. It is assumed that the additional hydrogen required for vehicle cooling, during this phase, can be available at a small cost penalty. As no additional hardware is needed, the cryogenic heat exchanger is the selected means of cooling during the ferry flight.

EMERGENCY

Two emergency conditions are considered, one in which the radiator is operable, and the other where the emergency is made more critical due to a failed radiator.

An on-orbit emergency condition with a loss of the radiator requires the vehicle to operate nominally during an orbit hold for a maximum of twelve hours. Under these conditions, the methods of heat rejection considered are two expendable heat sinks; water evaporator and cryogenic (hydrogen) heat exchanger. The two factors which affect the selection of the expendable heat sink are the storage penalty and the heat capacitance of the expendable under consideration.

The evaporator sized for the nominal baseline mission can not supply adequate thermal control under these conditions and, therefore, would require resizing. Furthermore, the excess fuel cell water (approximately 60 pounds of water per day) would have to be supplemented with stored water (approximately 580 pounds). An alternative would be to supply the cryogenic heat exchanger with hydrogen fluid from the vehicle propellant storage system (OMS). The cryogenic heat exchanger is sized to handle the thermal load during the reentry phase. As the heat load during reentry is greater than that required for the orbit phase, a redesign would not be necessary. Should resizing of the OMS tankage be required to handle the additional expendable, it would result in less of a system impact than if water is stored for evaporation. The cryogenic hydrogen also possesses a higher heat capacitance (1600 Btu/lb) than water (1050 Btu/lb) thereby providing a greater capability for heat rejection. For the above reasons, it is recommended that the cryogenic heat exchanger be used as the heat rejection method during this emergency condition. In addition, the available excess fuel cell water can be used for supplementary cooling should the need arise.

For an emergency condition with an operable radiator (48 hours), subsystem operation is identical to the nominal on-orbit operation. That is, the radiator and evaporator providing the required thermal control. Therefore, this emergency condition results in no direct impact on the selected heat rejection subsystem.

IMPACT OF MISSION PARAMETERS

The effect of increases in crew size and mission length on the selected heat rejection subsystem are discussed below.

Crew Size

Increases in crew size can be accommodated by using the cryogenic heat exchanger to supplement the radiator and evaporator in reducing the heat rejection loop temperature. A temperature of 34 °F was selected as the minimum heat rejection loop temperature to prevent the water from freezing in the interface heat exchanger. At the minimum temperature, the crew size can be increased to six men while still maintaining the 65 °F cabin temperature requirement. As the crew size is increased above six men, the minimum cabin temperature that the system can attain would be greater than 65 °F. In addition, the fuel cell outlet temperature will exceed 150 °F at maximum heat loads with a crew size of seven or eight men. Therefore, under these conditions, a resizing of the interface heat exchanger and an increase in the heat rejection loop flow rate would be required to meet the cabin temperature and fuel cell outlet temperature requirements.

Mission Length

Increases in mission length have no impact on the heat rejection subsystem weight. The radiator size being fixed, requires the excess fuel cell water to be evaporated for the subsystem to handle the total thermal load. No additional expendables are required.

WATER MANAGEMENT

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WATER MANAGEMENT

The function of the water management subsystem is to store and deliver potable water for use on demand for drinking, food preparation, washing, urinal flushing and heat rejection. The water for these uses is supplied by the vehicle fuel cells.

Figure 64 illustrates the amount of stored water available or required per day as a function of crew size for various water use schemes. With a 5.0 kW fuel cell, more than sufficient water is available for a four-man crew, when using water for drinking, food preparation, washing, and urinal flushes. Table 24 shows the water delivery requirements for the baseline system. The detailed shuttle requirements are defined in the Requirements/Guidelines (appendix A) of this report. The remaining water (62.4 lb/day) is available for heat rejection or for other purposes. Since a surplus of water exists, no water reclamation system is proposed for the baseline shuttle mission.

In performing the functions of storage and delivery of potable water, the subsystem must meet the following water contamination control requirements:

- Potability requirements established for space applications are defined by NASA-MSC "Potable Water Specification" SD-W-0020 and the Space Science Board (SSB) Ad Hoc Panel on Water Quality Standards for Long-duration Manned Space Missions. These standards are shown together with a typical analysis of Apollo fuel cell water in table 25. This comparison shows that the water is essentially potable as received from the fuel cells.

- In the event of microbiological contamination of the water supply, provisions must be available to assure sterility at crew consumption delivery points.

- Required maintenance operations, if necessary, such as changing filters, should not contaminate the potable water supply, the crew or the cabin atmosphere.

Subsystem equipment includes storage tanks, delivery lines, valves and controls. The subsystem meets the fail operational-fail safe requirement using redundant hardware as necessary.

POTABLE WATER STORAGE

Fuel cell water, because it is available, is directed to the potable water storage tanks for future subsystem use. This water (102 lb/day) is free of bacteria and microorganisms on leaving the fuel cells.

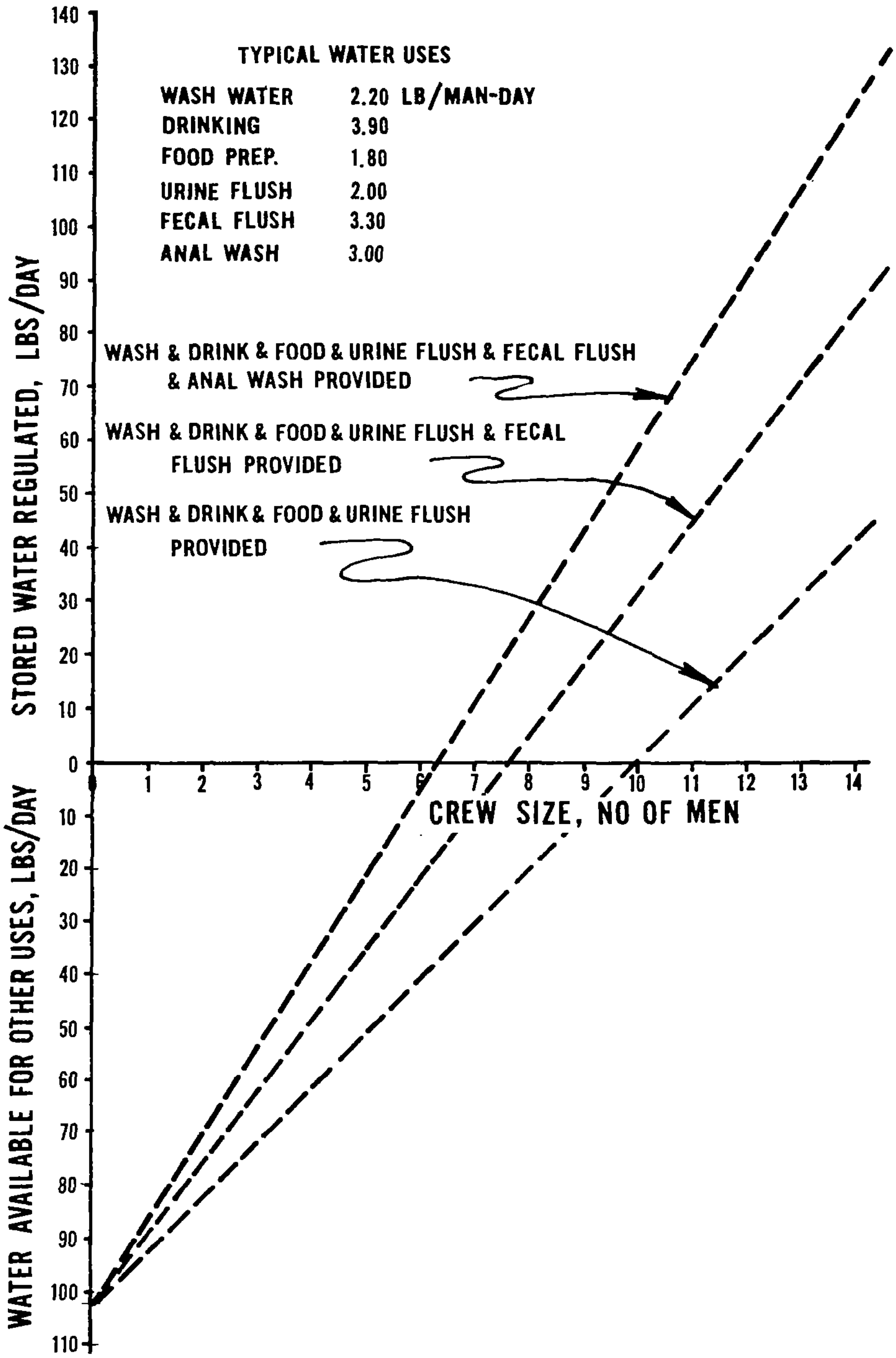

FIGURE 64. STORED WATER VERSUS CREW SIZE

TABLE 24

WATER DELIVERY REQUIREMENTS (FOUR-MAN CREW)

Use	Temperature (°F)	Nominal Delivery (lb/day)
Wash Water Required	As required	8.80
Drinking	45	15.60
Food Preparation (hot)	160	3.20
(cold)	45	4.00
Urine Flush	60 to 100	8.00
Heat Rejection	60 to 100	As required

TABLE 25

POTABLE WATER STANDARDS

Compound or Property	MSC-SPEC-SD-0020	Space Science Board	Apollo Fuel Cell Water Analysis Kelsey-Seybold Clinic (except as noted)
Chemical (mg/l)			
Arsenic	——	0.50	0.0*
Barium	——	2.00	0.30*
Boron	——	5.00	Not tested
Cadmium	0.01	0.50	0.01 0.00*
Chloride	——	450.0	0.10
Chromium	0.05	0.05	1.0 Lowest sensitivity 0.0*
Copper	1.0	3.00	0.05 0.01*
Fluoride	——	2.00	0*
Iron	0.3	Unobjectionable	0.1 0.01*
Lead	0.05	0.20	0.1 0.001*
Magnesium			Trace*
Manganese	0.05	Unobjectionable	0.05 0.01*
Mercury	0.005	——	1.0 Lowest sensitivity
Nitrate	——	10.00	0.04*
Nickel	0.05	——	0.05
Selenium	0.05	0.05	Not tested
Silver	0.05	0.50	0.05 0.001*
Sulfate	——	250.00	0.20*
Zinc	5.0		0.05 0.0*
Alkyl benezene sulfonates (ABS)	No foam	No foam	0.0*
Chemical oxygen demand (COD)	< 100	100	0.0*
Physical			
Turbidity (Jackson) max.	11 units**	10 units	0.9 units
Color, true (Pt-Co) max.	15 units***	15 units	5 units
Odor (TON)****	None at TON of 3	Unobjectionable	Unobjectionable
pH	6.0 - 8.0	——	7.0
Solids (ppm)***** max.	500	1000	3
Taste	None at TON of 3	Unobjectionable	Unobjectionable
Microbiological			
Coliform test (MPN)******	None	——	0.0
Total count/ml.	0	10 organisms	0.0

* Pratt and Whitney analysis

** Length of a light path (cm) as measured by a candle turbidimeter (lower the turbidity (units), the longer the light path).

*** 1 mg platinum, in the form of the chloroplatinate ion

**** Threshold Odor Number

***** Parts Per Million

****** Most Probable Number

A properly designed water management subsystem does not introduce contaminants into the system and should maintain the potability of the water. This is accomplished in the selected shuttle EC/LSS by using water obtained from the fuel cells and by storing and circulating the water at 160°F. This conclusion was reached after considering various methods of microbiological control of the water.

Microbiological Control

The sterilization procedures considered as applicable for the shuttle water subsystem include: pasteurization, chemical addition(chlorine or iodine) and silver ion generation. These processes are discussed below.

Pasteurization. - Microorganisms have a limited temperature range in which they can grow and reproduce. The addition of heat to increase the contaminated environment temperature above 140°F for an established period of time will kill most vegetative organisms (figure 65). Pasteurization of water is accomplished by maintaining the water between 140°-160°F continuously or for a specific time interval. Pasteurization processing is well established commercially but has not been included in previous spacecraft.

Chemical addition. - Chemical treatment of water for microbial control has been a successful method for past and present spacecraft, municipal water supplies and industrial processes. The primary characteristic of chemical disinfectants is that to be effective, continuous chemical contact with contaminants is required. Since most of the chemical additives are readily soluble in water, the chemical microbial suppressant is readily diffused throughout the water management system. Chemical compounds can be neutralized, however, and depleted to levels which allow the microorganisms to grow. Monitoring the chemical concentration levels becomes a necessity to assure decontamination effectiveness. Additional factors that must be considered with the shuttle water management subsystem include: chemical toxicity, efficacy against varied organisms, outgassing, corrosivity, palatability and ease of use. Although many chemicals are available for control purposes, few can satisfy the requirements for use as a disinfectant for potable water. The addition of chlorine or iodine were considered as possible candidate concepts for this discussion.

Iodine: One of the best germicides available for all around activity and use is iodine. It is effective against a wide spectrum of organisms, over a wide pH range and with little variation in concentration. Water disinfection with iodine occurs in 10 minutes at eight ppm. Organ-iodides have been used including tetraglycine hydroperiodide (20 mg). Iodine is a strong oxidizing agent and reacts with many materials causing a rapid depletion from contaminated solutions. Residual iodine content of 0.5 ppm should be maintained to guarantee water sterility. The main disadvantage of iodine treated waters is the obvious iodine taste.

1. SALMONELLA TYPHOSA
2. VIBRIO COMMA
3. CORYNEBACTERIUM DIPHTHERIAE
4. STREPTOCOCCUS PYOGENES
5. PSEUDOMONAS AERUGINOSA
6. MYCOBACTERIUM TUBERCOIOSIS
7. STAPHYLOCOCCUS AUREUS
V. VIRUSES

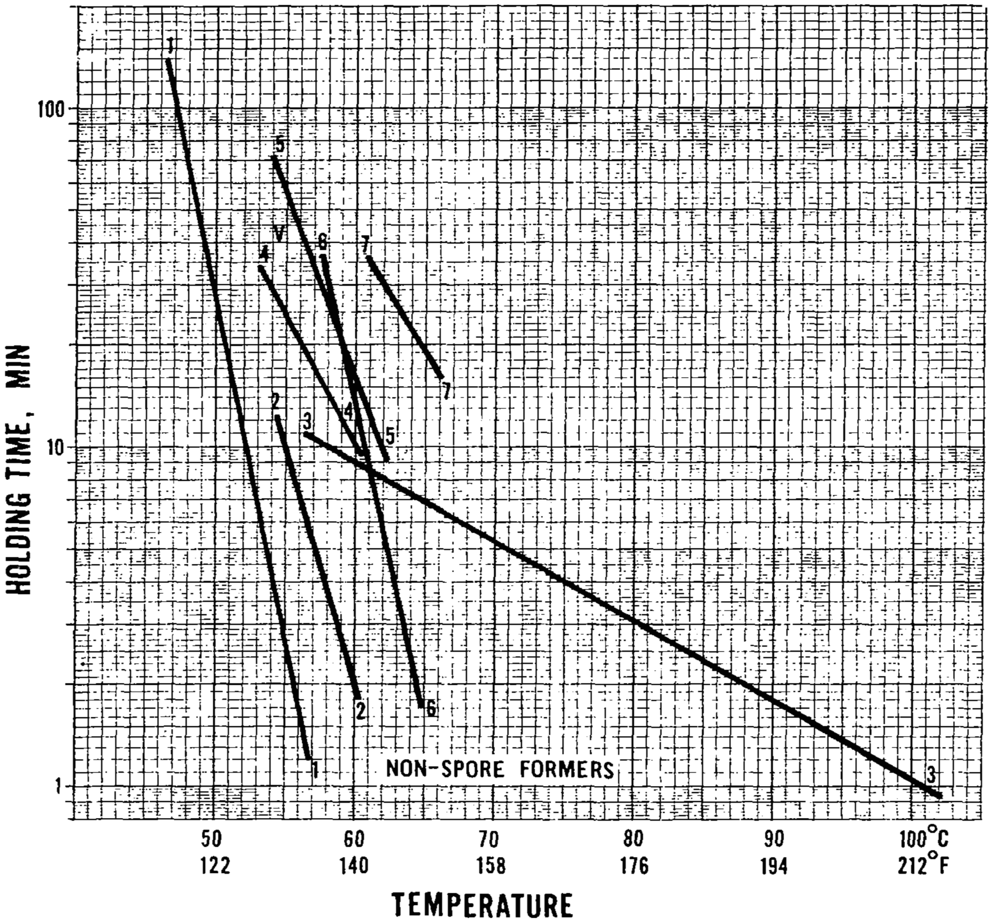

FIGURE 65. VEGETATIVE ORGANISM KILL RATE VERSUS TEMPERATURE

Chlorine: Chlorinated compounds such as sodium or calcium hypochlorites, chloramines and chlorine dioxide are effective microbicidal agents. Their effective range is not as wide as iodine and they are more reactive in an acidic environment. Chlorine treatment of water was used on the Apollo flights with the astronauts complaining of the chlorine taste. In the field, Halazone tablets (p-sulfondichloramidobenzoic acid) are used with success for emergency disinfection of water. Like iodine, contaminating compounds deplete the chlorine content of treated solutions. A residual of 0.5 ppm chlorine is required, after satisfaction of the initial chlorine requirement has been met, to guarantee sterility.

Both chlorine and iodine have been previously used in Apollo command module and lunar module flights respectively. Primary problems associated with their use have been maintaining an adequate concentration of the chemical in water.

Silver ion generation. - The sterilization or disinfection of water with metallic salts or ions is an established procedure for industrial uses. Copper, mercury, and zinc salts are used for bacteria and algae control but are required in high concentrations to overcome chemical neutralization. This results in processed water that is toxic for human consumption. However, some metals if retained in an ionic state provide effective antimicrobial activity in concentrations of less than 10 ppm. It is this oligodynamic activity of silver ions that is applicable for spacecraft water sterilization. There are a number of approaches for producing silver ions in the water management subsystem. Three methods are discussed below:

Static silver ion generator: In this approach, the water is passed over a piece of silver material. For effective bacteria control, a minimum ion concentration of 50-200 ppb must be maintained. Since silver oxide builds up on this type of generator, progressive degradation of the ion generation rate occurs and, therefore, this method is considered unacceptable.

Electrolytic silver ion generator: This process involves the passage of electrical current through water-immersed silver plates, which results in the release of silver ions into the water. The electro-chemical process is:

$$\text{ANODE:} \qquad Ag \longrightarrow Ag + e^-$$

$$\text{CATHODE:} \qquad H_2O + e^- \longrightarrow 0.5H_2 + OH^-$$

The water flow carries the silver ion away before it can travel to the cathode for reduction to silver oxide; hence, the ion generation rate does not degrade with time. Its major drawback is that its generation rate is difficult to hold within the required band.

Silver chloride column: In this approach, silver chloride is absorbed by the water where it forms silver and chloride ions, with only the silver ions acting as a bacteriocide. Limited development status of this approach makes an assessment of its suitability impossible at this time.

In addition to specific approach limitation as described above, there are more general limitations to the silver ion approach.

During the McDonnell Douglas 60-day Life Support System test, a flight prototype silver ion generator was used for periods of 21 and 10 days, respectively, providing a concentration of approximately 200 ppb. With the generator operating, bacteria filters located immediately downstream had to be replaced every ten days; without the generator operating the filters required replacement every four days. The silver ions provided only local sterility for organisms of the coliform group, and did not provide complete sterilization for the water management system. This inadequacy is attributed to two known characteristics of the silver ion; first, the fact that it is known to be most effective against intestinal bacteria and viruses and less effective against skin bacteria, and second, to its tendency to combine with trace chemicals in the water and/or plate out on metallic components in the system.

Finally, it is always possible that ion concentrations at water dispensers may be higher than acceptable concentrations for potable water. Therefore, ion exchange resin beds are required just upstream of dispensers to absorb the silver ions prior to water consumption.

It is concluded that silver ion generators themselves may be potentially attractive for increasing the life of bacterial filters but should not be the primary means for sterilizing a complete water management system.

Selection. - The pasteurization method is selected as the primary water microbiological control method because it offers the best performance at the least cost since the water is received at the pasteurization temperature of 160°F from the fuel cell. In addition, the method produces the most palatable water with a minimum of extra hardware. Heaters are installed in the insulated storage tanks to maintain the water at 160°F for positive bacteria control and for food preparation and washing. The power required to maintain the tanks at temperature is ten watts.

The iodine chemical addition method is recommended for maintaining bacteria control of the stored backup water because it is effective against a wide spectrum of organisms, over a wide pH range and with little variation in concentration. This water (100 lb) is stored for emergency (fail safe) use for the life of the mission. This method provides positive control of a fixed amount of water with no power or weight penalty. In addition, it is compatible for use in all types of water evaporators.

In between flights, the potable water supply lines will be sterilized by steam or by use of chlorine which will be flushed out prior to the start of the mission.

Liquid Tankage

Discounting design details, liquid tank concepts generally fall into two categories: bladder or diaphragm tanks, where the gas-liquid interface is positively maintained by a membrane; and bladderless tanks, where surface tension forces maintain the gas-liquid interface. Each of these are discussed below.

Bladder tanks. - Bladder tanks employ an elastomeric or metallic bellows flexible membrane so that positive expulsion is always possible. They provide good volume utilization, a means of fairly accurate quantity sensing, are easy to pressurize, and stable zero gravity fluid interface control.

The basic disadvantage of this type of tank lies with the bladder itself. Even allowing for substantial state-of-the-art advances in flexing bladder (or diaphragm) design, it must always be less reliable than a static tank. Any tank concept that requires maintenance is at an extreme disadvantage when compared to a tank concept where the reliability is identical to a structure with a high safety factor (virtually 1), and where no maintenance is anticipated.

Bladerless tanks. - Bladderless zero gravity tanks make use of the surface tension forces at a liquid-gas interface which cause the liquid surface to assume a geometrical shape yielding the smallest surface area, generally a quasi-spherical segment within the boundaries of the tank. This bladderless type of tank appears to comply with most of the tank requirements needed for storing the potable water prior to use in the Shuttle. The biggest asset of bladderless tanks is that they exhibit a potential for high reliability and long life. Their prime drawback, however, is that a true zero gravity water capability has yet to be demonstrated, particularly in the situation where accelerations (from maneuvers in space) tend to exceed the present tank surface tension capabilities. This results in floating liquid in the tank and loss of a positive interface. Also, liquid level indicators and heaters have to be designed for adequate tank operation.

Design concepts for this type of tank have ranged from relatively simple tapered cylindrical shapes (where the liquid will migrate to the smaller end) (figure 66) to spherical shapes with internal baffling ranging from simple to quite complex (figure 67). The purpose of internal baffling is to reduce a large area into many smaller areas, often with multidirectional acceleration resistance. At one concept extreme, then, a single cavity (i.e., tapered cylinder) tank would have little resistance to accelerations, while at the other extreme, a wick-filled tank would have a high resistance to accelerations, and might not even need a tank wall. As an example of a possible configuration, figure 66 shows a concept which incorporates a tapered

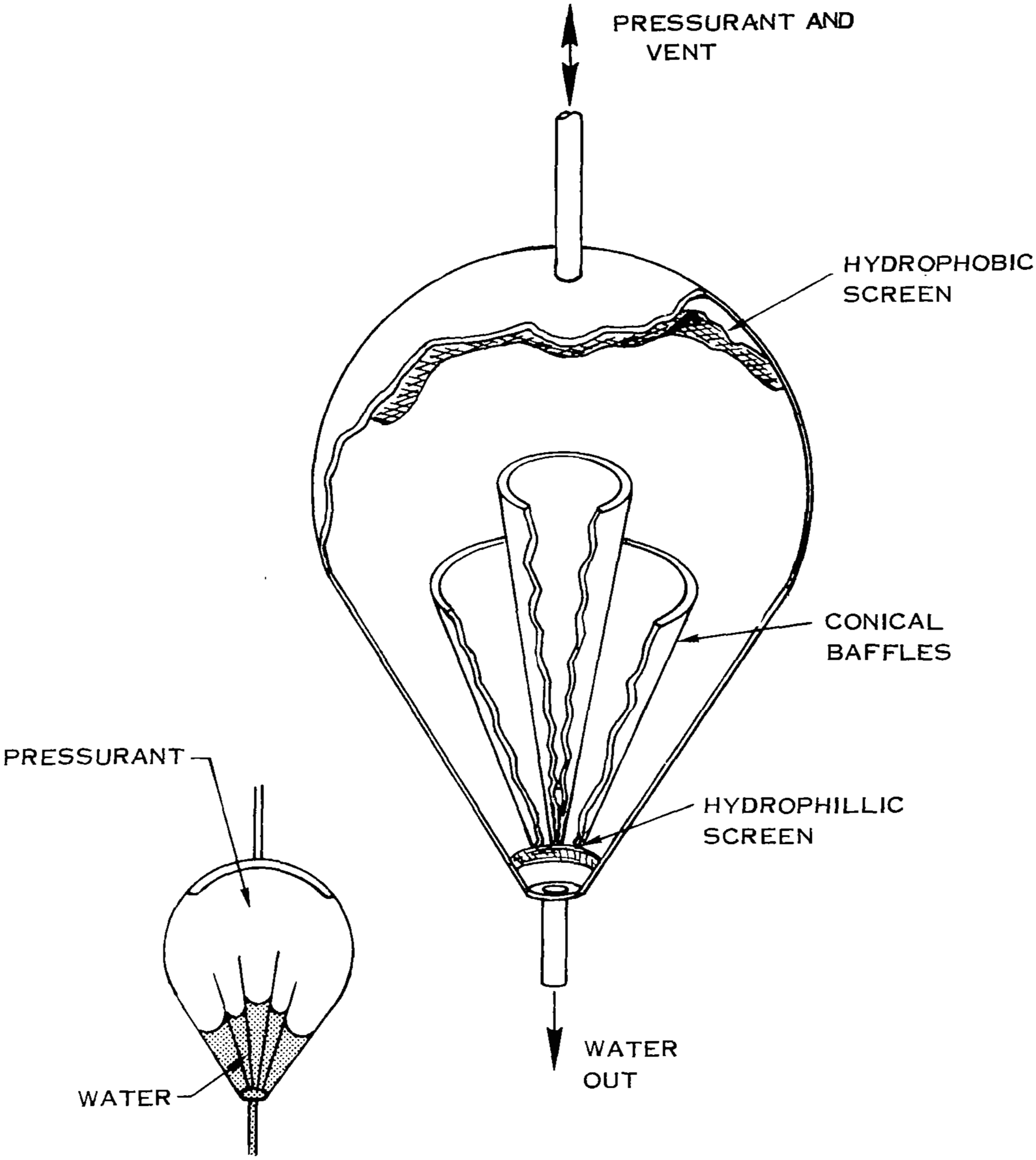

FIGURE 66. TAPERED CYLINDRICAL BLADDERLESS TANK CONFIGURATION

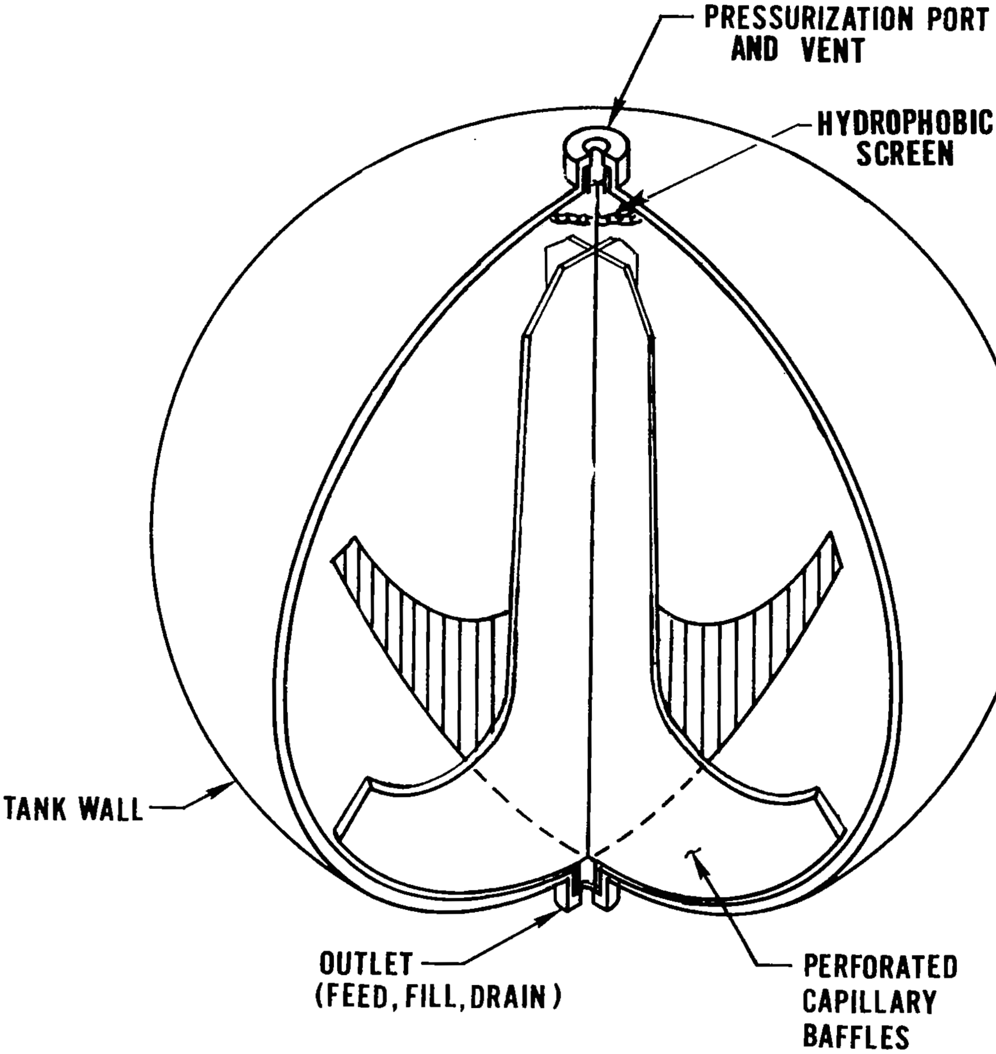

FIGURE 67. SPHERICAL BLADDERLESS TANK CONFIGURATION

cylindrical tank with simple conical baffles to resist small accelerations. This principle of the positive expulsion by surface tension phenomenon has been used on earth for some time; e.g., cigarette lighters and ball-point pens.

Another design consideration has to do with the venting of gas from the tanks. Basically, this requires control of the position of the gas bubble as well as of the liquid mass. While the problem is again one of controlling the interface, methods of assuring liquid at the outlet do not necessarily assure a coherent gas bubble. The same method of baffle design can, however, be used to accomplish this, or the vent tube opening can be hydrophobic. In this latter case, there still must be a single or a group of coherent bubbles. The most desirable configuration depends on the specific operating condition to which the tank will be subject and cannot be determined in general.

Selection. - Bladderless tanks, where applicable, are preferred over bladder tanks because of increased reliability and greatly reduced maintenance problems. They do pose a significant design problem, however, and more experimental work will be required to develop them practicable. In view of the improved performance they appear to offer, such development is deemed entirely warranted and possible by the shuttle flight date. Bladderless tanks therefore, are selected for storing the potable water supply as noted by the above reasons. Quantity sensing requires development. At the present time a sonar sensor device specially made to sense the tank configuration and liquid content offers the most promising method of sensing liquid quantity.

POTABLE WATER SUBSYSTEM

Potable water is collected and fed to the potable water management subsystem (figure 68) from the fuel cells.

The potable water storage tanks for the water management subsystem hold the potable water in an uncontaminated state until used. A bladderless zero gravity potable water tank, as discussed previously, is selected for use on the shuttle. In line with the recommendations for bacteria control, the primary tank contains a heater and insulation to hold the contents economically at 160°F. This will provide hot water at the required temperature and keep the stored water sterile. Two tanks are used, one on-line and the other for standby (fail safe) use. The equivalent of two failures must occur before the standby tank is used. Iodine is used to eliminate bacteria growth in the water stored in the standby tank. This method provides positive control of a fixed amount of water with no power or weight penalty.

The tanks size is based on a consideration of fill and drain times, failure cycles, and potable water requirements. These factors, including consideration of the 48-hour contingency period, led to the selection of two 100-pound capacity tanks.

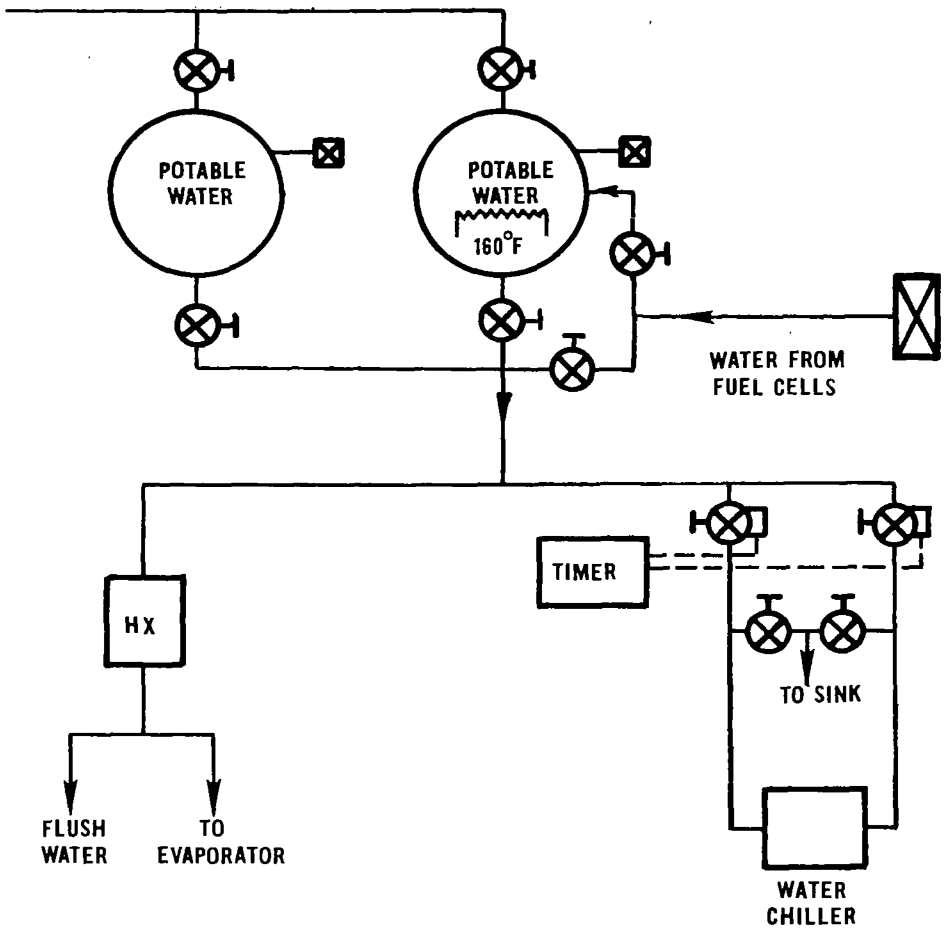

FIGURE 68. WATER MANAGEMENT SCHEMATIC

The amount of water available from the fuel cells is determined by the number and size of the cells (102 lb H_2O/day for a 5.0 kW power output). The amount of water required for food preparation, drinking, washing and urinal flush by the baseline system is 39.6 lbs H_2O/day (for a four man crew), with the remainder available for heat rejection. Both hot and cold water are processed and available for use. Hot (160°F) water, directly from the potable water storage tank, is used in food preparation. Hot or cold water, or any temperature between, is available for washing. Warm water (60-100°F) is used for evaporator operation and urine flushes to eliminate the possibility of ammonia formation during urinal flush, to reduce odor control requirements, and to prevent breakthrough during evaporator operation. It is derived by passing hot water through a heat exchanger located in the cabin coolant loop downstream of the cabin heat exchanger. Cold water (45°F) used for drinking and some food preparation, is obtained by flowing the hot water through another heat exchanger (chiller) located upstream of the cabin heat exchanger.

Urinal flush water (0.33 lb of warm water per urination) is automatically injected into the urinal after each use to flush away residual urine. A total of 2.00 lb H_2O/man-day is used for urinal flushes. A bactericide, silver nitrate (0.002 lbs per urination) is also added with the flush water to maintain microbiological control of the urinals.

The balance of 62.4 lb H_2O/day is available for a heat rejection. The warm water, (60-100°F) is directed to the evaporator for cooling the radiator loop fluid on demand as required. If the quantity of water exceeds the demand, the excess water is dumped into the urinal automatically and subsequently dumped overboard.

One of the major subsystem design considerations is to avoid contamination of the potable water supply. Three sources of potential water contamination are present: humidity condensate, ambient air and urinals. They are controlled as follows: The humidity condensate (normally considered as a source of potable water) contains a high concentration of bacteria. As such, it is recommended that the condensate be isolated from the product water completely. To accomplish this, the condensate is transferred directly to the waste water dump system.

It is more difficult to isolate the potable water from the ambient airborne bacteria. The most frequent source of entry is at the crew cold water dispenser. The microorganisms can alight at water delivery points and enter the system through shut-off valves and swim in stagnant lines. This problem became evident during the McDonnell Douglas 90-day test where an accumulation of contaminants became readily visible on the tips of the cold water dispenser. To prevent bacteria entrance in this way, the hot and cold water lines are insulated and merged into one common line to the sink. The common line is periodically flushed with hot (160°F) water controlling bacteria buildup on the water dispenser. In addition, the hot and cold water inlet lines are automatically cycled every 24 hours. This cycling procedure with 160°F water automatically controls bacteria growth in both potable water lines. Appropriate indicators for crew use will be employed to facilitate delivery of water at the temperature desired.

Water for urine flush is mixed with a biocide (silver nitrate) prior to entry to the urinals for control of bacteria within the flush lines and urinals. The biocide addition eliminates the possibility of back contamination of the potable water supply.

Bacteria growth in the primary water storage tank is eliminated by maintaining the tank surfaces (and inlet) and water contents at 160°F. The possibility of bacteria entering the potable tank is reduced by using clean air from the atmospheric supply line for tank pressurization. Any bacteria that enters the tank is killed by the hot environment.

IMPACT OF MISSION PARAMETERS

A review of the impact of crew size and mission length on the selected concepts for water management shows that the selected subsystem is relatively unaffected by these parameters. The impact of longer missions has no impact with a crew size of four men.

Sufficient water is available for up to almost ten men assuming the water is used for food preparation, drinking, washing and urinal flush only. (See figure 64.) It would be advisable if the additional men are located in the payload module that additional water dispensers be provided.

WASTE MANAGEMENT

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WASTE MANAGEMENT

The function of the waste management subsystem is to collect, treat, store and/or dispose of all solid and liquid wastes. This includes collection, treatment, transport, storage and periodic evacuation of urine, waste waters and gases to space. The subsystem configuration must:

- Be psychologically and physiologically acceptable to the crew.
- Eliminate or control odors, aerosols, and irritating gases inside the cabin.
- Inhibit or eliminate micro-organism growth in the waste material.
- Eliminate manual handling of fecal material.

The major types of waste material found in the space shuttle cabin are:

- Liquid wastes including urine, humidity condensate, and wash water.
- Solid wastes including feces, tissue wipes, excess food, food packaging material and miscellaneous wastes as defined in the Study Requirements/Guidelines (appendix A). Included in this grouping are finger nails, clippings, hair, and vomitus.

For reporting purposes, this waste management subject is discussed in the following sections:

- Liquid Collection and Transfer
- Solid Waste Management Concepts
- Evaluation and Selection
- Waste Management Subsystem Description
- Impact of Mission Parameters

LIQUID COLLECTION AND TRANSFER

The objective of the liquid collection and transfer function is to provide a means for collecting urine, urinal flush water, wash water and humidity condensate and transporting it for storage or disposal.

Urine, collected separate from feces, can be readily accomplished and subsequently disposed of to vacuum. Thus, no long term storage for urine is required and the need for a large storage reservoir and a potential contamination problem is eliminated.

Urine

The collection and transfer of urine must be accomplished under zero gravity conditions while preventing the escape of urine to the cabin. A urine collection unit must be capable of being operated either separately or simultaneously with defeaction.

Three basic concepts are available for the collection and transfer of raw urine:

- Body contact seal urinal with manual transfer
- Liquid/gas flow with sponge/bladder pressurized transfer
- Air flow urinal with centrifugal phase separation/transfer

Body contact seal urinal with manual transfer. - This concept utilizes the velocity imparted to the urine by the crewman to transfer the fluid to a bladder. The urinal portion has an adjustable iris-type opening to prevent back flow during micturation. A penis seal diaphragm (each crewman is provided with his own diaphragm) is inserted after removing the sealing cap. The urinal is activated by closing a switch which energizes a blower-type phase separator. Cabin gas is drawn into the urinal through peripheral holes and transfers the urine to the bladder by pneumatic entrainment. A roller arrangement attached to the bladder is used to ensure that no air is present in the bladder prior to urination and to transfer the urine to the waste water storage tank. The urinal, flexible line, and separator are internally coated with teflon to prevent liquid adhesion. Provisions are made for water flush after each urination.

This concept has been used on Gemini and Apollo flights for urine collection. The seal prevents the leakage of urine to the cabin, but requires manual handling for operation. However, it is time consuming and considered unacceptable to the crew for future missions. A separate female body contact urinal, similar in function to the penis seal, could be designed to provide a seal against leakage of excreted urine and to incorporate a vaginal flush.

Liquid/gas flow with sponge/bladder pressurized transfer. - This second concept utilizes a blower that draws cabin air into the collector to provide a two-phase mixture during urination for zero gravity transfer. The mixture is drawn through a particulate filter to remove solid wastes, and a chemical disinfectant is added in a bacteria control unit. After passing through a selector valve, the mixture enters a reservoir containing a sponge-like substance with a nonpermeable membrane. Capillary action retains the urine while the cabin air is drawn through the sponge and returned to the cabin after passing through a charcoal bed for odor removal. Urine transfer is accomplished by changing the selector valve to expose the sponge material to a lower-pressure tank. The differential pressure across the bladder squeezes the sponge, thereby transferring the urine. This concept requires careful selection of the bladder and sponge materials and requires periodic maintenance of the sponge.

Air flow urinal with centrifugal phase separation/transfer. - This concept employs a motor driven fan/centrifugal water separator that draws air from the cabin through the urinal during urination. The air flow urinal, is similar to a conventional wall mounted urinal. It is adjustable in height so that the penis can be placed relatively near it. An air stream entering the collector entrains the urine, carrying it to the motor driven fan/centrifugal water separator. The mixture of air and urine passes through the unit where the liquid is separated from the process air flow. The air passes through a system bacteria filter and odor removal bed before returning to the cabin. The pressure head generated by the fan/centrifugal water separator transfers the raw urine to the waste water storage tank where it is held prior to discharge overboard. A water flush and a bactericide dispenser provide odor and bacteria control at the urinal. Appropriate filters are used for odor and bacteria control of process air flow. Male crew members will find this urinal "earth-like" and acceptable, since it does not require any body contact. An artist concept of this design is shown in figure 69.

Selection. - The air flow urinal with centrifugal phase separation/transfer concept is selected to collect and transfer urine because it provides an "earth-like" no body contact means of collecting urine commensurate with maximum crew acceptability. It also provides a pumping head to transfer the urine to the waste water storage tank without a manual operation.

The air flow urinal can be conveniently combined with a commode, forming a split-flow commode. The urine collector is built into the front half of the commode. A deflector separates the urine section from the feces collector for use by females. This concept requires two distinct openings in the commode. One is strictly for defecation, the other for urination. No problems arise during male use of this device. Female use of this commode requires raising the deflector and proper positioning on the commode, only because the direction of the urine stream is not assured as it

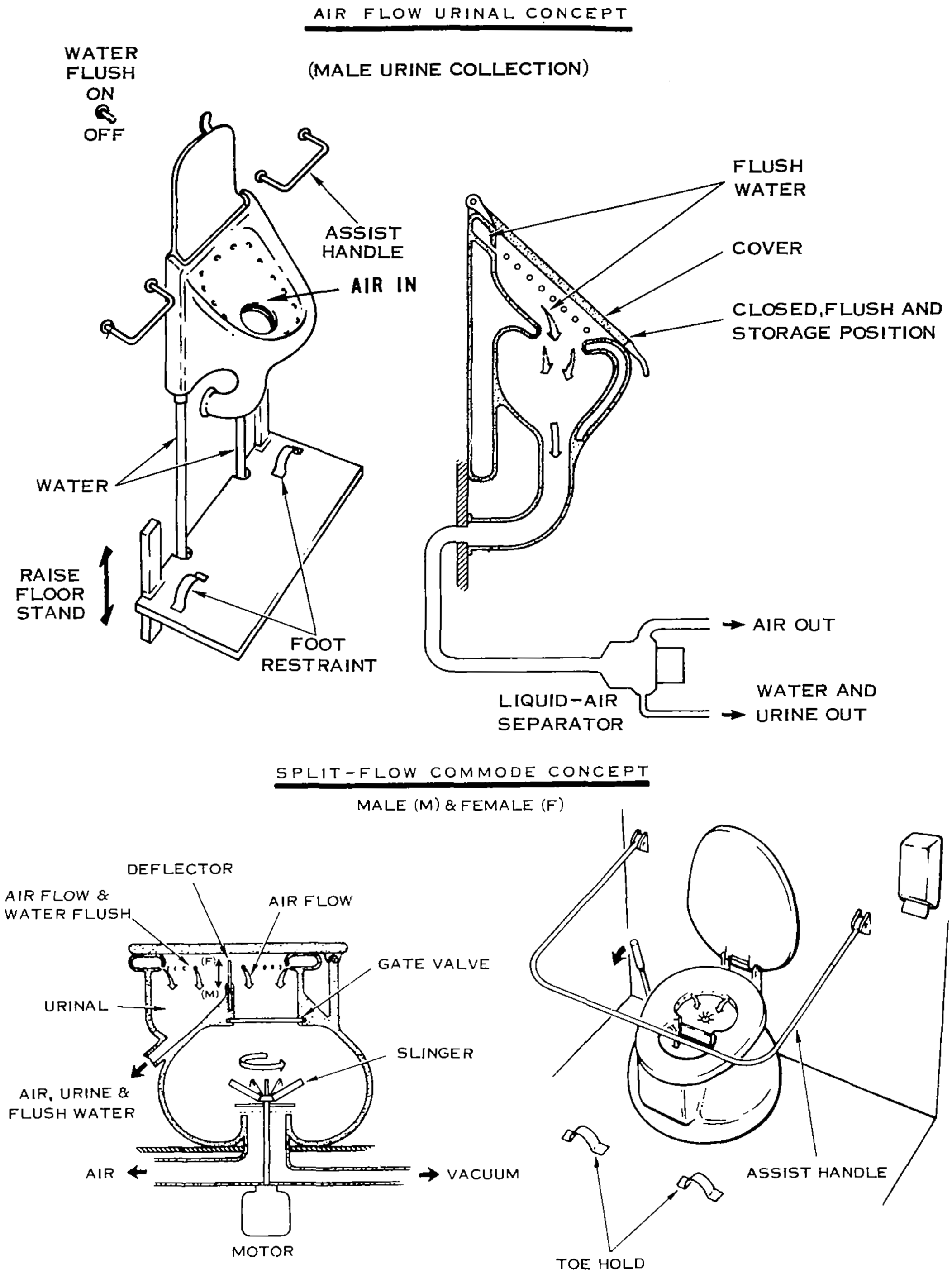


FIGURE 69. AIR FLOW URINAL AND SPLIT-FLOW COMMODE CONCEPTS

is with a male. Tissue wipes or a hand vaginal flush to clean after female urination is recommended. The wipes will be placed in the feces collector portion of the commode. This system provides a conventional "earth-like" waste collector which is acceptable to all crew members. An artist concept of this design is shown in figure 69. The development of these items is identified as pacing technology for the space shuttle.

In addition to the split-flow commode, a wall-mounted air flow urinal is recommended for male use for convenience and to provide an "earth-like" facility. A filter cover is provided to prevent material from entering the urinal when it is not in use.

A concept for a fan/centrifugal water separator is shown in figure 70. The motor driven unit must be operated at fairly high fan tip speeds to provide the required gas pressure rise and gas flow. Such high speeds, however, are not compatible with proper water separator operation, because splashing of the liquid (especially when it is displaced by a conventional pitot tube impact pump) will tend to cause foaming and re-entrainment of liquid droplets in the gas stream. This potential problem is eliminated by locating the air-water mixture inlet off center and opposite the fan inlet, so that a straight line path is not presented to the gas stream. The fan/centrifugal water separator consists of a rotating drum with an integrally-cast shrouded centrifugal fan wheel housing with its inlet facing the interior of the drum. Water droplets are forced to impinge on the spinning surface (interior of the drum) where they rapidly migrate under centrifugal action, to the gutter area (largest radius). Water is collected in a submerged torus with several small scuppers on its outer periphery. Since the toroidal pickup is in continuous contact with the water, with virtually no discontinuities in the water flow path to cause turbulence and splashing, water carryover is minimized. The pumping head generated by the rotating surfaces forces the water out of the separator.

Wash Water and Condensate

Wash water is collected in a liquid/gas flow sink, and transferred utilizing the liquid/gas flow with centrifugal phase separator/transfer concepts. The condensate is collected from the humidity control condensing heat exchanger elbow collector, and transferred, using again, the same liquid/gas flow centrifugal phase separators. Both the wash water and condensate are stored in the waste water tanks with the urine prior to disposal overboard.

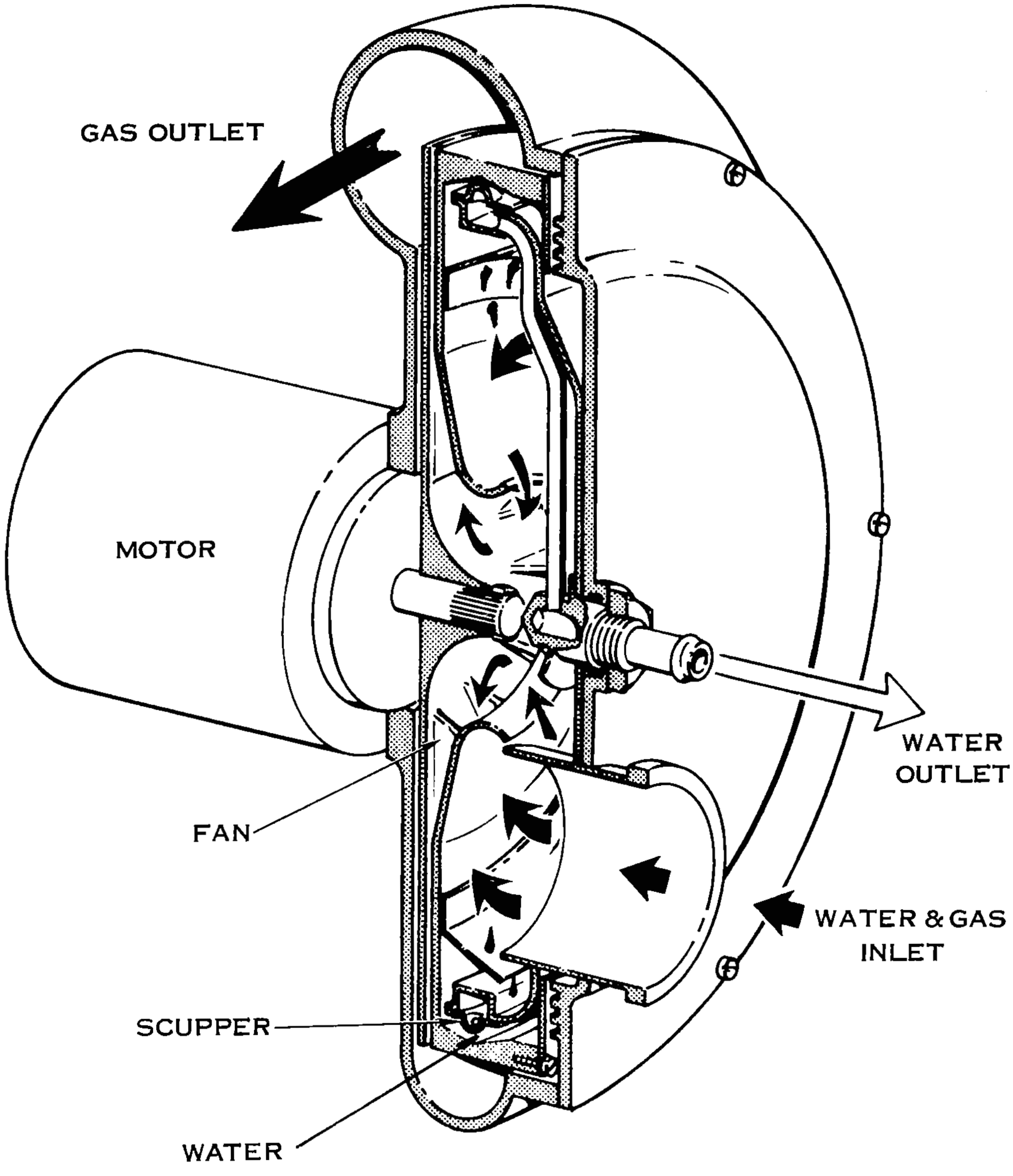


FIGURE 70. FAN/CENTRIFUGAL WATER SEPARATOR CONCEPT

SOLID WASTE MANAGEMENT CONCEPTS

The functions of the solid waste management subsystem include the collection, transfer, treatment, storage and/or disposal of feces, tissue wipes, unused food, food containers, and other miscellaneous debris generated in the cabin during a shuttle flight.

Fecal waste is delivered to a collecting device at a rate of 0.40 lb feces/man-day. Operation in zero gravity makes the collection and transfer of this waste more difficult than in the normal one "g" environment. The task is further complicated by requirements related to odor control, sanitation, convenience, psychological acceptance, and physiological suitability. An integrated vacuum drying concept is selected as the fecal waste management concept because of its low weight, power and volume and demonstrated ability to meet the above requirements.

A wall mounted urinal and one commode is provided in all fecal waste management candidates to fulfill the needs of a four-man crew in the cabin, unless the processing techinque, or reliability considerations requires two. Both urination and defecation (separately or simultaneously) can take place while seated on the commode. A process flow fan is utilized to provide positive zero gravity waste transfer into the collector, with odor and bacteria filters to prevent odors, aerosols, bacteria, etc., from escaping to the cabin. A single rechargeable charcoal filter cartridge for odor removal is provided with replacement scheduled after each mission. A separate bacteria filter removes the micron size bacteria from the process flow stream. The bacteria filter will be designed for replacement as a unit after each mission. If nausea occurs, vomitus collection and transfer to the waste collector is accomplished by an adapter. The adapter is a tube that can be fitted over the mouth of a sick crewman and used to direct all wastes including stomach gases into the commode.

Solid and liquid food wastes, which amount to approximately 0.5 lb/man-day, can rapidly become contaminated and colonized by micro-organisms, resulting in the production of fermentative and putrefactive gases and odors. Therefore, these wastes must be sterilized or treated to inhibit the growth of micro-organisms. Liquid food wastes 0.4 lb H_2O/man-day) are transferred to the waste water storage system via the liquid/air flow sink and solid food wastes (0.10 lb/man-day) are deposited into the commode. Frozen food containers are returned to the food freezer. Dry food packages and other dry wastes are stored in an air tight container. Bactericide is used to control bacteria growth within this dry waste material. It is sprayed into and on the item by the crew member when placed in the container.

In order to minimize the amount of particulate matter in the atmosphere, hair and fingernail clippings, etc. are collected using a debris collector attached to the commode. This device consists of a collector nozzle and flexible hose. It functions like a household vacuum cleaner. All candidate concepts evaluated possess identical debris and vomitus collection equipment.

During flights of the Mercury and Gemini programs, fecal waste collection was accomplished with a hand-held plastic bag. The bag contains a liquid chemical which is later manually kneaded with the feces to provide sterilization. Processes of this type were considered for evaluation, but discarded due to psychological considerations, and possibility of contamination. Long term storage of untreated wastes in pressure vessels is rejected for safety considerations, and overboard dumping of wastes is limited to gases and liquids.

Several waste management systems have been or are being developed that reclaim fecal water. However, as noted in the liquid collection and transfer section, the recovery of waste and urine water is neither necessary nor desirable for the shuttle mission. The use of a conventional sitdown commode is considered as the only practical feces collection system. It involves no actual handling of feces and is acceptable to all crew members. Tissue wipes will be used instead of an anal wash to ensure cleaning of the anus after defecation for the following reasons:

- The anal wash system requires complex controls and operation for a reliable operating system. Proper positioning of the body on the commode is mandatory to retain water within the commode and achieve the cleansing objective.

- Anal wash water temperature must be controlled to 90°-105°F for physiological reasons. In addition, the drying air must also be warmed to prevent excessive cooling in the area of the anus.

- An anal wash is not fully compatible with female use. The risk of contaminating the vaginal area with anal wash water is possible.

- The use of tissue wipes requires little training and it is as close to normal ground operation as possible.

- The tissue wipes system is lighter in weight, uses less power, and is less costly.

- No water is required. Although at the present time, an ample supply of water is available, if the heat load were to increase, the water saved could be used for heat rejection purposes.

Foot restraints and a body restraining belt (similar to a seat belt) or hand bar are provided to enable zero gravity operation.

The seven fecal waste management concepts evaluated are listed below:

- Freezing
- Bag Collection
- Liquid Germicide
- Integrated Vacuum Drying
- Pyrolysis
- Incineration
- Wet Oxidation

Other fecal waste management concepts such as anaerobic or aerobic biodegration, gamma or beta excited x-ray treatment were considered but rejected because of their early state of development and likely unavailability for the shuttle.

Each of the fecal waste management candidates contain a common process flow circuit consisting of an odor removal filter, a bacteria filter, process flow fans, transfer piping and shutoff valves, urine collection and transfer components.

Freezing

Freezing and storage of wet wastes at approximately $-20^{\circ}F$ inhibits production of micro-organisms and odors. The refrigeration system required may be provided by a low-temperature space radiator utilizing appropriate low freezing-point heat transport fluids.

Several inherent problems exist in such a system. First, a common collection and processing unit is not practical. Since the processed wastes must be held continuously at $-20^{\circ}F$, problems will arise in preventing heat up of the waste material during the collection mode. Second, transfer from the collector to the process unit will require manual transfer which is unacceptable. Longer collection periods could be incorporated; however, germicides or some vacuum drying would be required to inhibit the formation of bacteria until the wastes are refrozen. Addition of an automatic transfer system would result in unnecessary hardware complexity. Third, failure of the freezing unit presents a safety hazard in that considerable amounts of bacteria and contaminants will be produced. The addition of proposed hardware and procedures to eliminate some of these inherent problems presents no significant advantages over the liquid germicide or vacuum drying concepts.

In summary, manual handling is unacceptable, freezing presents no advantages over the germicides or vacuum-drying concepts and an automatic transfer system presents many disadvantages over those systems that do not require transfer. The concept in any arrangement presents an inherent safety hazard in that a failure of the freezing equipment results in production of considerable amounts of harmful bacteria and contaminants. Thus, freezing of wet waste was rejected bacause of performance and safety considerations.

Bag Collection

This concept utilizes a plastic bag (in conjunction with a fixed seat installation) for collection of waste that is sealed and manually transferred to a separate dryer after each use. One waste collector is provided. A hydrophobic patch is contained in the plastic collection bag to allow air to be drawn through during collection (to allow positive zero gravity transfer and to prevent the escape of odors and gases to the cabin) and to allow vapors to escape during drying. Exposure of the bagged waste matter to heat/vacuum reduces the original water content to a bacteriostatic condition. Two dryers are provided for alternate collection and treatment modes (24 hour cycle). Drying is accomplished by applying thermal energy to the dryer and venting it to space vacuum. After completion of the drying cycle, the solid residue remaining in the plastic bag (56 percent of total wastes processed) is manually transferred to a storage container. Since manual transfer operations are an inherent part of the vacuum drying bag collection concept, this candidate was rejected due to its inability to meet the absolute performance criterion which required no manual handling of feces.

Liquid Germicide

In the liquid germicide concept, feces are collected using a split-flow commode to reduce the required waste storage volume. Inside the fecal portion of the commode, the feces and tissue wipes are blended with a germicide into a slurry and pumped to a holding tank. The germicide kills micro-organisms and maintains storage sterility. The holding tank is emptied upon completion of the mission.

The waste collector contains a blender, germicidal metering equipment and a phase separator. The blender (requiring about 150 watts) is utilized to ensure thorough mixing of the wastes and germicide. The phase separator is used to eliminate gas from the slurry mix. The collector inlet gate valve is opened only during waste collection.

Chemicals suitable for bacterial treatment are either gases or liquids. The use of a gas such as ethylene oxide is rejected for safety reasons. Any gas leaks due to equipment failure during treatment and/or storage would introduce these gases directly into the cabin atmosphere. The presence of sterilizing gases in the cabin would probably constitute a greater hazard to the crew than the escape of microorganisms from the waste matter. Liquid chemical preservatives are available that provide positive killing action against all types of bacteria. Leakage of the liquid could produce minor odor control problems, but would not be hazardous. Effective mixing of the chemical and germicide is critical in ensuring that a bacteriostatic mixture results. To obtain adequate mixing, a blender is used to mix the germicide to form a slurry.

Germicides have differing kill properties against microbial species such that the treatment concentration must be high enough to destroy the most resistant of the fecal organisms. In addition, the organic content and chemical constituents of feces tend to inactivate antimicrobial agents, requiring excessive doses. Use of a single disinfectant cannot be trusted. A multiple-biocide approach is much more reliable.

A wide variety of chemicals are available for use as fecal disinfectants. These include quaternary ammonium compounds (Zepharin, Roccal); chlorinated and other derivatives of phenol (Lysol, Dowcides, Metasols), which appear the most promising; phenyl mercurial compounds (PMA, PMO, Super-Ad-It); chlorine and other halogenated compounds (HTH, Chloramine-T, Iodophors); sulfur-containing compounds (Drewicides, Thiostats); tin compounds (TBTO, TPTO); arsenical compounds (Vynezene); and a multitude of other applicable industrial and pharmaceutical compounds.

Germicides present toxicological problems when used at high concentrations. Therefore, odor, inhalation toxicity, vapor pressure, irritation properties, and explosive and ingestive toxicity properties play a part in selecting a suitable disinfectant for fecal decontamination. A degree of risk will be present regardless of the ultimate choice. The liquid germicide concept and system data are shown schematically in figure 71.

Absolute criteria. - It has been assumed that an adequate germicide is stored and there is no significant impact on the atmospheric contaminant control subsystem due to excess odor, gases, or leakage. This is the only concept considered that does not require an overboard vent. Two commodes are required to meet the fail operational-fail safe requirement due to the complexity of the phase separation, blending and fecal transfer system. This increases the weight of the concept 40 pounds.

The ability of this candidate to effectively kill all micro-organisms present, is limited by the performance of the blending equipment, assuming a safe germicide. Isolated pockets of untreated waste present a potential crew hazard because live microorganisms could be generated. In this event, the process flow equipment should limit their escape to the cabin.

The germicide concept as discussed has not been developed although it resembles some waste management concepts now being evaluated. Two items require development; the zero gravity collector blender, because it represents the key to

SUBSYSTEM: WASTE MANAGEMENT

CONCEPT: LIQUID GERMICIDE

FLIGHT AVAILABILITY: 1977

Mission Phase Application

Launch ____ Orbit X Reentry ____ Cruise X

RELIABILITY: 0.999917 MTBF: = 18,500 hrs.

4 Men - 7 Days Plus 48 Hours Contingency

	Total Equivalent Wt. (lb)	Volume (ft^3)	Power (watts)
Installed Unit	152	21.0	270.0
Expendables	51.0	1.0	
Power Equiv. Wt.	43.2	-	
Totals	246.2	22.0	270.0

Cost Factor	
Recurring -	1.3
Nonrecurring -	1.2
Total -	1.2

Crew Time (hrs)	
Scheduled -	0
Ground Refurbishment -	2.75

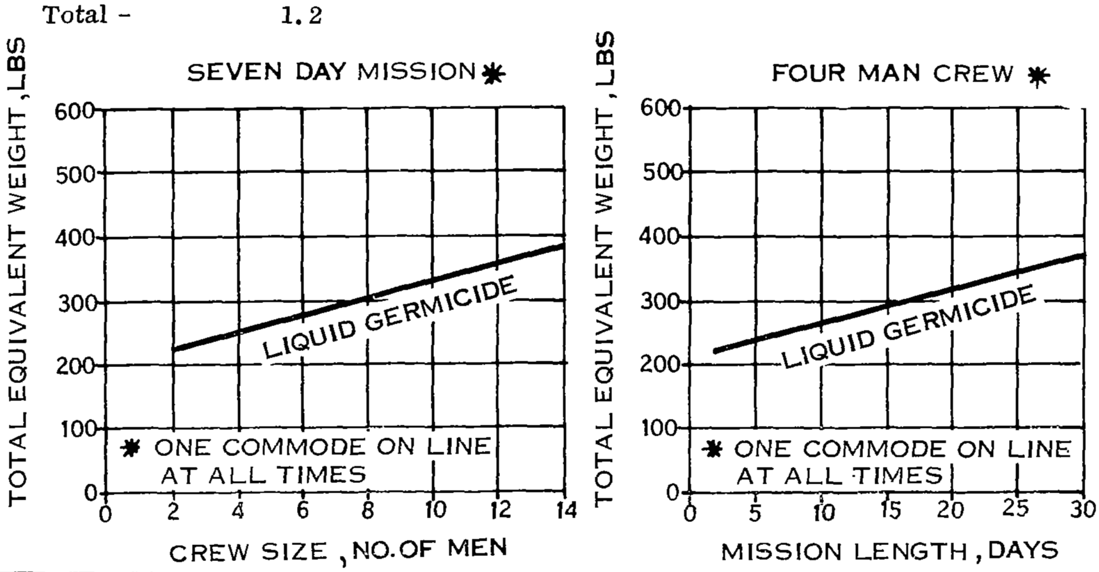


Figure 71 (Page 1 of 2)

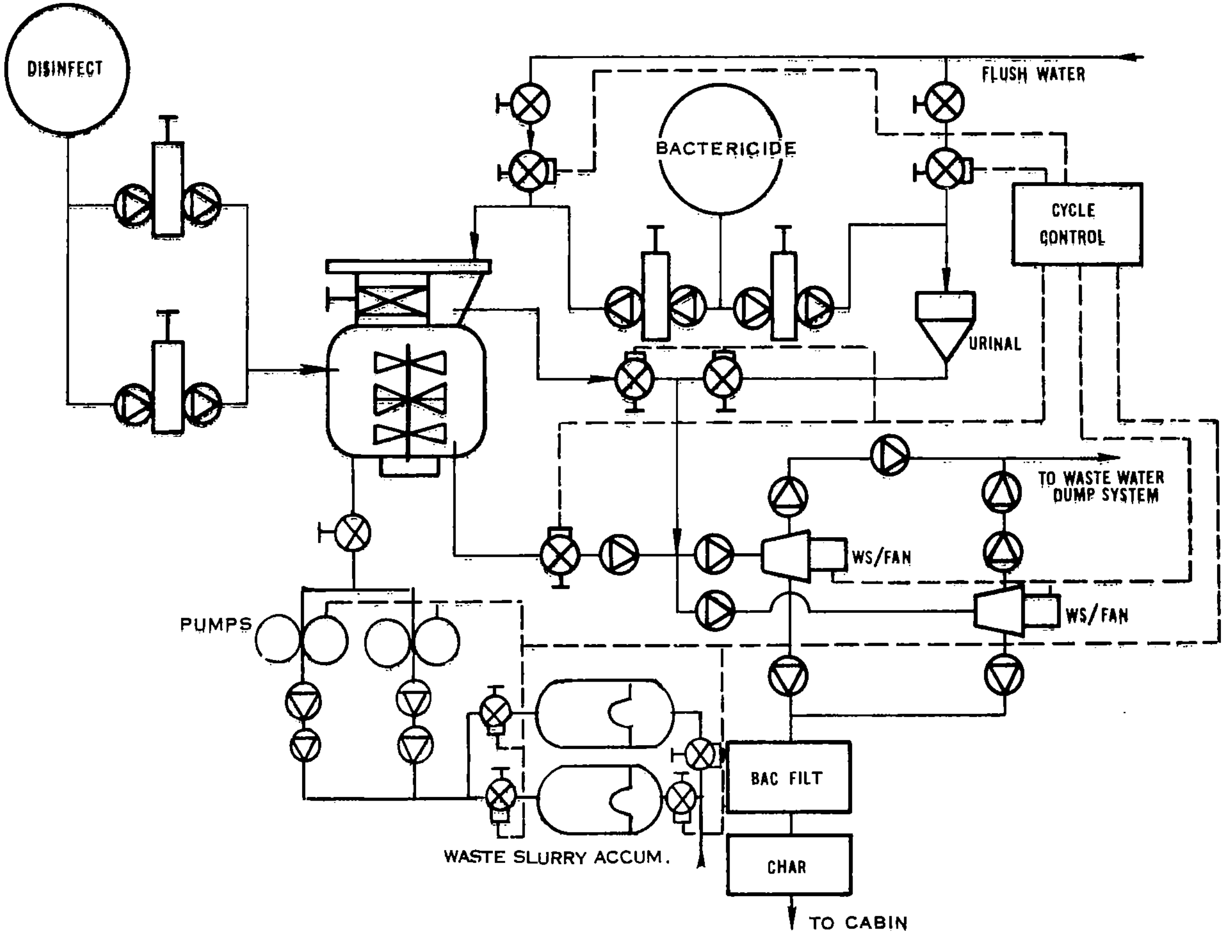


FIGURE 71. LIQUID GERMICIDE CONCEPT (PAGE 2 OF 2)

this system's operation and the germicide, which must provide effective kill properties while possessing acceptable toxicity levels. The germicide concept is presently considered to be in the early research phase. Normal development could result in suitable flight hardware by 1977.

The requirement to blend and transport feces makes this system less reliable than those concepts which require no transfer of feces.

Quantitative criteria. - The total equivalent weight and volume of the germicide concept including storage containers is summarized on the data sheet of figure 71. The concept is one of the lightest considered because very little ancillary equipment is required.

Qualitative criteria. - The liquid germicide concept is more complex than the other concepts because it requires blending of the feces with a germicide and pumping of the slurry out of the commode to a holding tank. The concept has limited flexibility because of dependency on the germicide storage tank and the size of the holding tank. However, if required within its designed capacity, it can operate almost continuously with no need for cool down or a drying cycle. The system is less durable than some other concepts because of the complexity required to mix, transport and transport a gas free slurry in a zero gravity environment.

Refurbishment requires replacement of the germicide supply and emptying of the slurry holding tank which are relatively simple tasks. Checkout capability is simple requiring only that the blender and pump operation be checked. No in-flight maintenance is planned. The disinfectant system may also require flushing prior to maintenance, depending on the germicide chosen.

Integrated Vacuum Drying

This method of treatment consists of vacuum drying waste matter to 10 percent water, by weight. This treatment stops micro-organism activity, thus permitting safe storage while also minimizing storage volume. Elimination of transfer operations is achieved by collecting, treating, and storing wastes in a common container. After each defecation (or collection of other wastes), a gate valve seals the container from the cabin ambient and it is then exposed to space vacuum. Ambient cabin atmosphere heat, transferred through the container walls, assists in the dehydration of the fecal matter. Efficient operation is provided by a motor-driven slinger (requiring about 30 watts) to break up the waste matter and centrifugally slings it to the container walls (shown schematically with related system data in figure 72). The waste storage area is always exposed to vacuum except when being used by the crew. This assures more than adequate drying of the wastes over any 24 hour period assuming four to six usages per day. It also prevents odors from excaping into the cabin.

SUBSYSTEM: WASTE MANAGEMENT

CONCEPT: INTEGRATED VACUUM DRYING

FLIGHT AVAILABILITY: 1974

Mission Phase Application

Launch ____ Orbit X Reentry ____ Cruise X

RELIABILITY: 0.999909 MTBF: = 16,400 hrs.

4 Men - 7 Days Plus 48 Hours Contingency

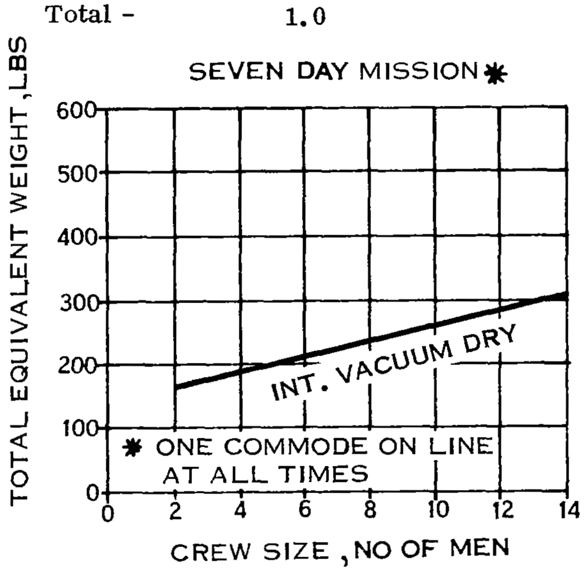
	Total Equivalent Wt. (lb)	Volume (ft^3)	Power (watts)
Installed Unit	108.0	15.0	190.0
Expendables	51.0	2.0	—
Power Equiv. Wt.	30.4	-	—
Totals	189.4	17.0	190.0

Cost Factor

Recurring -	1.0
Nonrecurring -	1.0
Total -	1.0

Crew Time (hrs)

Scheduled -	0
Ground Refurbishment -	2.50



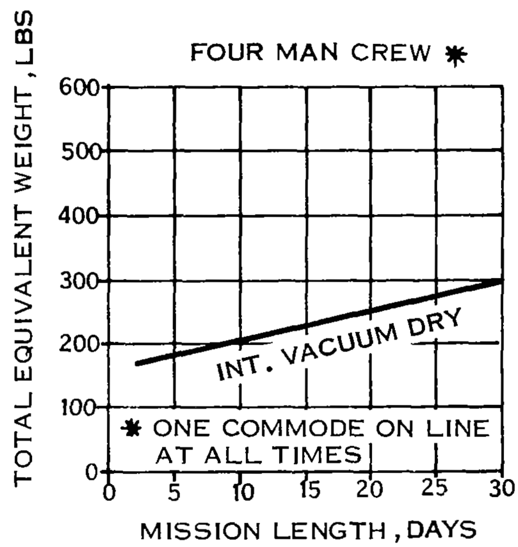


Figure 72. (Page 1 of 2)

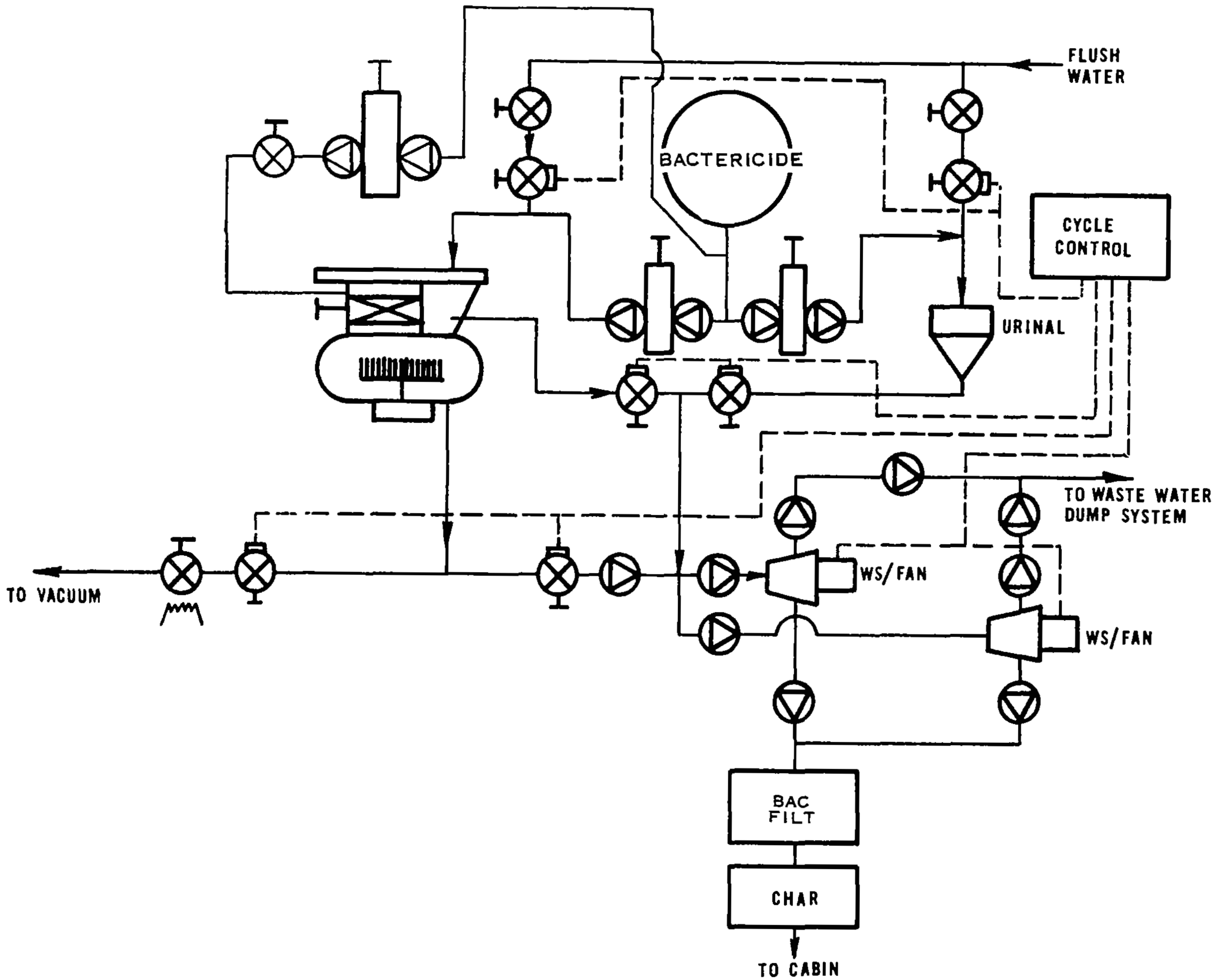


FIGURE 72. INTEGRATED VACUUM DRYING CONCEPT (PAGE 2 OF 2)

Higher-temperature (300°F) vacuum drying operation is possible and has the advantage of providing better bacteria control during each cycle. The higher temperatures, however, cause partial decomposition of waste material, and considerably increase the odor control problem. For this reason, the 300°F vacuum drying process, which offers no real advantage over a low temperature system and in fact may create additional problems, is not treated as a separate candidate. Further elevation of the process temperature to 1200°F will result in much greater waste decomposition, and the process is then considered as pyrolysis, the candidate concept discussed next.

Absolute criteria. - The integrated vacuum drying concept uses a slinger to break up and provide efficient distribution for drying of the wastes. In addition to eliminating a need for direct container heating, the slinger ensures good utilization of vessel volume by slinging the waste matter in thin layers around the walls of the container. A filter is installed in the process air flow circuit to retain airborne solids and liquids while the slinger is operating. The process flow fan must be sized to allow for flow degradation as the filter is filled. While the integrated vacuum drying concept can treat all waste categories, the system is somewhat limited by cabin-to collector heat transfer because as the layer of waste material buildup the amount of heat transfer is reduced. The capacity of the collection system is limited by the total collection volume within the commode. Only one waste collector is required as the unit will fail operational under all conditions except for a slinger failure. Under this failure condition the slinger must be repaired or replaced. In lieu of this, a collector bag with a hydrophobic patch (retain liquids and solids yet pass process flow) can be placed on the seat and used. A bactericide is automatically added to prevent bacteria growth. After use the bag is stored in the commode and the commode vented to vacuum.

The integrated vacuum drying concept reduces the original weight of collected wastes to approximately 60 percent of the wet weight. No direct handling of wastes is required because the vacuum drying process occurs directly in the collection vessel where the dried waste is stored. Isolated pockets of undried waste present a potential crew hazard, because of the possible generation of live micro-organisms within the waste.

The availability of this concept is high. Similar hardware has been fabricated and used successfully for 90 days in a manned chamber test.

Quantitative criteria. - The total equivalent weight and volume of the integrated vacuum drying system is summarized in figure 72 data sheet. This system has the lowest cost, weight and volume of the concepts considered. The unit capacity (approx. 120 man-days) is determined by the physical constraints of the commode inlet dimensions, rather than the actual amount of waste material accommodated during the baseline mission. The collection portion is designed to facilitate drying.

Qualitative criteria. - The vacuum drying concept is one of the simpliest concepts considered. There are few moving parts, and no transfer of feces required. The flexibility of the concept of handle larger crew size or mission length is limited by the size of the commode. The system is durable because it has few moving parts. Refurbishment time is higher than the other concepts since the dried wastes must be removed from the commode. This can be accomplished by dissolving the waste with chemical and flushing the system, scraping out the residue, using a removable liner as used on the 90-day test or replacing the collector part of the commode. The checkout capability is simple and requires little crew time. There is no scheduled maintenance required.

Pyrolysis

The pyrolysis (integrated vacuum decomposition) concept utilizes vacuum and high temperature electrical heat to decompose waste materials collected in disposable bags into gaseous products which can be exhausted to vacuum. The collector chamber is subsequently allowed to cool down, and the residue (approximately 12 percent of total wastes processed) is vacuumed from the chamber into a separate ash collector. No oxygen is required for vacuum decomposition. The pyrolysis concept is shown schematically in figure 73.

Two waste collector/incinerators are required, with alternate availability for collection during succeeding 24-hour period. The "down" unit will undergo pyrolytic waste elimination during the first 12 hours of the cycle and the remaining 12 hours of the cycle provided for chamber cooldown. A new incinerator collection bag with a hydrophobic patch (to retain liquids and solids, yet pass process flow) are provided for each 24-hour cycle for the waste collector/incinerators. The collection bags eliminate the need for a high temperature slinger and microbiological problems of filter replacement. Clogging of the hydrophobic patch is not anticipated with collection bags which are replaced every 24 hours.

Absolute criteria. - The concept employs electrical heat to raise the temperature within the commode to 1200°F. Chamber cooldown is provided by directing process air flow around the internal chamber of the waste collector/incinerators prior to exhausting to the cabin. Heat rejection is provided via the heat rejection subsystem without necessitating the incorporation of a separate heat exchanger loop.

Testing accomplished during 1961 and 1962 on a three-man, 14-day laboratory system has shown that vaporization and pyrolysis of the plastics in the wastes results in the formation of solidifying fractions. If these materials are allowed to condense, the chamber exhaust tubes eventually clog. Thus, the gases must be rejected at a high temperature (with the vent line to vacuum heated). The products of the decomposition process should be vented overboard without attempting heat and/or byproduct recovery. Since collected wastes are processed within a 24-hour period, and

SUBSYSTEM: WASTE MANAGEMENT

CONCEPT: PYROLYSIS

FLIGHT AVAILABILITY: 1976

Mission Phase Application

Launch ____ Orbit X Reentry ____ Cruise X

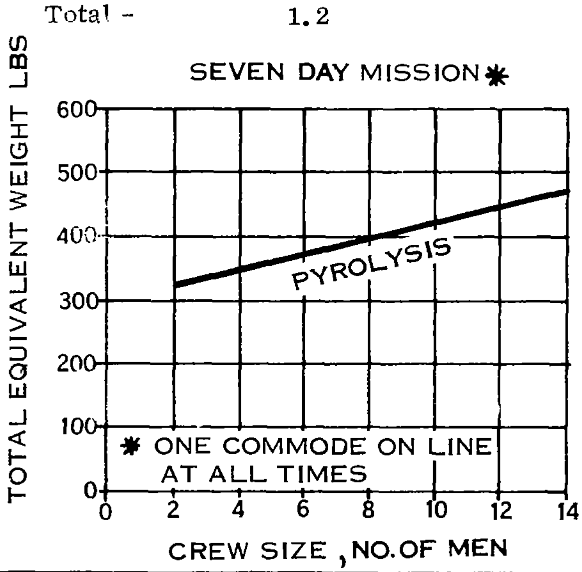
RELIABILITY: 0.999923 MTBF: = 21,300 hrs.

4 Men - 7 Days Plus 48 Hours Contingency

	Total Equivalent Wt. (lb)	Volume (ft^3)	Power (watts)
Installed Unit	187.0	23.0	750.0
Expendables	47.0	1.0	--
Power Equiv. Wt.	120.0	-	--
Totals	354.0	24.0	750.0

Cost Factor	
Recurring -	1.4
Nonrecurring -	1.0
Total -	1.2

Crew Time (hrs)	
Scheduled -	1.17
Ground Refurbishment -	2.00



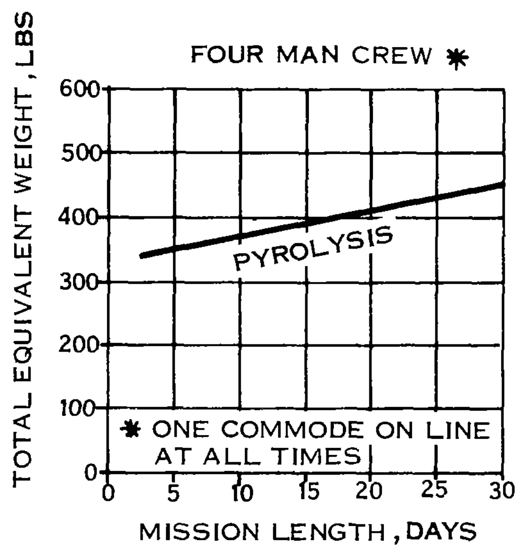


Figure 73. (Page 1 of 2)

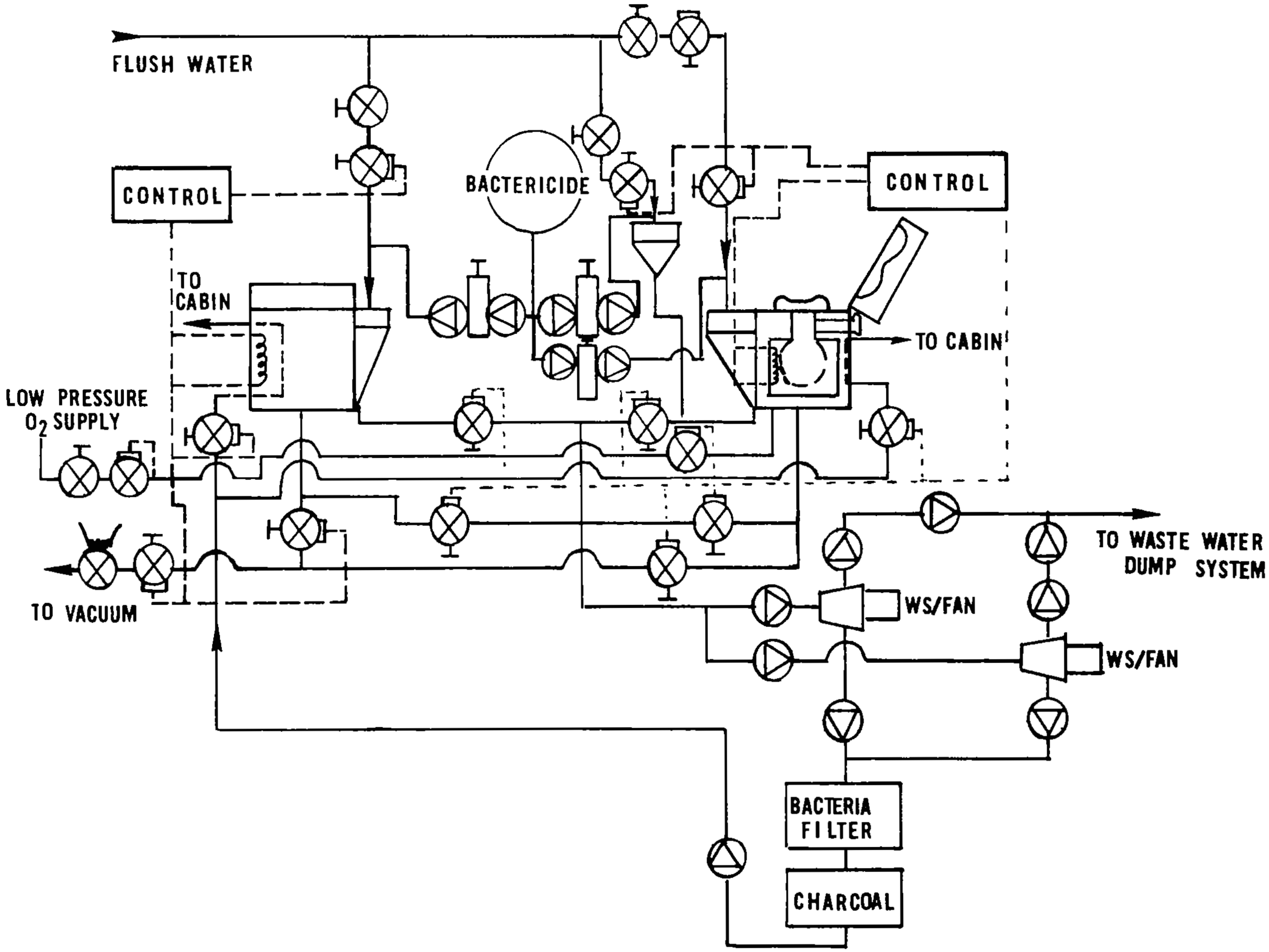


FIGURE 73. PYROLYSIS CONCEPT (PAGE 2 OF 2)

the process residue consists of a sterile ash which is later vacuumed from the chamber, crew stress due to the presence of wastes is expected to be very low.

Potential safety hazards are not apparent in the components of the process in its normal operation. Redundant heaters are required in each collector to insure that the material can be pyrolyzed. Development effort has indicated the feasibility of this concept. The pyrolysis concept is in the early prototype development phase, and flight hardware is expected during 1976 with normal development progress.

Quantitative criteria. - The total equivalent weight, volume and cost for the pyrolysis process are summarized in figure 73, and are about average for the candidates considered. The power requirement (750 watts) is the highest of the concepts considered.

Qualitative criteria. - The pyrolysis concept is simple since no slinger or rotative element is used. It has only two system interfaces; electrical heating and space vacuum. The concept is quite flexible as it can accomodate changes in crew sizes or mission length with little penalty. Cycle time can be decreased by providing for more rapid chamber cooldown, therefore providing increased (or decreased) capacity. Furthermore, the overall growth potential is not limited by expendable supply requirements. The unit is very durable because few moving parts are involved. Refurbishment is minimal requiring only removal of the collected ash and installation of the collection bags. Checkout capability is simple. The pyrolysis concept has a relatively high scheduled maintenance time requirement. This is due primarily to the need to install the collecting bags daily and for ash removals. Although total system operating times do not vary significantly among the candidates evaluated, the pyrolysis concept has one of the highest operating time requirements. Refurbishment is simple, requiring only ash removal, bag replacement and checkout of the system.

Incineration

Incineration is the complete oxidation of wastes using either pure oxygen or oxygen diluted with an inert gas. The incineration concept collects urine, feces, and tissue wipes; mixes these in the commode with waste water which includes, urine plus urine flush water from the standup urinal, bactericide, wash water and humidity condensate to form a slurry. The slurry is pumped to a waste slurry accumulator for storage. From the accumulator the slurry is pumped to the incinerator where oxygen is added to oxidize the waste mixture. The product gases are vented to space vacuum.

This system differs from the preceding concepts in that all of the waste water is transported to the commode rather than to a separate storage tank and dump system. Two commodes are required, one for standby use, due to the need to have the commode operating at all times and the complexity of mixing, phase separation, and pumping features which are accomplished in the commode. This increases the weight of the concept 40 pounds.

The incineration process consists of three steps. The waste slurry is fed into the incinerator, heat is applied for a specified time period (usually 30 minutes) or until a predetermined internal pressure due to vaporization of the entrained water is reached (approximately 30 psia). Next, the gas and vapors are vented to space vacuum and the vent valve left open.

Heat is applied electrically to bring the incineration chamber temperature to $1000^\circ F$, while a controlled flow of oxygen is continuously supplied to the chamber. The products of combustion are vented to space vacuum. The incineration process continues for approximately 12 hours and results in a 97 to 99 percent reduction in the processed waste. Solid residue in the form of a dry powder, are retained in the incinerator by a filter.

The incineration process is shown schematically in figure 74, with related candidate data appearing on the data sheet. Two waste collector/incinerators are provided for redundancy. The waste storage tank is sized to hold 48 hours of waste slurry. Oxygen is assumed to be an expendable and is stored in gaseous form at 3000 psia.

Absolute criteria. - The concept employs electrical heating to raise the incineration temperature prior to oxidation. The presence of high pressure oxygen presents a potential safety hazard.

A three-man, 14-day prototype incinerator was developed during 1961-62, and testing indicated the feasibility of this concept. The incineration concept is in the early prototype development stage, with flight hardware expected during 1978 with normal development progress. An incinerator is currently being developed for NASA/Ames using both electrical and microwave energy. However, insufficient data prevented its evaluation.

Quantitative criteria. - The total equivalent weight and volume and other characteristics for the incineration process are summarized on the data sheet of figure 74.

Qualitative criteria. - The incineration concept is complex because it involves fecal slurry transport and controlling a high temperature reaction by regulating high pressure oxygen. The system is very flexible in regard to changes in crew size and mission length as it requires only an oxygen supply to extend its capability. The high temperature and pressure operation will impose some limit on its durability. Refurbishment is simple requiring only removal of ash, and checkout of the system. No in-flight maintenance is planned.

SUBSYSTEM: WASTE MANAGEMENT

CONCEPT: INCINERATION

FLIGHT AVAILABILITY: 1978

Mission Phase Application

Launch____ Orbit X Reentry____ Cruise X

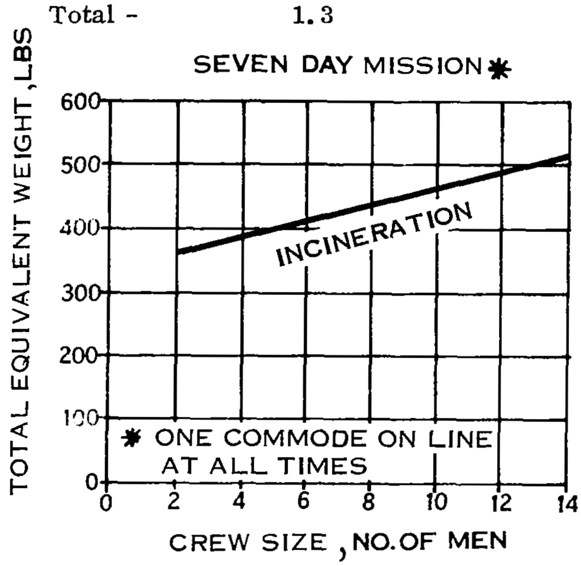
RELIABILITY: 0.999922 MTBF: = 19,400 hrs.

4 Men - 7 Days Plus 48 Hours Contingency

	Total Equivalent Wt. (lb)	Volume (ft^3)	Power (watts)
Installed Unit	245.0	25.5	550.0
Expendables	56.0	2.0	—
Power Equiv. Wt.	88.0	-	—
Totals	389.0	27.5	550.0

Cost Factor	
Recurring -	1.4
Nonrecurring -	1.3
Total -	1.3

Crew Time (hrs)	
Scheduled -	.5
Ground Refurbishment -	2.25



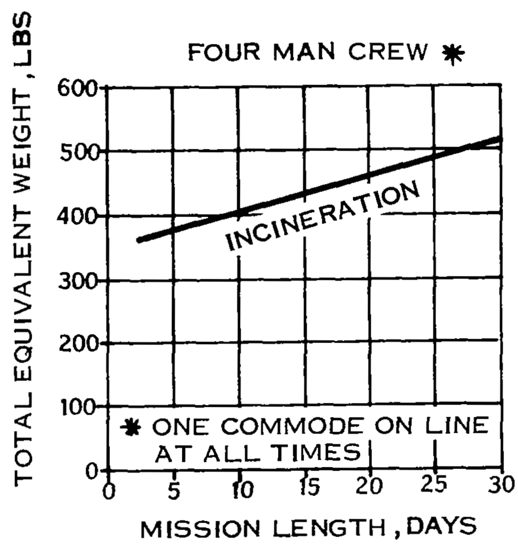


Figure 74. (Page 1 of 2)

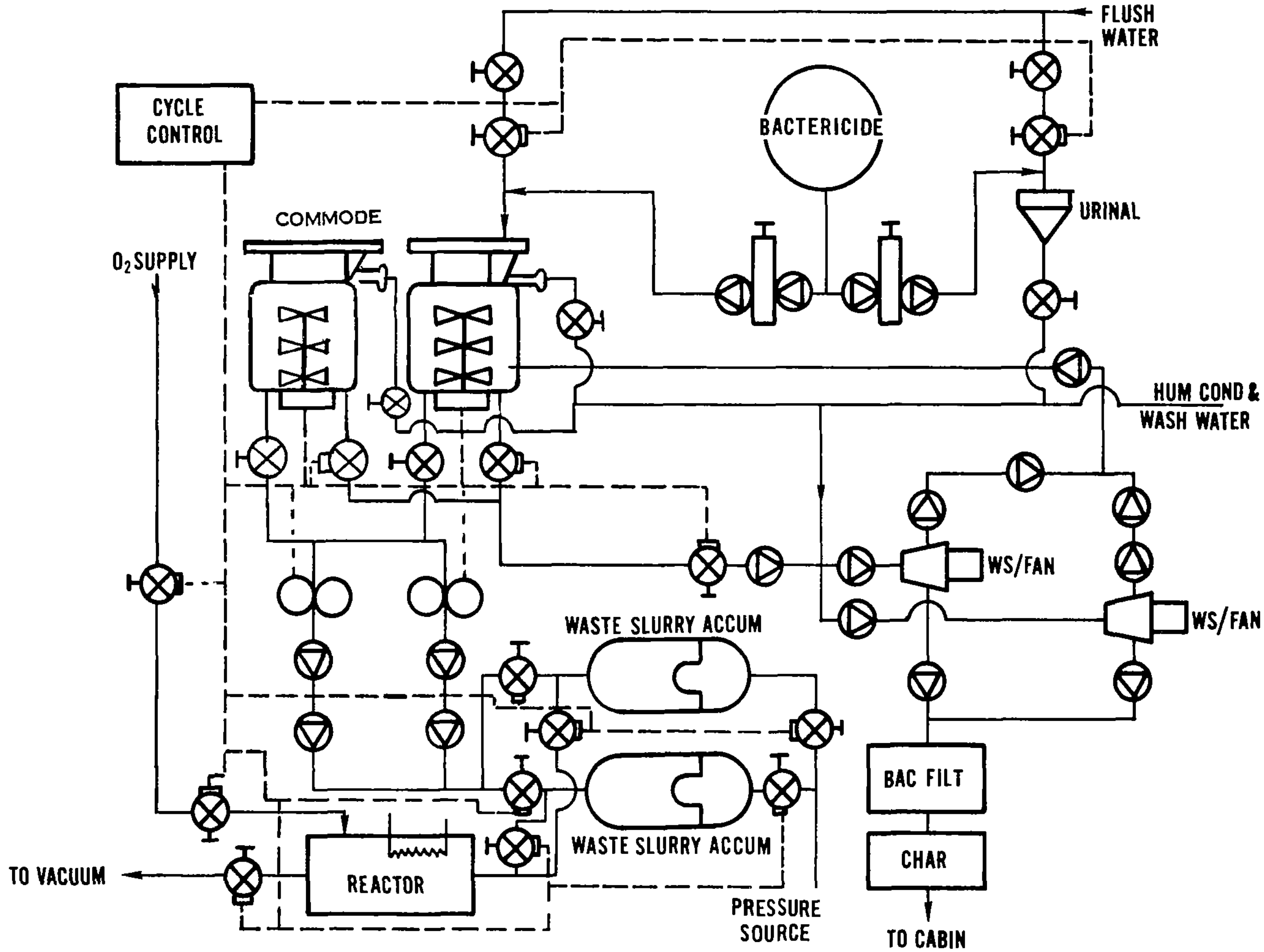


FIGURE 74. INCINERATION CONCEPT (PAGE 2 OF 2)

Wet Oxidation

The wet oxidation concept collects urine, feces and tissue wipes, mixes these in the commode with waste water which includes urine and urine flush water from the wall urinal, bactericide, wash water and humidity condensate to form an air free slurry. The slurry is pumped to a waste slurry accumulator for storage. The accumulator is pressurized and the slurry is transported to a reactor where oxygen is added to oxidize and decompose the waste mixture. The product gases and liquid effluent are vented to space vacuum through a heated discharge duct.

This system like the incineration concepts, differs from the previous concepts in that all of the waste water is transported to the commode rather than to a separate storage tank and dump system. Two commodes are required, one for standby use, due to the need to have the commode operating at all times and the complexity of blending, phase separation, and pumping features which are accomplished in the commode. This feature is more complex than the one for the incinerator concept because the fecal slurry should be essentially air free in order to obtain the proper process control and to facilitate pumping the slurry to a high (500 psia) pressure.

Wet oxidation is a moderate temperature, high pressure process (500° to 600°F and 1200 to 2000 psia) used commercially on a large scale in industrial sewage treatment plants. The wet oxidation process (known as the Zimmerman process) employs an insulated chamber similar to the incineration concepts. Waste treatment is accomplished by charging the chamber with 500 psia oxygen at ambient temperature and applying heat to bring the chamber up to oxidation temperature. The final pressure and temperature are approximately 1750 psia and 550°F, respectively. The process effluent consists of a dark organic ash and a clear-to-pale liquid consisting mostly of water containing carbon dioxide and traces of acetone vapor, carbon monoxide, hydrogen, and nitrogen. No sulfur compounds have been detected in the liquid effluent.

A motor driven stirrer is employed in the oxidation chamber to ensure that sufficient oxygen is dissolved in the wastes undergoing oxidation, thereby increasing the rate of reaction. The wet oxidation system is shown schematically in figure 75 with related system data. Oxygen is assumed to be an expendable and is stored in gaseous form at 3000 psia.

The primary difference in the wet oxidation process from the incineration process is the high operating pressure and the method employed for residue expulsion and filtration. Each chamber is provided with an orifice for a pressure bleed. A filter housing with replaceable cartridges is used to remove solid residue from the effluent. The unfiltered effluent, consisting primarily of carbon dioxide and salt-like water is dumped overboard through a heated discharge nozzle.

SUBSYSTEM:	WASTE MANAGEMENT
CONCEPT:	WET OXIDATION

FLIGHT AVAILABILITY: 1978

Mission Phase Application

Launch ____ Orbit X Reentry ____ Cruise X

RELIABILITY: 0.999882 MTBF: = 9,400 hrs.

4 Men - 7 Days Plus 48 Hours Contingency

	Total Equivalent Wt. (lb)	Volume (ft^3)	Power (watts)
Installed Unit	289.0	27.0	560.0
Expendables	55.0	2.0	——
Power Equiv. Wt.	90.0	-	——
Totals	434.0	29.0	560.0

Cost Factor

Recurring - 1.6

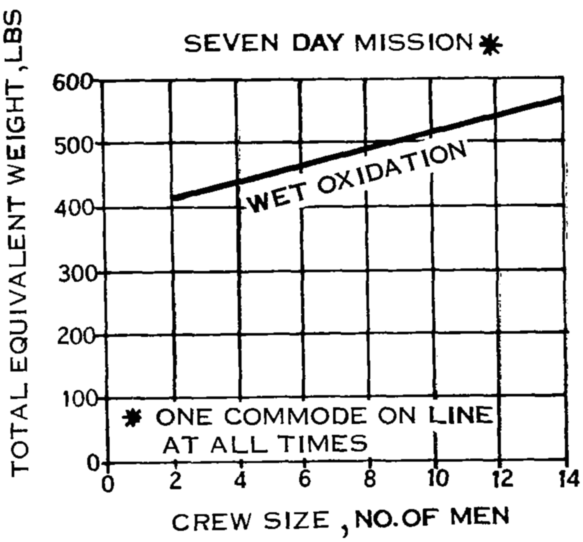
Nonrecurring - 1.8

Total - 1.7

Crew Time (hrs)

Scheduled - 0

Ground Refurbishment - 2.33



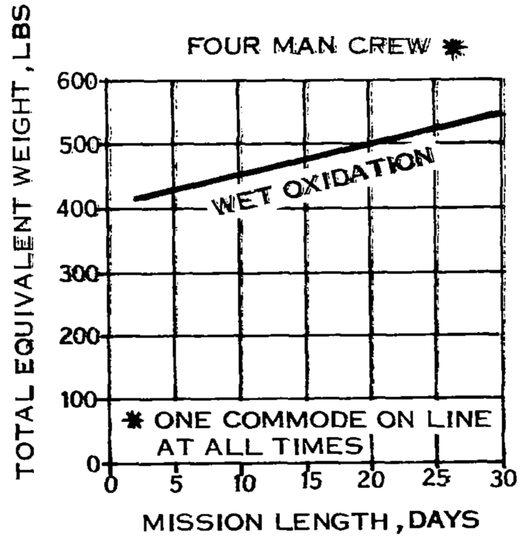


Figure 75. (Page 1 of 2)

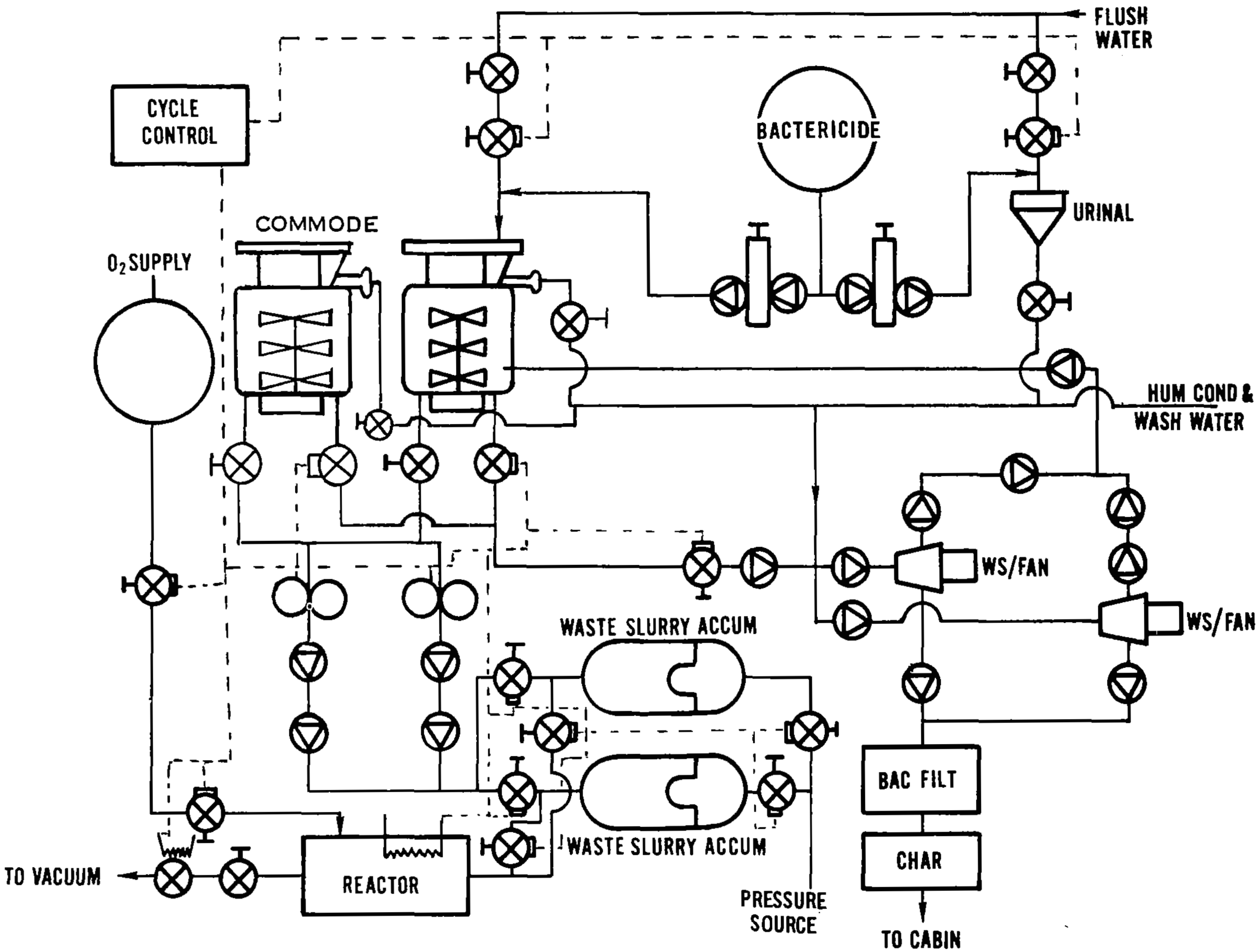


FIGURE 75. WET OXIDATION CONCEPT (PAGE 2 OF 2)

Absolute criteria. - The wet oxidation concept has good performance and can be operated on a continuous basis. Solid residue quantities are expected to be approximately 20 percent of the total wastes processed.

Safety considerations are similar to those described for the incineration process. The requirement for a high pressure process operation is expected to impose additional safety hazard.

While the feasibility of wet oxidation for spacecraft waste control has been demonstrated, substantial effort is required to reduce it to working flight hardware. Practical means of mixing and transporting the fecal slurry, pressurizing the system and effluent expulsion and filtration, together with integration with other subsystems, will require development effort. Operation under zero gravity conditions remains to be demonstrated. The wet oxidation concept is expected to produce flight hardware by 1978 with concentrated development efforts.

Quantitative criteria. - The quantitative data for this concept is shown in figure 75. This system has the highest cost, weight and volume of the concepts considered.

Qualitative criteria. - The system is the most complex concept considered. Its flexibility in regard to crew size and mission length is very good as it is dependent only on the availability of a high pressure oxygen supply. Durability, due to the large number of parts operating at high temperatures and pressure is expected to be poorer than the other concepts. Refurbishment is relatively simple, requiring only ash removal and checkout of the system. No in-flight scheduled maintenance is planned.

EVALUATION AND SELECTION

An integrated vacuum drying concept using tissue wipes is selected as the fecal waste management concept because of its low weight, power and volume. Its superior performance is due to the fact it collects, processes and stores solid waste in a single unit. One commode is used for the nominal crew size of four men. For an increased crew size (5 - 14 men) in the same cabin, the weights of the system would increase as shown in figure 76. If a payload module is used an additional commode would be recommended. In the unlikely event that it is required, the emergency fail safe waste management concept is hand held gloves as used on the Apollo missions. While considered entirely inadequate for normal use, this approach is selected as an acceptable fail safe backup system for all the concepts evaluated.

Seven candidate concepts were considered. Two concepts were eliminated on the basis of failing to meet the absolute criteria. The other five were evaluated in detail. The Evaluation Summary Chart is shown in table 26 for all the candidates considered. Table 27 summarizes the quantitative data for the five competing concepts.

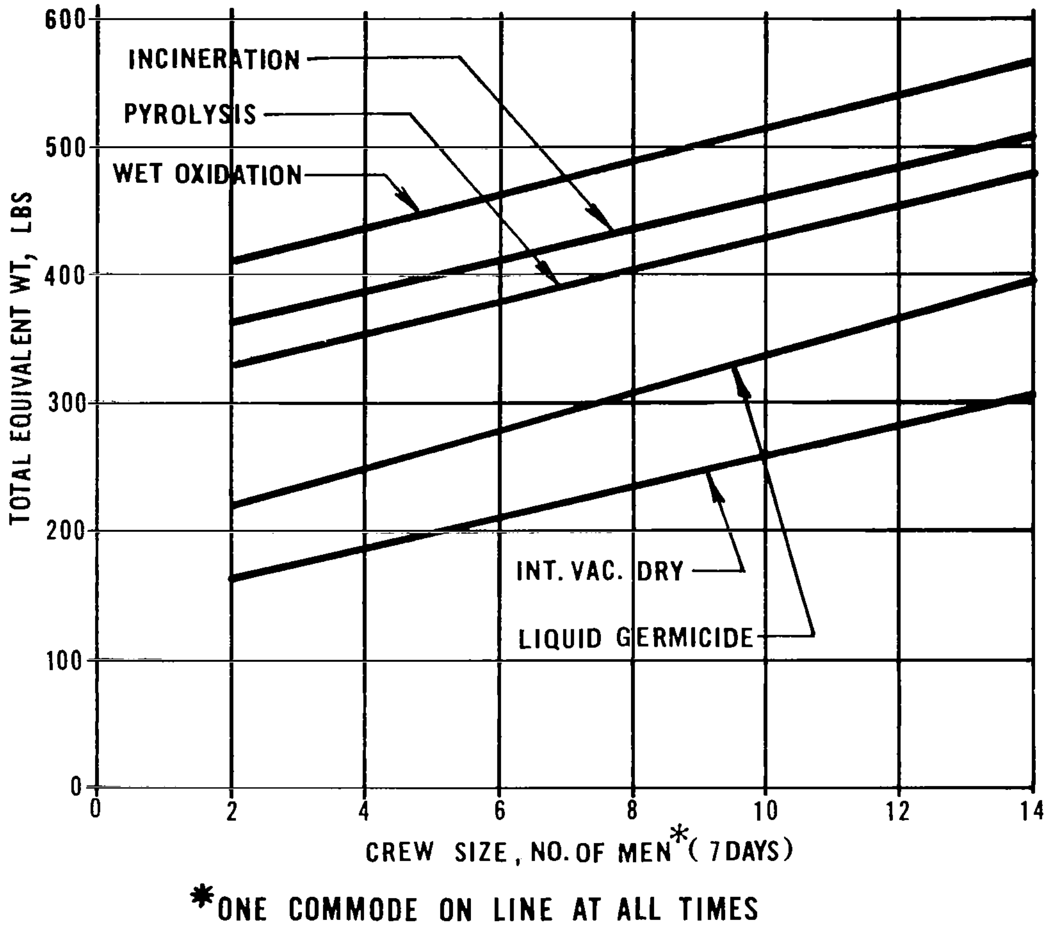


FIGURE 76. WASTE MANAGEMENT WEIGHT VERSUS CREW SIZE

TABLE 26

EVALUATION SUMMARY - WASTE MANAGEMENT

Criteria		Freezing	Bag Collection	Liquid Germicide	Integrated Vacuum Drying	Pyrolysis
Absolute	Performance	Unacceptable	Unacceptable	Good	Good	Good
	Safety	Unacceptable	Fair	Fair	Good	Good
	Reliability	Fair	Fair	Good	Good	Good
	Avail. /Conf.	Good	Good	Fair	Very Good	Good
		Eliminated	Eliminated			
Quantitative	Total Equivalent Weight			Good	Very Good	Poor
	ROM Cost			Good	Very Good	Fair
	Volume			Good	Very Good	Poor
						Eliminated
Qualitative	Complexity			Fair	Very Good	
	Flexibility			Fair	Good	
	Durability			Fair	Good	
	Refurbishment			Good	Good	
	Checkout Capability			Good	Good	
	Maintainability					
				Eliminated	Selected	

TABLE 26 (Concluded)

EVALUATION SUMMARY - WASTE MANAGEMENT

Criteria		Candidate Concepts				
		Incineration	Wet Oxidation			
Absolute	Performance	Good	Good			
	Safety	Fair	Fair			
	Reliability	Good	Good			
	Avail. /Conf.	Fair	Fair			
Quantitative	Total Equivalent Weight	Poor	Poor			
	ROM Cost	Fair	Fair			
	Volume	Poor	Poor			
		Eliminated	Eliminated			
Qualitative	Complexity					
	Flexibility					
	Durability					
	Refurbishment					
	Checkout Capability					
	Maintainability					

TABLE 27
WASTE MANAGEMENT CONCEPTS (FOUR MAN-SEVEN DAYS)
QUANTITATIVE SUMMARY

Concept	MTBF (hrs)	Fixed Weight (lbs)	Power (watts)	Total Equivalent Weight (lbs)	Total Prog. Cost Factor	Volume (ft^3)	Crew Time (hrs)
Liquid Germicide	18,500	152	270	246.2	1.2	22	2.75
Int. Vacuum Dry	16,400	108	190	189.4	1.0	17	2.50
Pyrolysis	21,300	187	750	354	1.2	24	3.17
Incineration	19,400	245	550	389	1.3	27.5	2.75
Wet Oxidation	9,400	289	560	434	1.7	29	2.33

The following is a discussion of the evaluation conducted.

Absolute criteria. - Two concepts were eliminated, freezing and bag collection because they required manual handling of feces which is considered unacceptable performance. All the remaining concepts are rated equally in performance and reliability because they are all capable of meeting the shuttle requirements. The vacuum drying concept are rated Good on safety because they continuously control the bacteria within the accumulated wastes. They do not require the use of a potent germicide or high pressure oxygen either of which could be a potential safety hazard. Integrated vacuum drying is the most developed and proven concept to date, and is rated Very Good on availability. The other concepts are in various states of development and need further work prior to flight.

Quantitative criteria. - The total equivalent weight summary is shown in figures 76 and 77. The integrated vacuum drying concept has the lowest total equivalent weight, followed by the liquid germicide concept. All the other concepts use a high rate of expendables and/or power. They require two collectors for operation in order that the waste decomposition process can take place and cool down before reuse or to provide adequate backup redundancy. The volumes of these concepts are correspondingly high. As a result of the quantitative evaluation, three concepts are eliminated because of high total equivalent weight and volume. These are wet oxidation, pyrolysis, and incineration.

Qualitative criteria. - Two candidates remain after the quantitative evaluation. These are liquid germicide and integrated vacuum drying. The integrated vacuum drying concept is considered less complex and therefore more durable than liquid germicide because thorough mixing and/or transfer of a fecal slurry is not required. Since no expendables (other than tissue wipes, charcoal and bacteria filters, which are common to all candidates) are required, the integrated vacuum drying concept is considered to be more flexible. The rest of their characteristics are about equivalent.

On the basis of the qualitative criteria and consideration of the absolute and quantitative criteria, the integrated vacuum drying concept is selected as the waste management concept for the shuttle. It has very low weight and volume, good reliability and is relatively simple with good mission flexibility.

WASTE MANAGEMENT SUBSYSTEM DESCRIPTION

A schematic of the selected waste management subsystem is shown in figure 78.

Two collection tanks for the waste management system serve to collect waste waters and store it prior to venting to space. A bladdered tank is used for waste

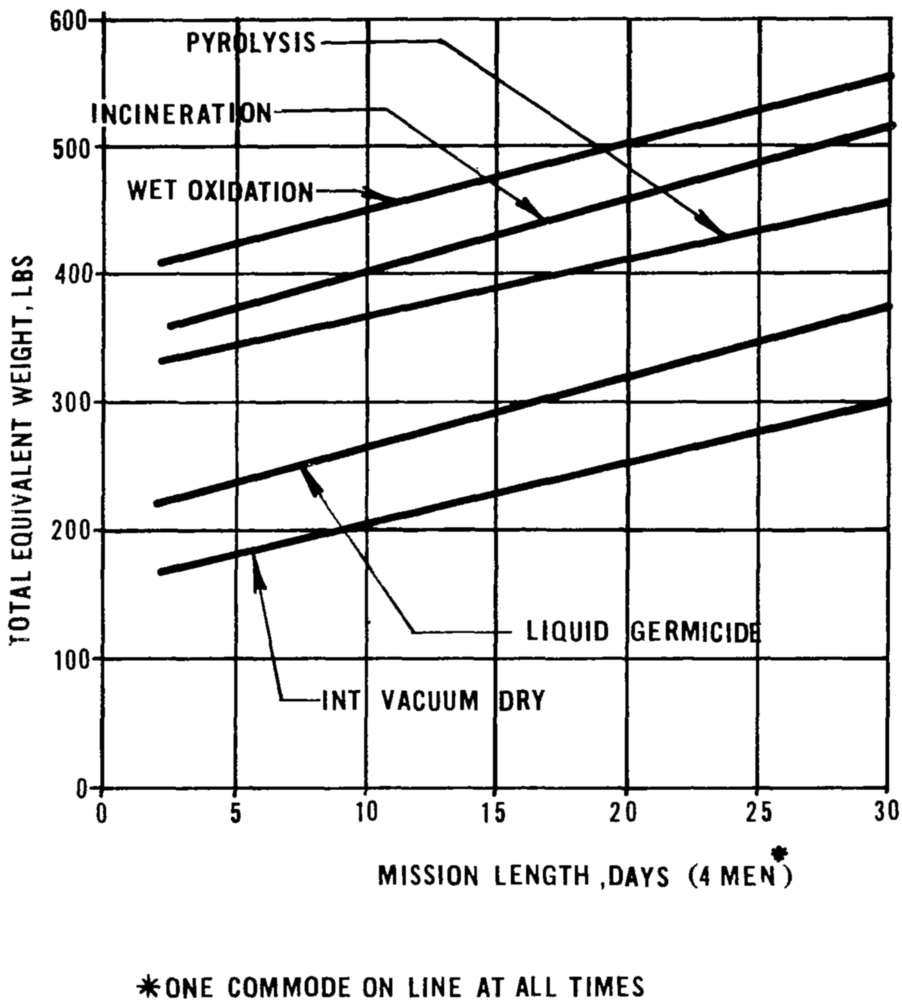


FIGURE 77. WASTE MANAGEMENT WEIGHT VERSUS MISSION LENGTH

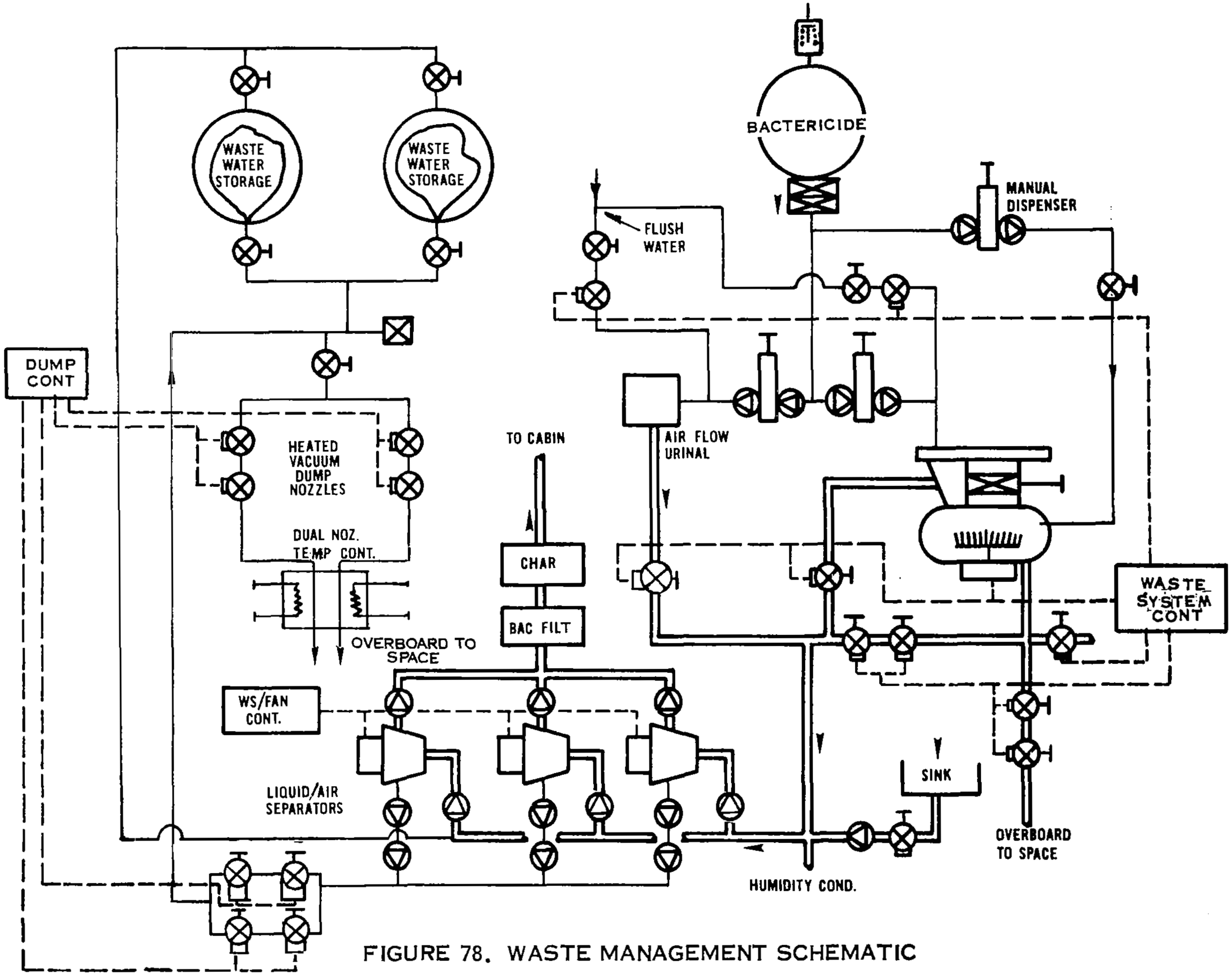


FIGURE 78. WASTE MANAGEMENT SCHEMATIC

water storage tankage because of the nature of the stored liquid which would make a zero gravity capillary type tank inoperative.

For purpose of sizing, each tank must hold at least enough water for a 12-hour hold period when the shuttle is docked with the space station and no venting of gases is allowed. In addition, each tank must be large enough to accept all fuel cell water if not required for heat rejection. As a result, each tank is sized to hold a 100 pounds of liquid. Only one tank is on-line at a time. The other is for standby use in case of a tank failure. All water quantities stated are for a 70°F cabin temperature.

Used water is collected and fed to the waste management subsystem at several points throughout the spacecraft. Urine is received at the urinals at the rate of 14.32 lb/day. For purposes of design, it is assumed that each of the four crewmen will urinate six times a day. After each urination, an additional 0.33 pound of water will be injected into the urinal together with 0.002 pound of bactericide (silver nitrate) to flush away any residual urine. The total input received at the urinal is thus 22.37 lb/day.

Water used in the preparation of food and drink, and for washing is received in the sink which is connected to the fan/centrifugal water separator in parallel with the urinals. The flow rate from these sources is 10.3 lb/day.

All cabin condensate resulting from crew perspiration and respiration (12.85 lb/day) is also transferred to the main waste tank. Thus, the total inflow to the waste water storage tanks is 45.52 lb/day.

This liquid waste is stored in the waste water tank until it reaches a predetermined level. At this point, heat is automatically applied to the discharge nozzle and the liquid vented overboard.

This flow rate overboard is approximately 12.0 pounds liquid/man-day. None of this water is used for heat rejection because of the excess fuel cell water available and the problems of handling and utilizing waste liquids for heat rejection.

IMPACT OF MISSION PARAMETERS

A review of the impact of crew size and mission length on the selected concepts for waste management shows that the selected concept is relatively unaffected by these parameters, as shown in figures 76 and 77. These figures are based on having one commode on-line at all times and having the system sized for the proper mission parameter. The basic commode size represents approximately 120 man-days capacity, ample for virtually all anticipated missions without change. The baseline unit would be sized for 28 man-days of operation with a reserve capacity of eight additional man-days.

For crew sizes above 4 men when a separate payload module is used, an additional split-flow commode and urinal is recommended to eliminate the need to enter or leave the payload module.

<u>CREW PROVISIONS</u>

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CREW PROVISIONS

The crew provisions subsystem consists of the equipment and supplies needed for food, personal hygiene, clothing and housekeeping.

Unlike other life support subsystems, crew acceptability is of paramount importance for the crew provisions subsystem. Thus, the basic objective here is to define concepts that are psychologically acceptable to the crew, but still represent a sound engineering approach. Alternative concepts sometimes have lower weight, power, and volume than a particular selection, but selecting such concepts would result in an undesirable amount of crew psychological stress.

FOOD MANAGEMENT

The food management subsystem includes the supplies and equipment necessary to maintain and feed the Shuttle crew and passengers for the mission duration. Unlike other life support subsystems, crew acceptability and ease of use are of paramount importance when considering food management. The basic objective, therefore, is to define a food concept and associated equipment that are psychologically acceptable to the crew, and keep crew time at a minimum.

A diet adequate to sustain the crew throughout a Shuttle mission must provide approximately 2600 kilocalories of energy per man per day. Exact caloric, protein, fat, carbohydrate, mineral, vitamin requirements for the crew should be based on actual individual crew body weight, age, height, and activity level for the specific mission duration.

The following is a list of nutrients and their daily recommended quantities for the Shuttle crew. These recommendations, from the Food and Nutrition Board of the National Academy of Sciences - National Research Council on dietary allowances (NAS - NRC), are for a typical crew member. He is defined as a male, age 35 to 45, weight 160 pounds, and height 70 inches. It is also recommended that the same diet be used for female crew members.

Kilocalories		- 2600 Kcal - 100%
Protein	76 gm	- 310 Kcal - 12%
Fat	82 gm	- 780 Kcal - 30%
Carbohydrates	365 gm	- 1510 Kcal - 58%
Calcium	0.8 gm	
Iron	10 mg	
Vitamin A	500 International Units	
Thiamine	1.0 mg	
Riboflavin	1.6 mg	
Niacin	17 mg equivalent	
Ascorbic Acid	70 mg	

Protein, fat, and carbohydrates will supply substantially all the calories required. Although fats provide a high caloric density per unit weight, the amount of fat in this diet is limited to 82 grams per man per day (30% of the total caloric intake). This avoids problems of storability, reconstitution, palatability and possible medical side effects. Proteins and carbohydrates supply the balance of the calories. Vitamins and minerals are supplied by the food and dietary supplements as required.

If completely consumed, the selected diet will result in the following metabolic balance:

O_2 consumed	1.84 lb/man-day
CO_2 output	2.20 lb/man-day
Metabolic water	0.71 lb/man-day
Respiratory quotient	0.84

In addition to the physiological requirements, the diet must be acceptable to the crew, be easy to prepare, and remain free of deterioration in taste or in bacterial content when stored for the duration of the mission. Several diets have been examined, with the result that the basic consideration is between crew acceptability and total equivalent subsystem weight. A large number of diets and diet combinations are available which satisfy the Shuttle requirements. For example, the nutritional needs of the crew and passengers could be satisfied by two chemical meals a day and one freeze-dried meal. Another would be by a freeze-dried diet made up of bite-size pieces eaten dry.

The basic diet types considered include the following:

- Dried
- Frozen
- Freeze-Dried
- Liquid
- Chemical

In evaluating these diets, the performance consideration includes an emphasis on crew acceptability, in addition to considering equipment associated with the diet. Crew acceptability is based on such factors as flavor, texture, variety etc.

Dried Diet

The dried diet consists of food items dried either by dehydration to form a powder (such as orange juice), or by warm air to form a dry compact edible solid (such as raisins or beef jerky). Normally, drinks are reconstituted from dried or dry prepared mixes. As a main meal, the dried diet, in general, has a bland taste, unusual appearance and overall crew unacceptability. To remain consistent with the plan of providing the most pleasing and least laborious meals for the Shuttle, only the powdered drinks and snack portion of this diet were evaluated. All dry powders, used for varied drinks, are contained in individual flexible food feeders. Water is dispensed directly into the bag feeder. In addition to providing a method for rehydrating food, the dispenser is utilized for drinking water. Dry solid snacks need no rehydration and are eaten by hand directly from the storage containers.

Frozen Diet

The frozen foods diet is based on use of standard commercially available food products, except that they are frozen, stored in a freezer, and packaged for the Shuttle mission. This diet consists of a combination of precooked frozen main dishes, desserts, soups, and baked goods. This diet is different from others in that all the original water content of the food is frozen with it. In addition, drink powders, snack items, and other items that are carried dry also constitute a part of this diet. Frozen portions of this diet are stored in foil containers which provide a moisture barrier and a cooking and eating container for the food. Foods eaten dry are contained in wrappers for protection against atmospheric oxygen or moisture and are stored at ambient temperature. The frozen foods are prepared in their storage containers by infrared oven heating. An infrared oven was chosen over microwave oven to restrict the power drain on the fuel cells. Hot and cold powdered drinks are mixed with water at 160°F and 45°F, respectively, for consumption. Snack bits are consumed without preparation.

All cooked solid and semisolid items can be eaten with either standard eating utensils or a special tool with a food-holding device. Solid snack-type foods are eaten in bite-sized pieces to avoid crumbing and are dispensed from packages. Liquids are consumed from disposable squeeze-type containers or reusable rigid containers with a piston or bellows for dispensing the fluid through a mouthpiece.

Frozen foods rate high on crew acceptability especially as main course meals. With recently developed direct-contact liquid refrigerant freezing techniques, taste and general quality should be close to that of fresh food.

The safety characteristics of the frozen food diet are principally limited by the possibility of freezer failure. The freezer coolant liquid would be a toxicity hazard if accidentally released into the atmosphere, although cooling by direct radiation to space might be practical.

The availability of the frozen diet is good since the basic frozen food items are available. Some development work is required to determine the most economical combination of freezer temperature and packaging material to arrive at an optimum storage condition.

Freeze-Dried Diet

The freeze-dried diet discussed here is currently used in Apollo space flights. It is prepared by quick freezing followed by vacuum sublimation of the frozen water content. This process preserves the basic food structure and most of the taste, by preventing loss of flavor oils. Food is stored at ambient cabin conditions in appropriate containers with air and moisture barriers.

Food items in whole form require rehydration and heating to a palatable eating temperature. This is done through rehydration with hot water (160°F) in the package and placement of the package in an oven. A metering unit adds water at a preselected temperature to the food container. Freeze-dried foods of smaller piece size are reconstituted in hot water and should stay warm long enough for consumption. Drinks are reconstituted with hot or cold water in a zero gravity drinking device.

Whole reconstituted freeze-dried foods and some solid foods are eaten from the packaging container with modified reusable, food-holding eating utensils. Bite-size snack items are eaten as is from the packaging container. Liquids are consumed from a reusable container having a mouthpiece and a piston or bellows to force the liquid out.

The freeze-dried diet is nutritious and does not deteriorate in storage. Compared with frozen food, it does not usually taste as much like fresh food, but its flavor and related qualities are still quite acceptable.

Freeze-dried foods have been stored for several years without any serious deterioration in bacteria content or in taste. In instances where the packaging breaks, there may be some degradation in food quality, although this would take place over several weeks. The deterioration of some of the food items would result in use of a contingency food supply or perhaps a restricted caloric intake.

Freeze-dried foods are carried on current and planned space missions. There are a variety of foods which have been developed and are available. Further development of freeze-dried foods is required for production of whole items which are attractive and tasty. The constant use of food squeezed from a tube is not acceptable for a Shuttle mission.

Liquid Diet

The liquid diet is a nutrient-defined diet composed of purified food substances; The United States Army Natick Laboratories Diet No. 1, which is typical, consists of sodium caseinate, corn starch, sucrose, vegetable oils, flavoring, and emulsifier. It is prepared by mixing with water, but can be dried and ground into a powder. This powder could then be rehydrated prior to crew consumption.

This food can be packaged in large quantities and dispensed in meal amounts. Preparation consists of adding water from a metering dispenser to a reusable container. The water is mixed with the food powder with a blender. No hot water or heating is necessary. Consumption is in liquid form at ambient temperature from a liquid dispenser.

Initial low crew acceptability of this diet could become even lower due to monotony. Even the use of several flavors is not expected to help. With low acceptability, it can be expected to have an adverse effect on crew attitude and health, and must be considered undesirable.

No information is available on storage of the diet compounds. If browning (a reaction between protein and glucose) takes place, it could be overcome by the addition of a preservative or by separate storage of the caseinate until rehydration.

Several diets of this general type are available. However, decomposition during long duration storage must be eliminated. Further development would also be required for crew acceptability. New methods of flavoring, coloring, and preparation might improve the current low acceptability of this diet.

Because of the poor crew acceptability the liquid diet concept was eliminated from further consideration.

Chemical Diet

The chemical diet is a combination of nutrient chemicals, amino acids, and vitamins. A typical formulation consists of glucose, ethyl linoleate, a group of mineral salts, a group of amino acids, and a group of vitamins. The diet may be stored in dry powder form and mixed with water just prior to crew consumption.

The chemical diet is unique in that it is almost completely digestible. As a result, fecal elimination is sharply reduced, although this would benefit the waste control subsystem only slightly. The major advantage of this diet would be low weight.

Acceptability characteristics are very similar to those of the liquid diet, previously discussed. Thus, the chemical diet also has unsatisfactory crew acceptance. It is therefore eliminated on this basis.

Summary and Selection

The basic requirements of the Shuttle food management subsystem are high crew acceptability and low crew stress during subsystem operation. The diet must be psychologically pleasing, and associated equipment needed for subsystem operation must be of a simple, reliable nature.

The recommended diet for simplicity, conventional-type and most appetizing food, includes a combination of dry, frozen, and freeze-dried foods with a total energy value of 2600 kilocalories per man per day. Dry food is recommended for drinks and snacks because it is simple to reconstitute, and natural in flavor. These items would include for example, dehydrated orange and grape juices, cocoa, dried apricots, raisins, chocolate with almonds, mints, beef sticks and fruit cakes.

Frozen food is recommended for main meals. Frozen dinners (similar to TV dinners) would consist of a soup, meat, vegetable, dessert all on the same tray. The dinners are heated in an infrared oven, sized to accommodate four dinners at a time. Total cooking time for the meals would not exceed 15 minutes. The mission's supply of dinners are stored in a small refrigerator. Each used dinner tray may be replaced in its original position in the refrigerator for storage.

Freeze-dried food is also included in the crew's diet. This type includes coffee, fruit blended in with cereals to form bite-sized cubes, small sandwiches, and vegetables mixed in with meat or fish to form varied salads.

It is estimated what the food diet will consist of 2.32 lb/man-day food. This will be broken down into approximately 1.82 lb/man-day frozen food, and 0.25 lb/man-day each of dry and freeze-dried foods. Figures 79 and 80 illustrate the total equivalent weight for each food concept independently, as well as the selected food concept, as a function of crew size and mission duration respectively.

The selected diet will provide 2600 kilocalories per man-day in energy, as well as being appealing and more convential than past space diets. This diet will be quite suited to the untrained personnel who are scheduled to be crew members of the Shuttle. Common eating utensils may be used for meal consumption. The spoon however, will require a cap-like cover to insure against leakage to the cabin.

Impact of Mission Parameters

The impact of either crew size and/or mission length on the diet chosen results is proportionally increasing or decreasing food weight and storage. For short missions (2 days) however, an entire diet of freeze-dried food would be more economical. Food weight would be reduced and much subsystem equipment eliminated.

PERSONAL HYGIENE

Personal hygiene is both a functional and a psychological necessity on missions of more than a day. It is needed to prevent mouth and skin disease. Also, hygiene provides the psychological line with "earth-like" habit patterns and attitudes. Personal hygiene may be divided into four areas: grooming, dental hygiene, selective body cleaning and whole body cleaning. They are discussed in the following text.

Grooming

Grooming consists of cutting finger and toe nails, and shaving. Equipment used for these purposes must be designed to collect these items before they drift free into the cabin.

<u>Nail clipping</u>. - For Shuttle, it is recommended that all crew and passengers clip their hair and nails before flight takeoff. This will alleviate the problem of providing for these flight operations during a nominal seven day mission. However if nail clipping is deemed necessary it can be accomplished by using a conventional nail

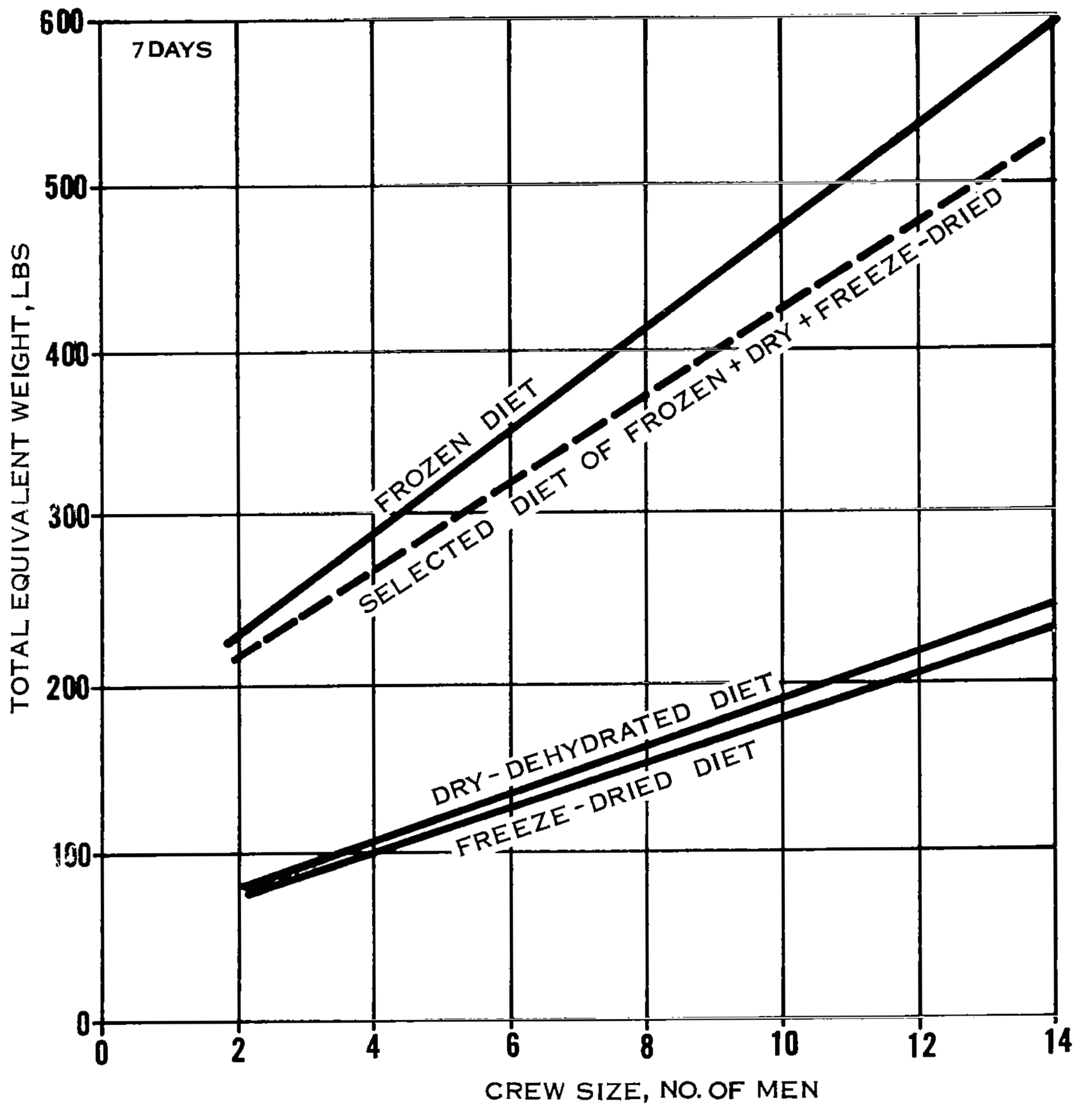

FIGURE 79. FOOD WEIGHT VERSUS CREW SIZE

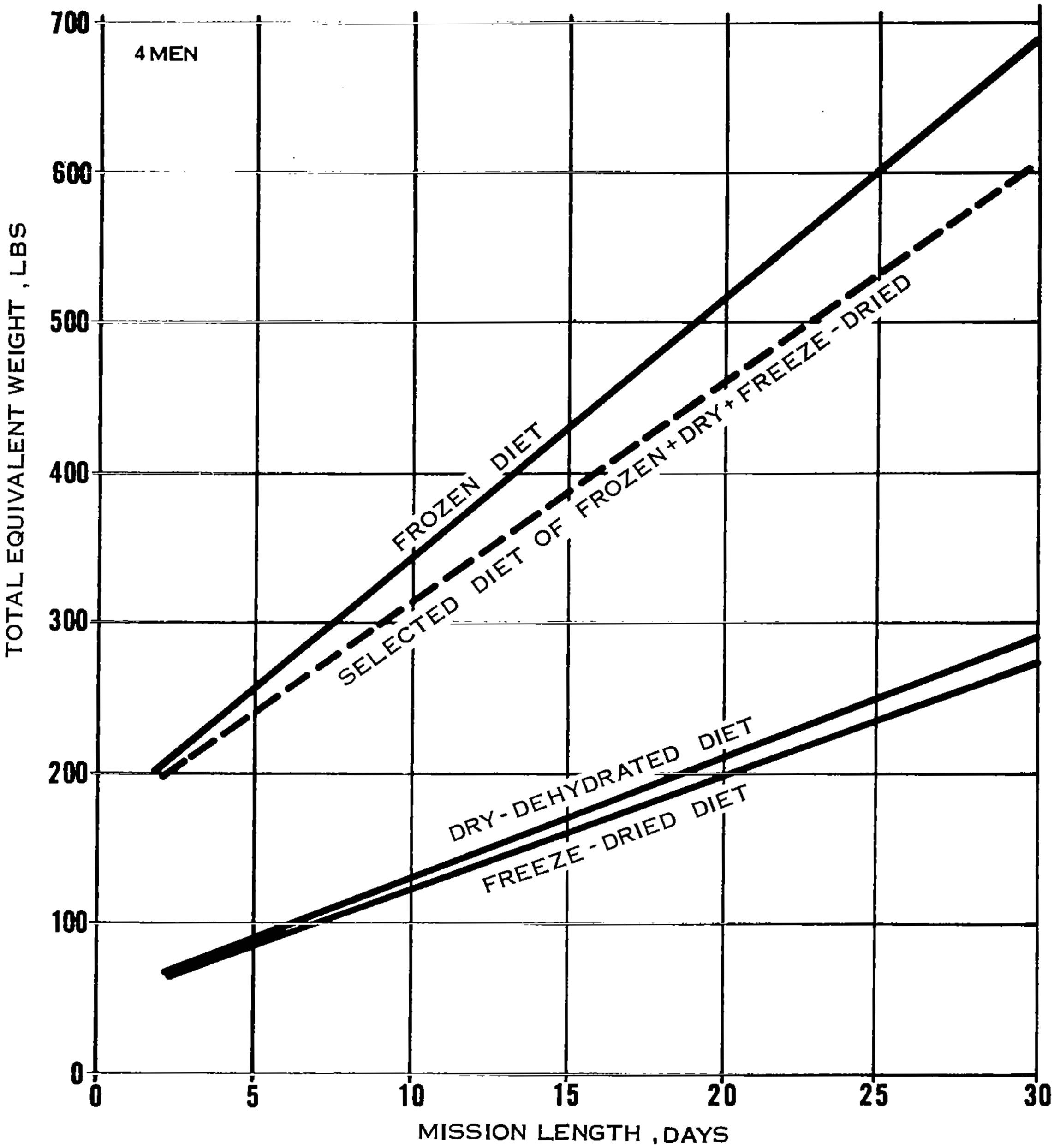

FIGURE 80. FOOD WEIGHT VERSUS MISSION LENGTH

clipper over the commode with the process fan and slinger operating. The process flow stream will carry the nail directly into the commode for storage.

Shaving. - Shaving, if desired, can be accomplished by using an electric or mechanically powered razor attached to a vacuum cleaner type hose as shown in figure 81. The hair will be entrained in a filter bag, which when full can be replaced. Filled bags can be emptied directly into the commode process air stream for storage in the commode.

Oral Hygiene

Oral hygiene is practiced at least once per day to keep teeth and mouth as clean and refreshed as possible. Because it is recommended that the shuttle diet contain solid foods, proper dental stimulation through brushing will assist in preventing softening of the gums and loosening of the teeth. Dental hygiene equipment includes a personal toothbrush, a paste-like dentifrice, a water delivery unit, and a waste collection unit.

The toothpaste is delivered to the toothbrush directly from its storage tube. When brushing is completed, water is used for rinsing. Thorough rinsing is mandatory to insure that there is no buildup of pastes in the collection tube. Liquid and ingestible dentifrices were considered, but were not selected because of the anticipated greater crew stress, possible medical problems relating to ingestion, and overall unnatural operation of these concepts for untrained crew. Expectorate is collected using a mouthpiece and adaption tube inserted in the waste water collection system. An air stream, provided by the liquid-air separator, sucks the mixture of water, saliva, dentifrice, and dental debris for delivery to the above mentioned system.

Selective Body Cleaning

The practical way to clean small body areas (face, hands, etc.) is with reusable wettable wipes and bar soap. The reusable wipe provides good flexibility in selection of the body area to be washed. The wipes are also reusable for general purpose cabin cleanup. Dry wipes are supplied, and water and soap is added to them to provide a suitable wash media. Cleaning agents such as alcohol, zepheral, etc. are not recommended for use because the possibility that contamination, from trace volatiles, of the cabin might occur. After each day (1 cloth per man-day) the used cloth wipes are placed in an air tight can with a disinfectant. Upon completion of the mission the wipes are either disposed of or washed prior to reuse.

Other selective body cleaning areas are the vicinities of the anus and vulva and nose (mucus control). The anus will be cleaned after each defecation using single

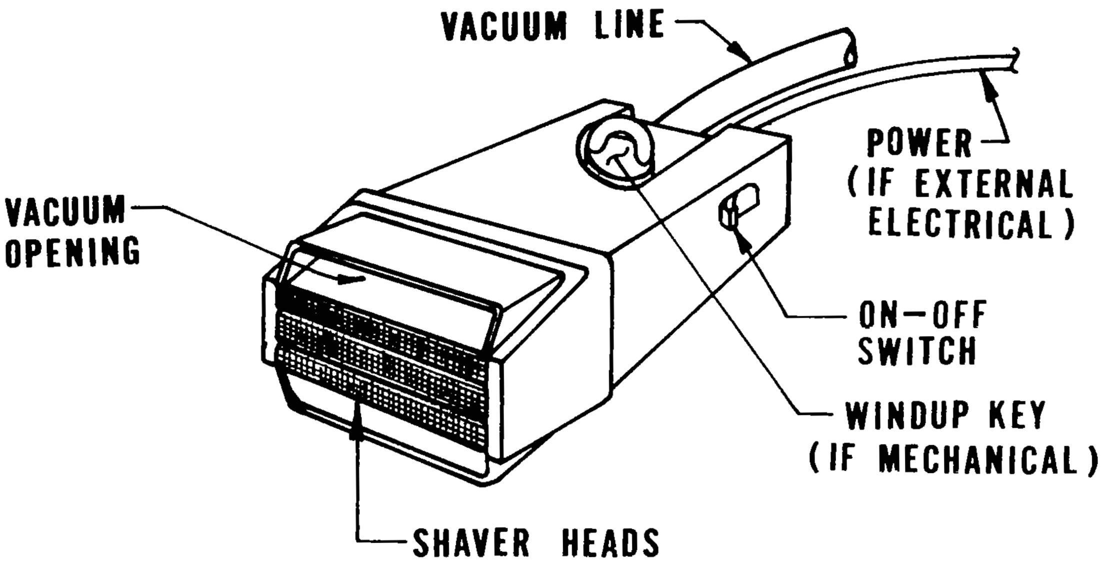

FIGURE 81. SHAVING CONCEPT, POWERED RAZOR – VACUUM CLEANING

sheet tissue wipes. The wipes, also used to clean the vulva after urination, will be disposed of into the slinger area of the commode. Facial tissue will be provided for mucus removal (nose - blowing). This too may be deposited into the commode for flight storage.

Whole Body Cleaning

Whole body cleaning must remove body surface contaminants as well as natural body products such as sweat, microbial growth, fecal matter, and other residues. Upon completion, the skin must be left dry with normal microbial levels and surface properties. Concepts such as a zero gravity shower, automatic sponge, immersion bath and sauna are not practical for the short duration flights of the Shuttle. A wash cloth (wetted with water and soap), concept is recommended for use. The reusable body wipes, as for selective body cleaning, are squares of woven fabric stored dry and moistened with water as required. Excess free water is removed by hand squeezing the wipes, the liquid being carried away by an air stream drawn through the cabin sink. The liquid-gas separator provides this air stream. The wipes are squeezed after use and allowed to dry in the cabin for the next washing.

This concept bathes one portion of the body at a time, so it is not entirely satisfactory as a whole body bath. Psychologically, the wipes provide a sense of refreshment through mechanical stimulation of the skin, and they closely resemble normal earth-like wash operations. One wash cloth per person per day is recommended. Used cloths are stored in an air tight can, with disinfectant added. A standard towel is recommended for body drying. These are also stored in an air tight can after two days use.

CLOTHING

Reusable clothing is recommended for crew wear. The wear schedule recommended is: outer garments are worn for seven days, and underwear and socks are changed daily. Since no clothing is washed during a flight, all soiled clothing is stored in an air tight container with a disinfectant which is added to prevent bacteria growth. Upon completion of the mission the clothes can be laundered and reused.

HOUSEKEEPING

The cleaning of surface areas, seats and general use tables, floors, etc. is psychologically and microbiologically necessary. A vacuum cleaner attached to the waste management subsystem appears to be a necessary piece of equipment to have on board for general cleaning. In addition sanitizer wipes impregnated with acid-anionic or a cationic surfactant appear appropriate for clean-up and prevention of residual bacterial action. The acid-anionic sanitizers usually have a low pH of approximately two, but are effective on stainless steel equipment surfaces. These sanitizers are non-staining, not objectionable in odor, effective against a wide spectrum of organisms, stable, and non-corrosive to stainless steel. For bacteria control of toilet seat surfaces, a quaternary compound (such as benzalkonium chloride) is recommended. This compound is safe and will be acceptable to the crew. Due to outgassing and odor considerations, the use of phenolics, chlorinated and iodinated compounds for sanitizing is inappropriate and not considered.

SYSTEM INTEGRATION

TABLE OF CONTENTS

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SYSTEM INTEGRATION

This report section describes the selected baseline EC/LSS, and the various interfaces, operating procedures and equipment associated with the baseline. Also included is a discussion of the effect of mission parameters on the selected system.

GENERAL DISCUSSION

The recommended subsystems integrate well into an optimum and straightforward Environmental Control and Life Support System (EC/LSS). Maximum use has been made of equipment that is well within today's state-of-the-art, and improvements are, for the most part, limited to eliminating the shortcomings of contemporary concepts, particularly in the areas of waste management, cabin humidity control, crew safety, and ground refurbishment or responding to new unique shuttle requirements.

To fully appreciate the basic concept of a life support system for a fully reuseable, multipurpose and economical manned spacecraft (as opposed to one-mission expendable vehicles now in use), a review of the salient points of the requirements, guidelines, and constraints governing the baseline space shuttle orbiter EC/LS system design is presented in table 28. It is in the areas of equipment life, reliability criteria, and flexibility/growth that the shuttle orbiter vehicle differs substantially from contemporary manned spacecraft. These factors share two common system influences: First, they all contribute towards the goal of making the shuttle orbiter vehicle reliable, safe, ana economical. The sea-level atmosphere promotes a simple "fly-away" operational concept, without preconditioning of crew, passengers, or the vehicle cabin atmosphere. The long equipment life and flexibility/growth concepts go far beyond the present one-mission, one design point system concepts of the past, and yield multi-mission capability without significant equipment changes. The fail operational-fail safe requirement virtually eliminates the risk of a catastrophic failure, enhancing the vehicle's usefulness and acceptance. Secondly, these factors all tend to increase system weight. The mixed cabin atmosphere requires additional diluent gas storage, special controllers, and a structurally heavier cabin wall, since it operates at roughly three times the absolute total pressure of contemporary manned spacecraft. Long life equipment can generally be considered heavier than short-life or "one shot" equipment. The reliability criteria requires virtually doubling of the equipment weight because double and often triple redundancies are required. The flexibility/growth parameter, though its effect is more subtle, infers deoptimization of the system to perform adequately at several design points thereby increasing system weight over an optimum single-mission design.

TABLE 28

OVERALL SYSTEM REQUIREMENTS
(BASELINE ORBITER MISSION)

PARAMETER	REQUIREMENT
Crew Size	4 Persons Total
Mission Duration	7 Days + 48 Hours Contingency
Cabin Atmosphere/Pressure	14.7 psia Air
Power Supply (See Note 1)	H_2 - O_2 Fuel Cells
Water Supply (See Note 1)	Fuel Cell Reaction Product
Primary Heat Rejection	Deployable Space Radiator
Equipment Life	10 Years - 100 Missions
Reliability Criteria	
Any Single Failure	No effect on mission - no crew action required
Any Two Failures	Maintain crew safety for 48 hours; crew action permissible
Flexibility/Growth	To 30 Days - To 14 Persons

Note 1: Power penalty used is for 1 active and 3 standby fuel cells.
Product water is hot, potable, and contains no entrained gases.

Of significant influence in the evolution of the space shuttle orbiter EC/LS system is the treatment of the use of space suits. All references to the two traditionally overpowering factors of space suits and of cabin wall punctures in the design of manned spacecraft are conspicuous by their absence. Except as an add-on for special individual missions, extra-vehicular activity (EVA) is not planned for the space shuttle baseline mission. The remaining purpose for space suits, using them as "last resort" in the event of a sudden accidental cabin decompression, has become less necessary as more manned spacecraft experience is accumulated on Apollo flights. Since the pressure shell of the orbiter vehicle is substantially thicker than present spacecraft, and since the orbiter also carries substantial structure and thermal shielding to withstand repeated reentries into the atmosphere, the likelihood of meteroid puncture through the primary envelope is remote. While a quantitative assessment is beyond the scope of this effort, there is evidence to suggest that the probability of a meteroid puncture of the shuttle orbiter pressure shell is reduced to a value so low, that it becomes insignificant compared to a double equipment failure probability. Thus, with the cabin puncture problem dispelled, the primary reason for the use of space suits within the vehicle is precluded. The use of a true shirtsleeve atmosphere is well justified for the space shuttle orbiter vehicle, and the penalties incurred in the greater structural integrity required may very well be offset by the savings in space suits and auxiliary EC/LSS equipment. But more important, the safety of the vehicle and its occupants is enhanced.

SELECTED SUBSYSTEMS

The various selected subsystems are summarized in table 29. A brief description of each major subsystem and its primary features is presented below.

Atmospheric Storage: The use of the vehicle propellant oxygen storage system is selected for the primary oxygen storage requirements because of its availability, low cost and weight. A composite material high pressure gas tank is selected for emergency oxygen storage because of its lower total equivalent weight and growth potential.

A composite material high pressure gas tank is selected for nitrogen storage because of its lower total equivalent weight, and growth potential.

Pressure and Composition Control: A pressure regulated nitrogen and oxygen two gas control was selected for maintaining the proper pressure and atmospheric composition in the cabin.

TABLE 29

EC/LS SELECTED SYSTEM

Subsystem	Description
Atmospheric Storage	Oxygen from vehicle propulsion system. Nitrogen stored in composite material tank at 3000 psia. Emergency Oxygen stored in composite material tank at 3000 psia.
Pressure and Composition Control	Pressure regulated, 2-gas control provided by cabin total pressure and oxygen partial pressure sensors.
CO_2, Humidity and Temperature Control	LiOH Bed for CO_2 control, humidity control utilizes condensing heat exchanger followed by an elbow type water separator connected to the waste management subsystem. Temperature control is obtained by bypassing air flow around the condensing heat exchanger.
Atmospheric Contaminant Control	Charcoal bed for odor and trace contaminant control. Copper sulphated sorbeads for ammonia control. Particulate filter for debris control. Bacteria filters for bacteria control.
Heat Rejection	Space Radiator for main heat sink. Water evaporator for on-orbit peak loads. Cryogenic Hydrogen heat exchanger for reentry and ferry mission cooling.
Water Management	Utilize fuel cell water for all crew water uses and as an evaporant. Heated 160°F zero gravity storage tanks. Hot and cold water lines automatically cycled every 24 hours for bacteria control.
Waste Management	Wall type urinal, male use. Conventional "earth like" split-commode for male and female use. Heated overboard dump nozzles for urine and waste water dump. Combination fan centrifugal separator for water transport and phase separation.
Crew Provisions	Combination frozen and freeze-dried foods. Reuseable wettable wipes and soap for body washing. Reuseable clothes for crew wear.

CO_2, Humidity and Temperature Control: LiOH is selected over solid amine (HS-C) for CO_2 control for the baseline system because it has immediate advantage of a low cost through first flight and good availability. The concept provides good performance at low CO_2 partial pressure levels and during all mission phases, including reentry and atmospheric flight.

A condensing heat exchanger and an elbow-centrifugal separator are selected for the humidity and cabin temperature control function requirements respectively to be used in conjunction with the LiOH, CO_2 control system. The static inertia-type wickless water separator is selected for integration potential with the waste management subsystem water separators, thereby eliminating wide refurbishment/ maintenance problems at very little weight and power penalty.

For cabin temperature control, the air bypass control method is selected over a coolant flow control to eliminate valves in the coolant circuit, improve system reliability, and eliminate additional heating or cooling heat exchangers.

Atmospheric Contaminant Control: The selected methods of contaminant control are charcoal, copper sulfate on sorbeads for ammonia control and particulate and bacteria filters. The inherent capability of the condensed water in the condensing heat exchanger is utilized to control pyruvic acid. A catalytic oxidizer is not required for the baseline mission.

Heat Rejection: A space radiator is used as the main heat sink for the on-orbit mission phase. A water evaporator is used for transient periods of high heat load or high radiator heat influx during the on-orbit mission phase to supplement the radiator heat sink. A cryogenic hydrogen heat sink is used for the reentry and atmospheric flight phases. A heat exchanger, installed in the vehicle's heat rejection loop is used for prelaunch and post launch mission phases. The heat exchanger is supplied with cooling fluid from a GSE unit, when operation is desired. The subsystem consists of two coolant loops. A non-toxic (water) circuit inside the cabin and a Freon 21 coolant circuit external to the cabin. Both circuits consists of two redundant loops, a primary and a secondary loop. The primary loop contain redundant pumps and accumulation. A single pump and accumulator is used in the secondary loop.

Water Management: Bladerless tanks are selected for potable water storage for increased reliability and greatly reduced maintenance problems. Pasteruization is selected as the primary water microbiological control method because it offers the best performance and the least cost.

Waste Management: The simplest method to comfortably accommodate the male/female crew with the restriction of no solids being dumped results in a split-flow commode utilizing vacuum drying and tissue wipes for the fecal waste management subsystem. A single male urinal will also be provided.

Crew Provisions: A combination of frozen and freeze-dried food is recommended. It is felt that the types and amount of food selected for the orbiter crew diet will not be an engineering decision, but a subjective one, based on personal preference and physiological (dietary) considerations not likely to result in a minimum overall system penalty. Reuseable wettable wipes and soap is used for local and whole body washing. Reuseable cloths are recommended for crew wear.

SYSTEM INTEGRATION

The baseline EC/LSS schematic is shown in figure 82. An itemized parts list is included in table 30. The subsystem characteristics of weight, power reliability and the materials balance are discussed below.

The weight summaries are shown in table 31, and do not include the weights of such prime contractor supplied items as electrical cold plates, the space radiator, and other miscellaneous cooling devices (i.e., wheel well heating and/or cooling panels, fuel cell heat exchangers, etc.). The weights of coolant circuit plumbing lines are heavily dependent on actual flight vehicle configuration, and an estimate is included separately, along with coolant fluid weights in table 32. These weights are a gross approximation to show that the lines themselves can have an overpowering influence on the EC/LSS weight, especially when redundant circuits are used. There is evidence to suggest the line and fluid weights could eventually reach as high as twice the values listed in table 32 dependent on final vehicle configuration.

Power

System power consumption is summarized in table 33 . As expected, most of the power is consumed by the main cabin circulating fan, the coolant pumps in both circuits, and the rotary water/urine separator. These four components account for 688 out of a total of 750 watts average power consumption. An additional 103 watts of power is consumed during the reentry and atmospheric flight phases to operate the cryogenic valves and controls. Peak power consumption occurs when the unrelated events listed in table 34 happen simultaneously. These events increase the maximum average power consumption of 750 watts, to an absolute maximum peak power requirement of 1083 watts. Except for the potable water tank heater (item 492) and the cabin temperature control valve (item 104), all this additional power is for operation of latching solenoid valves. The time duration of the power pulse is less than 50 milliseconds.

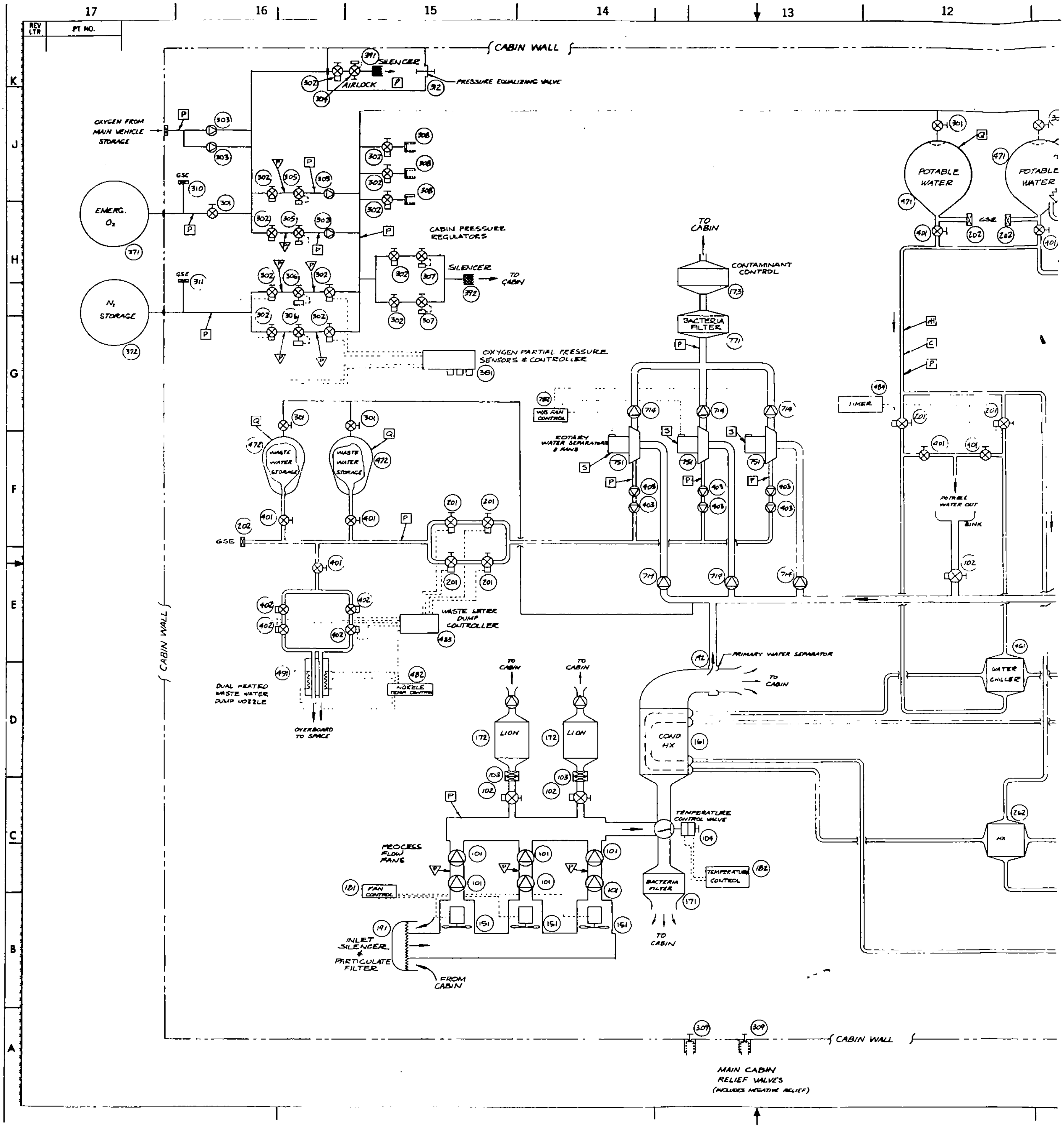
17
16
15
14
13
12
REV LTR
PT NO.
CABIN WALL
SILENCER
AIRLOCK
PRESSURE EQUALIZING VALVE
OXYGEN FROM MAIN VEHICLE STORAGE
GSE
EMERG. O2
N2 STORAGE
CABIN PRESSURE REGULATORS
SILENCER
TO CABIN
OXYGEN PARTIAL PRESSURE SENSORS & CONTROLLER
TO CABIN
CONTAMINANT CONTROL
BACTERIA FILTER
POTABLE WATER
POTABLE WATER
TIMER
POTABLE WATER OUT
SINK
WS FAN CONTROL
ROTARY WATER SEPARATORS & FANS
WASTE WATER STORAGE
WASTE WATER STORAGE
GSE
WASTE WATER DUMP CONTROLLER
DUAL HEATED WASTE WATER DUMP NOZZLE
NOZZLE TEMP CONTROL
OVERBOARD TO SPACE
PRIMARY WATER SEPARATOR
TO CABIN
WATER CHILLER
TO CABIN
TO CABIN
LIOH
LIOH
COND HX
TEMPERATURE CONTROL VALVE
TEMPERATURE CONTROL
BACTERIA FILTER
PROCESS FLOW FANS
FAN CONTROL
INLET SILENCER & PARTICULATE FILTER
FROM CABIN
TO CABIN
HX
CABIN WALL
MAIN CABIN RELIEF VALVES (INCLUDES NEGATIVE RELIEF)

TABLE 30 (Concluded)

Item	Description	Number	Item	Description	Number
502	Disconnect Half	5	714	Valve, Check	6
503	Valve, Solenoid Shutoff	2	715	Valve, Manual Shutoff (Chem.)	1
504	Disconnect Half	2	716	Disconnect Half (Chem.)	1
551	Pump, Coolant	3	751	Fan/Centrifugal Water Separator	3
561	Heat Exchanger - GSE	1	771	Bacteria Filter	1
571	Accumulator, Coolant	3	772	Waste Collector	1
601	Valve, Solenoid Shutoff	4	773	Bactericide Tank	1
602	Valve, Modulating	3	781	Waste System Controller	1
603	Valve, Solenoid Shutoff	2	782	Fan/Water Separator Controller	1
661	Cryogenic Heat Exchanger	2	791	Bactericide Dispenser	3
681	Temperature Controller	3	792	Urinal	1
712	Valve, Solenoid Repressurization	1	793	Sink	1

TABLE 30

PARTS LIST

Item	Description	Number	Item	Description	Number
101	Valve, Check	6	303	Valve, Check	4
102	Valve, Solenoid Shutoff	9	304	Pressure Regulator, Airlock	1
103	Disconnect Half	2	305	Pressure Regulator, Oxygen	2
104	Valve, Temperature Control	1	306	Pressure Regulator, Nitrogen	2
151	Fan, Process Flow	3	307	Pressure Regulator, Cabin	2
161	Heat Exchanger, Condensing	1	308	Valve, Pressure Relief	3
171	Filter, Bacteria	1	309	Valve, Cabin Pressure Relief	2
172	Canister, LiOH	9	310	Disconnect Half, Oxygen	1
173	Canister, Contaminant Control	1	311	Disconnect Half, Nitrogen	1
181	Controller, Fan	1	312	Valve, Pressure Equalizing	1
182	Controller, Cabin Temperature	1	371	Tank, Emergency Oxygen	1
191	Particulate Filter	1	372	Tank, Primary Nitrogen	1
192	Water Separator	1	381	Oxygen Partial Pressure Control	1
201	Valve, Solenoid Shutoff	12	391	Silencer, Airlock Inflow	1
202	Disconnect Half - GSE	8	392	Silencer, Cabin Inflow	1
203	Disconnect Half - Gas	6	401	Valve, Manual Shutoff	11
204	Valve, Check	3	402	Valve, Solenoid Shutoff	6
205	Water Pressure Regulator	2	403	Valve, Water Check	6
251	Pump, Water Coolant	3	461	Water Chiller	1
261	Heat Exchanger - Interface	2	471	Potable Water Tanks	2
262	Heat Exchanger - H_2O Precooler	1	472	Waste Water Tanks	2
263	Sublimator	1	481	Heater Controller (Tank)	1
271	Accumulator - Coolant Water	3	482	Temperature Controller (Nozzle)	1
281	Pump Controller	2	483	Water Dump Control	2
282	Accumulator Controller	2	484	Timer	1
283	Temperature Control	1	491	Water Dump Nozzle	1
301	Valve, Manual Shutoff	5	492	Tank Heater	2
302	Valve, Solenoid Shutoff	12	501	Valve, Coolant Check	3

TABLE 31

EC/LSS WEIGHT SUMMARY

SUBSYSTEM	WEIGHT - POUNDS	
	INSTALLED*	EXPENDABLES
Atmospheric Supply	167	251
Pressure/Composition Control	49	0
Waste Management	140	1
Waste Water Dump System	77	0
Cabin Humidity & Temperature Control	262	0
CO_2 Removal	60**	116
Contaminant Control	57**	0
Water Management	97	100
Cabin Coolant Circuit	249	0
Radiator Coolant Circuit	135	0
Crew Provisions	60	129
Total	1353	597

*Dry weight - includes packaging/gas ducting

**Installed expendables

TABLE 31 (Concluded)

EC/LSS WEIGHT SUMMARY

4 MEN–7 DAYS

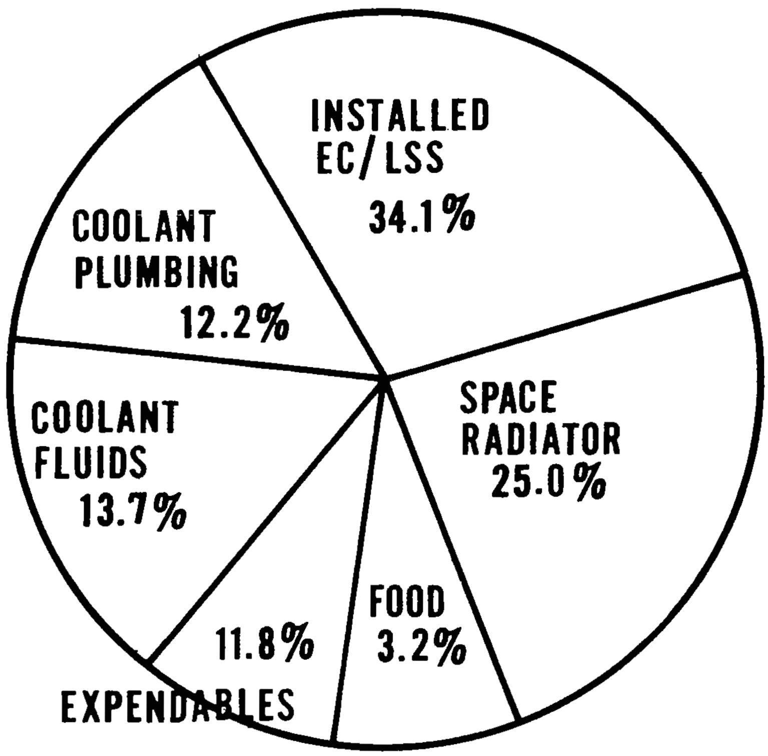

TABLE 32

ESTIMATED COOLANT CIRCUITS WEIGHTS

SYSTEM	WEIGHT - POUNDS		
	INSTALLED/ DRY	EXPENDABLES OR FLUID	TOTAL
Cabin Coolant Circuit Plumbing Only	25	65	90
External Coolant Circuit Plumbing Only	460	439	899
Space Radiator (Deployable)	996	40	1036
Totals	1481	544	2025
EC/LSS (For Comparison)	1353	597	1950

TABLE 33

EC/LSS POWER SUMMARY

SUBSYSTEM	AVERAGE POWER WATTS
Atmospheric Supply	0.0
Pressure/Composition Control	7.0
Waste Management	74.0
Cabin Humidity and Temperature Control	400.0
CO_2 Removal	0.0
Water Management	13.0
Cabin Coolant Circuit	57.0
Radiator Coolant Circuit	199.0*
Contaminant Control	0.0
Crew Provisions	0.0
Total	750.0

*Additional 103 watts for re-entry

TABLE 34

PEAK POWER

EVENT	POWER
Turn on waste collector; close vacuum valves (Items 102) and open repressurization valve (Item 712)	105 watts
Heater (Item 492) turns on in potable water tank	15 watts additional
Turn on supplementary heat rejection (sublimator, Item 263) by opening solenoid water valves (Item 201)	40 watts
Full swing of cabin temperature control valve (Item 104)	13 watts additional
Excess P_{O_2} condition turns on nitrogen inflow solenoid valves (Item 302)	50 watts
Waste water dump process is inhibited in mid-cycle, closing dump valves (Item 402) and opening water separator outlet valves (Item 201)	110 watts
Oven Power for food preparation	540 watts additional
Total Additional Power	873 watts

Reliability

The reliability for crew safety for the baseline EC/LSS is 0.999902. The reliability for each of the major subsystems is shown in table 35.

Materials Balance

Due to the duration of the Shuttle Baseline Mission (seven days), the selected system is basically "Open Loop". CO_2, humidity condensate, urine, and flush water are not reclaimed but are either stored or dumped to space. Solid wastes are vacuum dried and stored on board. Figure 83 shows a general materials balance for a 4-man crew. Vehicle leakage is not included in the general materials balance but is included in the subsystem weights. Included in the figure is an estimate of unused food and water.

A water balance which includes the man and the fuel cell is shown in figure 84. All of the excess fuel cell water can be evaporated to reduce the radiator size. Missions not experiencing peak heat loads or maximum radiator influxes, require some of this water to be dumped to space along with the humidity condensate and flush water.

SYSTEM OPERATION

General

On the ground prior to launch, the vehicle systems can be operated normally with the required heat rejection being accomplished by the ground support equipment heat exchanger, item 561. All subsystems are conceived to be fully operable in all orientations; the vertical launch orientation, in zero gravity and in the horizontal attitude during ferry and landing. One exception to this general requirement is in the waste management system; it does not appear that the solid waste collector will be useable with the vehicle vertically oriented, for obvious reasons. The remote urinal, item 792, is useable even in this awkward orientation, to cope with the eventuality of a prolonged "hold." There is ample capacity in the CO_2, humidity and temperature control subsystems to handle lengthy ground operations prior to launch. A flow chart for the prelaunch/post landing mission phases is presented in figure 85. The heat loads and system performance are the same as for the on-orbit design point except that heat rejection is provided by the ground support heat exchanger.

The vehicle is launched with the cabin at normal sea level pressure, so that there is substantially no dumping of excess atmosphere during ascent. Operation of the cabin at a normal 14.7 psia O_2-N_2 atmosphere, such as is planned for this vehicle, is a very desirable feature for the following reasons:

TABLE 35

BASELINE SHUTTLE EC/LSS RELIABILITY
(FOR CREW SAFETY)

SUBSYSTEM	RELIABILITY FOR CREW SAFETY
Atmospheric Storage & Pressure & Composition Control	.999972
CO_2, Humidity, and Temperature Control	.999989
Waste Water Management	.999975
Potable Water	.999992
Cabin Coolant Loop	.999988
Radiator Coolant Loop	.999986
Reliability for Crew Safety =	.999902

4 MEN, ALL VALUES IN lb/DAY

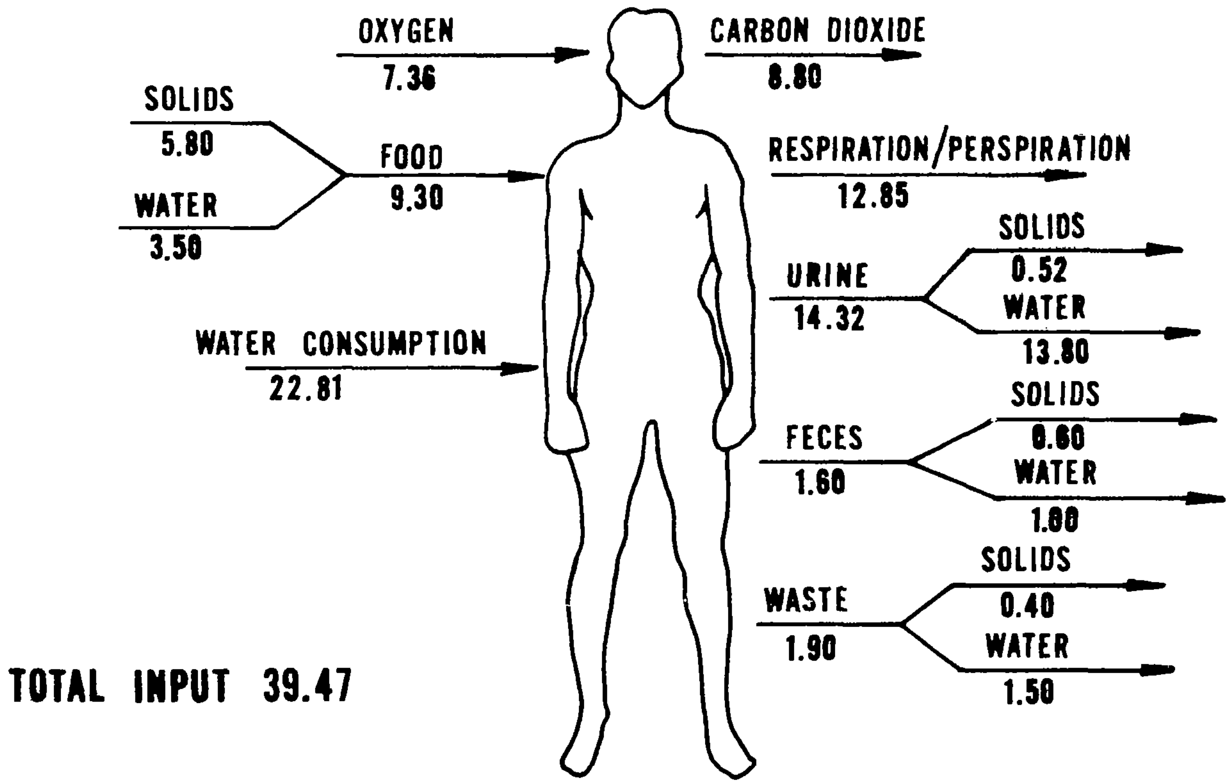

FIGURE 83. GENERAL MATERIALS BALANCE

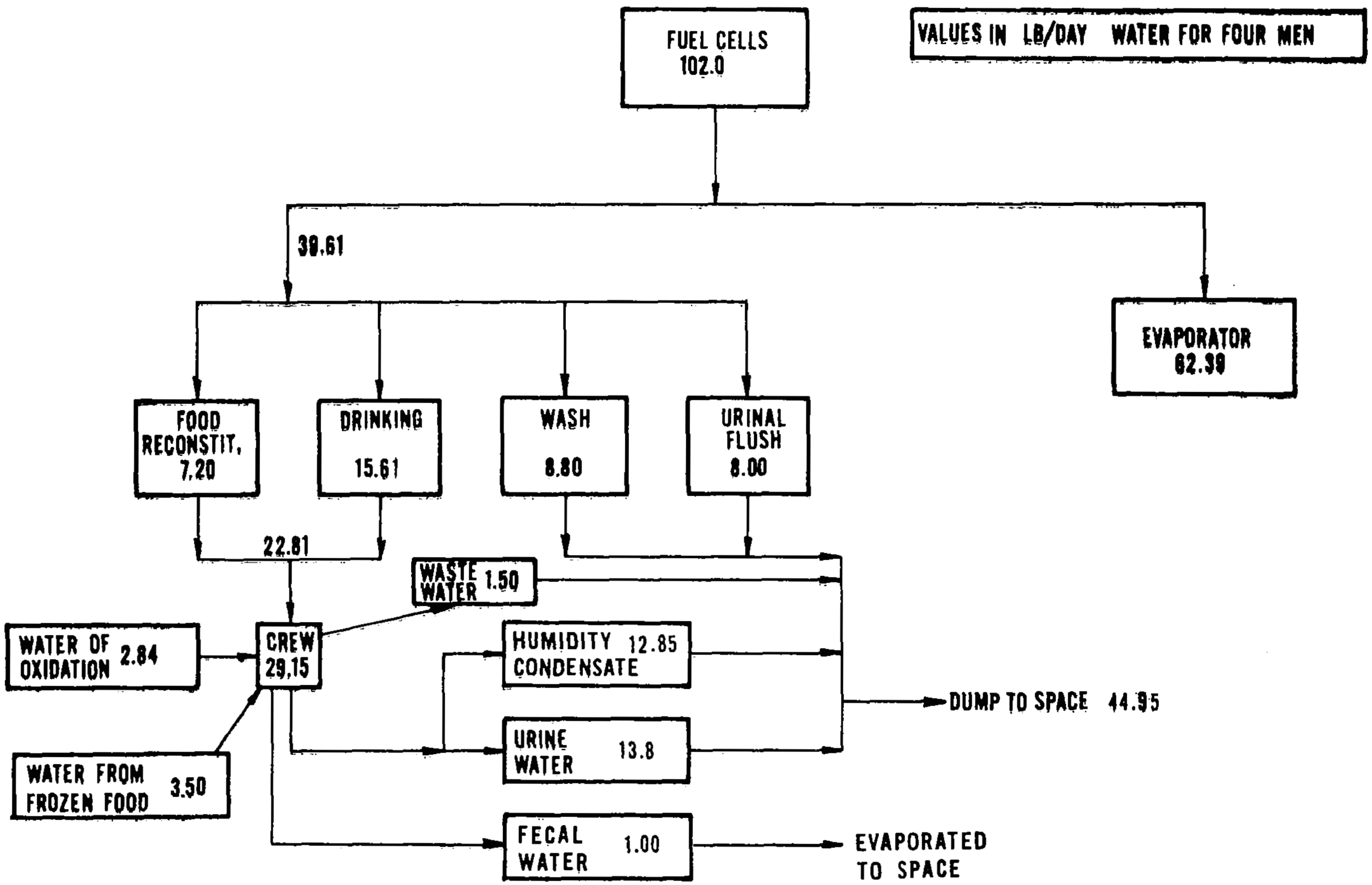

FIGURE 84. WATER BALANCE

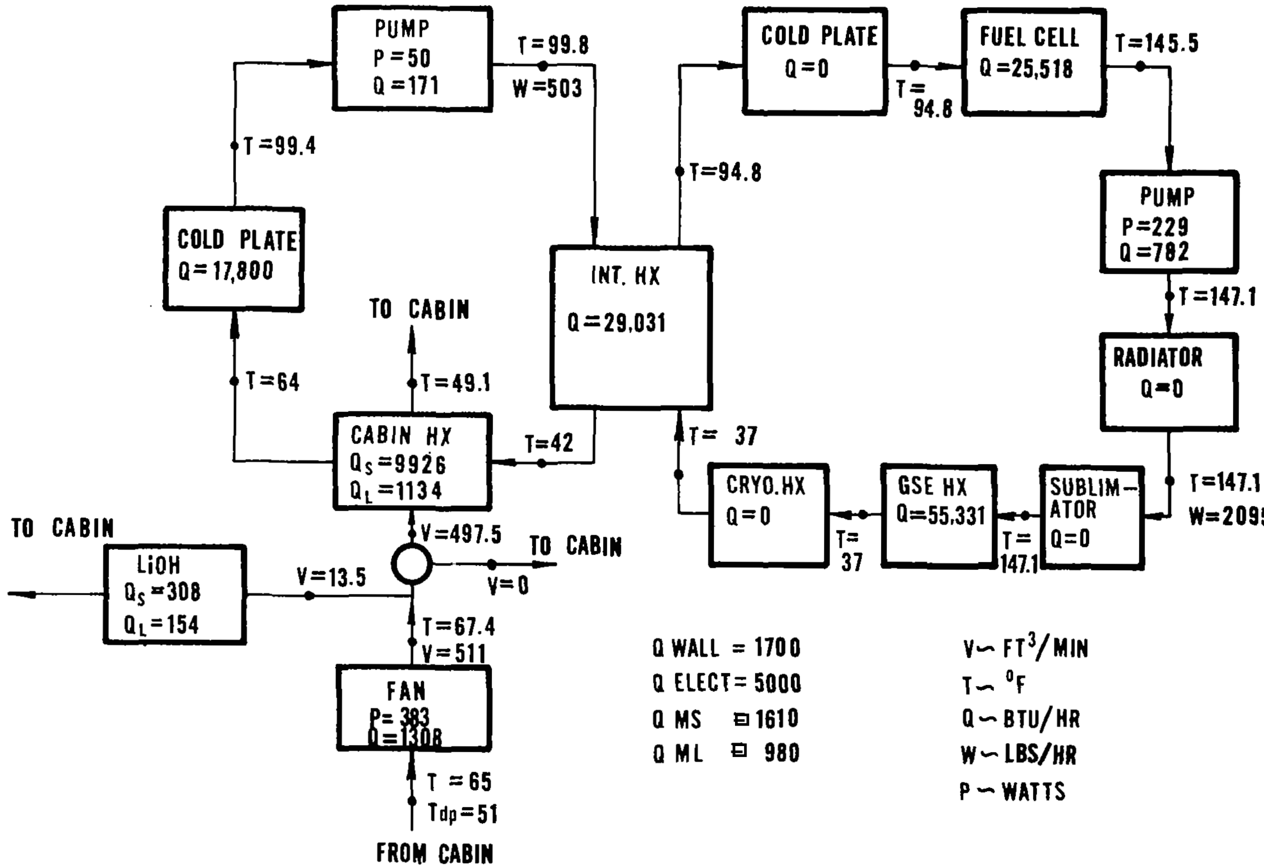

FIGURE 85. FLOW CHART, PRELAUNCH/POST LANDING PHASES

- It is the most physiologically acceptable atmosphere, requiring no preconditioning of the crew or passengers.

- It presents a much reduced fire hazard over oxygen rich mixtures common to the United States manned spacecraft, thereby allowing potential relaxation of materials useage limitations, especially non-metallics.

- It simplifies ground support and procedures, requiring only filtered air for the launch atmosphere, and simplifying cabin pressure relief valve requirements by deleting the ascent relief function (as stated above), which usually dictates the size and number of relief valves required.

- It prevents obsolescence, by assuring that the cabin atmosphere, assuming a sufficiently flexible pressure/composition control subsystem,will be fully compatible with any other space vehicle in the forseeable future.

During launch ($\sim$10 minutes to orbital insertion), heat rejection is accomplished by thermal lag within the coolant circuits (it takes over 5 minutes for the heat rejection coolant to flow around the loop). All other subsystems operate normally, except, the waste management subsystem as previously described. There should be no need to dump any waste water until the vehicle is at least 12 hours into the mission, since the waste water tanks (item 472) are launched in an empty condition. The primary potable water tank is also launched in an empty condition, while the standby tank is filled prior to launch with potable water containing iodine as a bactericide. This standby tank is isolated from the remainder of the circuit by manual shutoff valves, items 301 and 401. One Lithium Hydroxide CO_2 removal canister is "on line", while an installed standby LiOH canister remains isolated by a solenoid valve, item 102. The cabin temperature controller, item 104, may be overridden to the full cooling position for launch, if this proves necessary.

The system is sized by the on-orbit nominal heat load condition. A flow chart of this condition is presented in figure 86. Heat rejection is provided by the space radiator, primarily, with supplemental heat rejection provided by the sublimator utilizing excess fuel cell water. Two additional flow charts are presented for on-orbit operation. Figure 87 presents a flow chart for average heat loads and Figure 88 for minimum heat loads. In both cases, air is bypassed around the condenser to maintain a 65°F cabin temperature and all of the heat rejection is accomplished by the space radiator. The average heat load case represents the condition that will exist for the majority of the time on-orbit. The maximum heat load case will exist for short periods when the shuttle is maneuvering or docking with the space station. The minimum heat load case will exist while the crew is sleeping.

During the reentry phase of the mission, the vehicle experiences maximum heat loads. As a result, the vehicle skin temperature and therefore the cabin heat leak

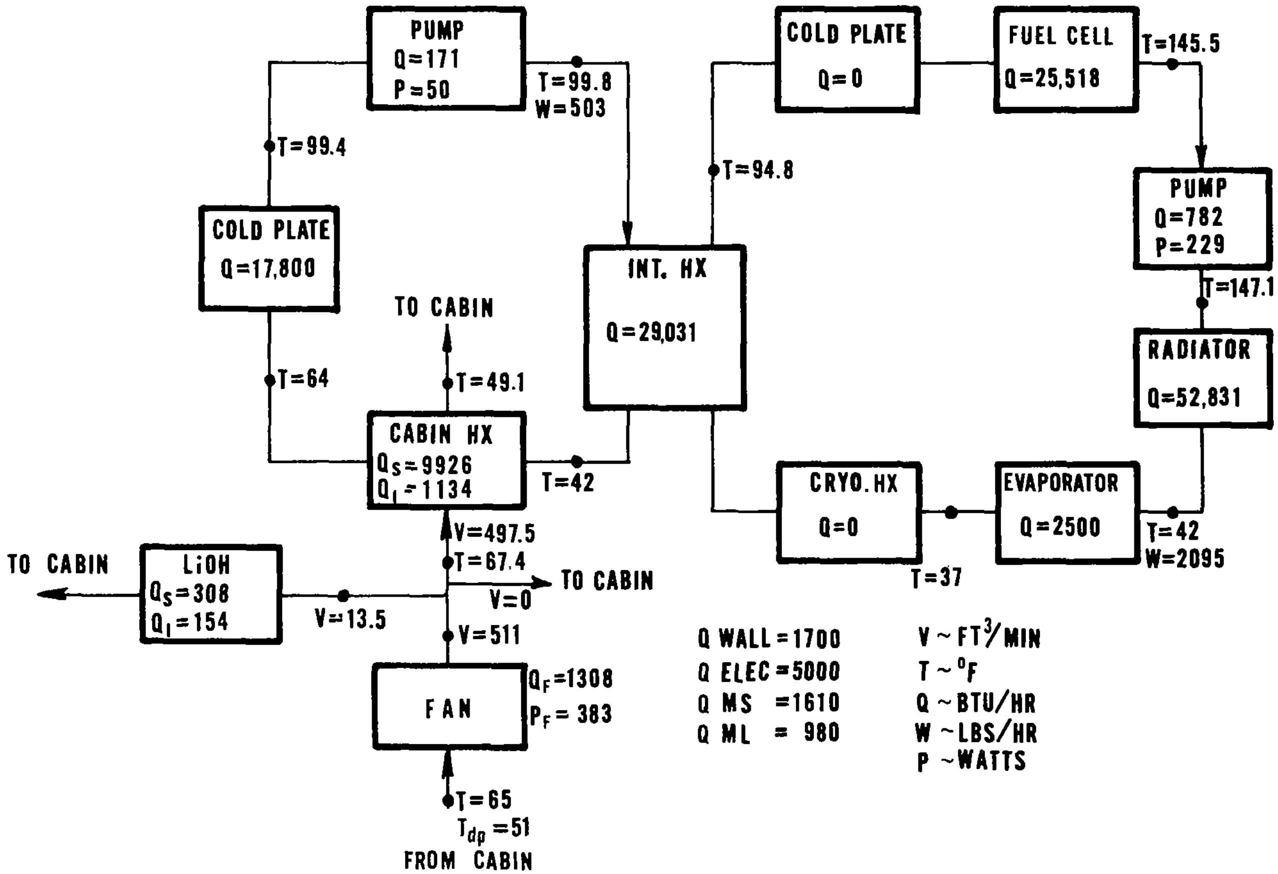

FIGURE 86. FLOW CHART, NOMINAL ON-ORBIT HEAT LOADS

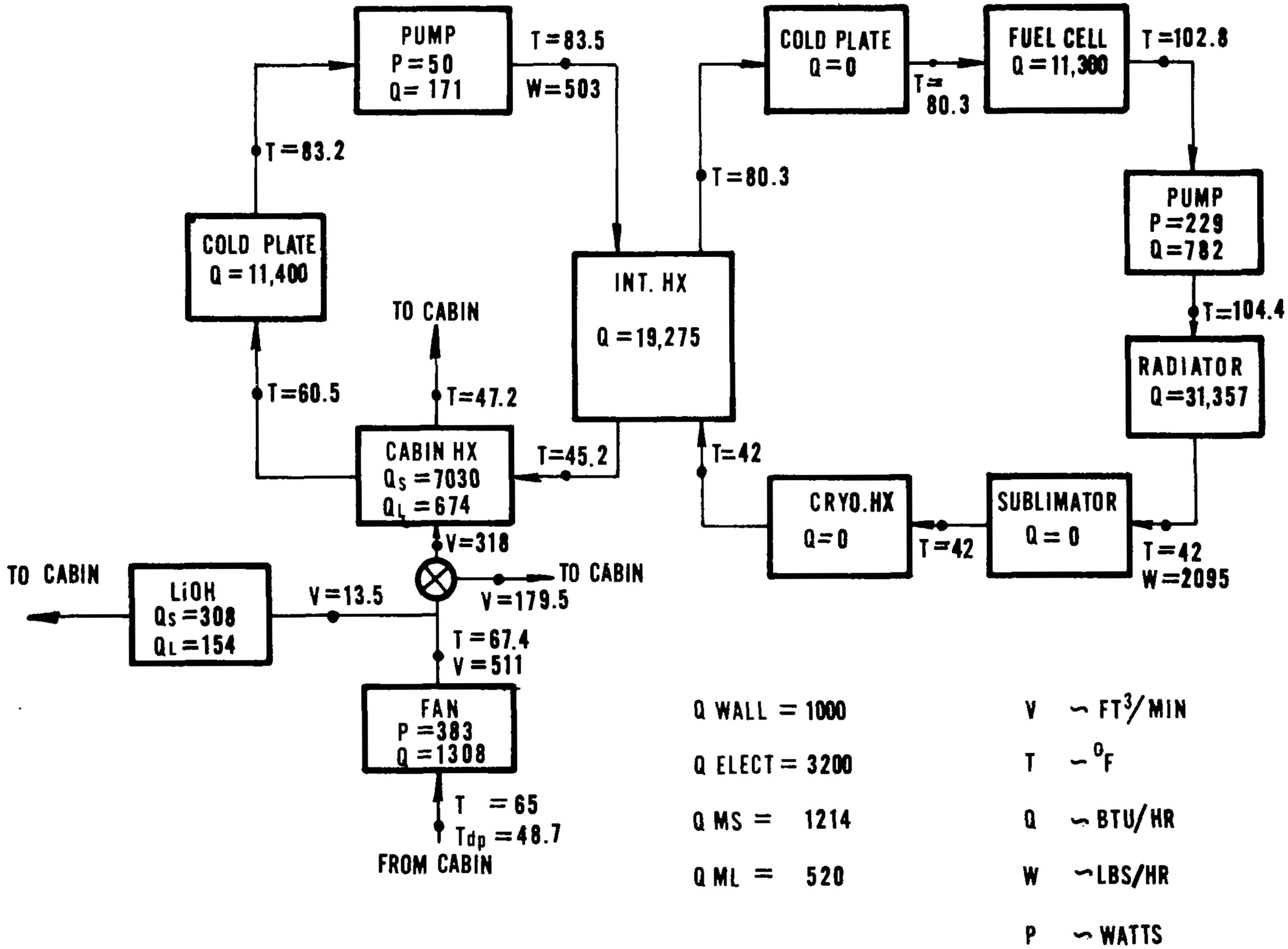

FIGURE 87. FLOW CHART, ON-ORBIT AVERAGE HEAT LOADS

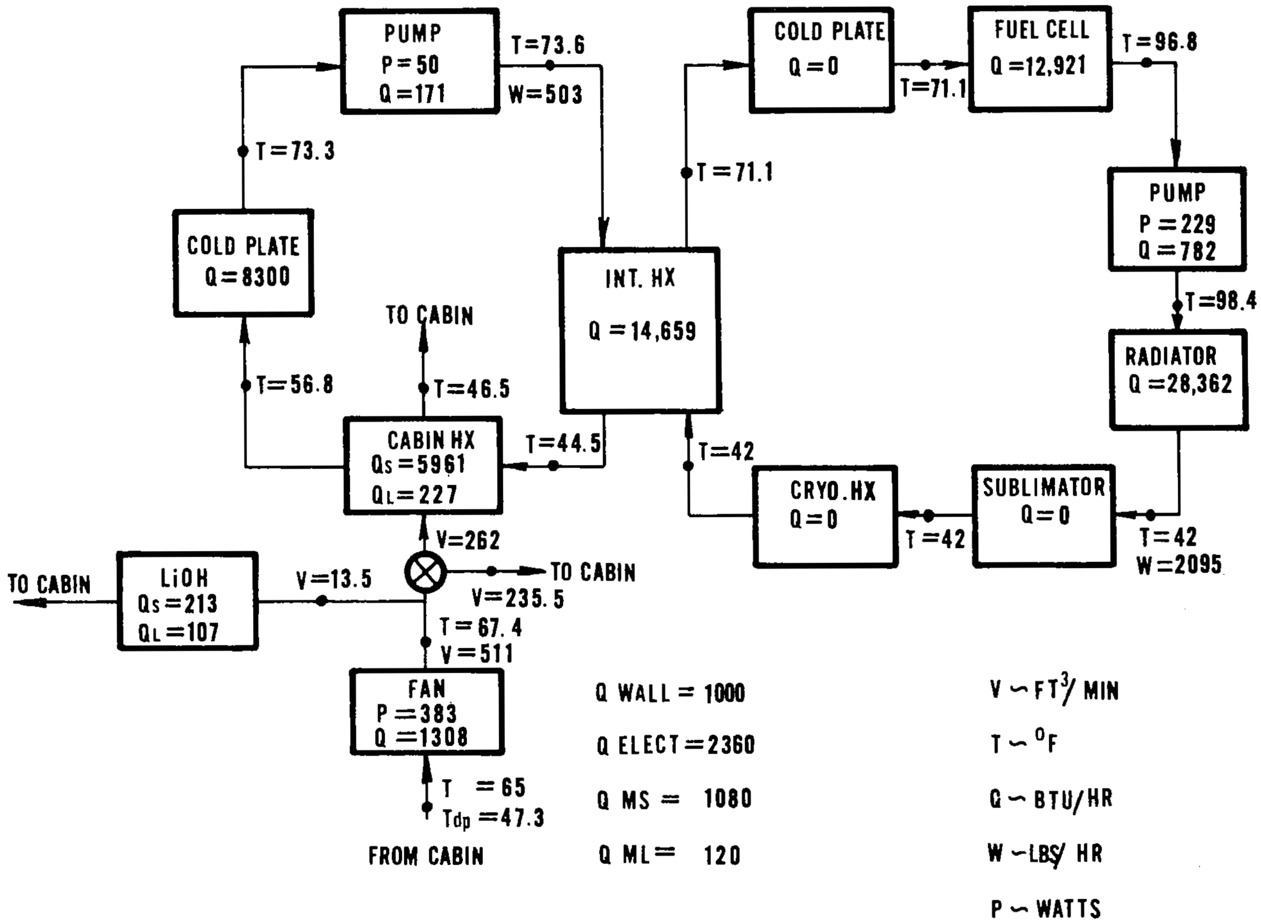

FIGURE 88. FLOW CHART, ON–ORBIT MINIMUM HEAT LOADS

increases. The performance of the EC/LSS designed to "maximum on-orbit loads" is shown in figure 89 for a reentry steady state condition. The result of this condition is that two parameters are out of specification, cabin temperature (76.6°F versus 75°F maximum) and outlet fuel cell temperature (151.9°F versus 150°F maximum). To successfully meet all the specifications during this phase would require a significant increase in the heat rejection loop flow rate, radiator size and heat exchangers size.

A system redesign for this condition is not justified because the transient time duration in which the out-of-specification conditions exist is only ten to twenty minutes and the anticipated steady-state condition is not, in fact, attained because it is unlikely that all of the peak loads would occur simultaneously

SUBSYSTEM DESCRIPTION

Atmospheric Storage and Pressure and Composition Control

Primary EC/LSS oxygen requirements are supplied from the main vehicle propulsion storage system. Nitrogen gas is supplied from a composite material high pressure storage tank. An emergency oxygen supply, also stored in a composite material high pressure tank, is normally isolated from the main oxygen supply line by a manual shut-off valve (item 301). The oxygen and the nitrogen gas are each routed through separate redundant pressure regulators (item 305 for oxygen, item 306 for nitrogen). The nitrogen is regulated to a slightly higher pressure than the oxygen, and turned on or off by high or low PO_2 signals which actuate solenoid valves (item 302) on both sides of the regulator (item 306). When the nitrogen solenoid valves are open, nitrogen enters the cabin pressure regulator supply manifold. It backpressures the item 303 oxygen check valves and assures "lock-up" of the 305 oxygen regulators. Thus, only nitrogen can enter the cabin under this condition. Conversely, when Oxygen Partial pressure is low, the nitrogen valves will close. Oxygen will then flow to the main cabin pressure regulators. The intermediate pressure level is used to pressurize the potable water tanks, and provided with redundant relief valves to protect against a failed-open (high pressure gas) valve failure. A felted-metal type silencer is used to reduce the noise level. The airlock is repressurized by remote actuation of the inflow valve, item 302. A regulator (item 304) allows the airlock to rapidly fill with pure oxygen to a 3.1 psia pressure level, after which the equalization valve, item 312, is manually opened to complete the repressurization.

CO_2, Humidity, and Temperature Control

The CO_2, humidity, and temperature control subsystem removes CO_2 from the cabin air, controls the humidity level and the cabin temperature to a preset level.

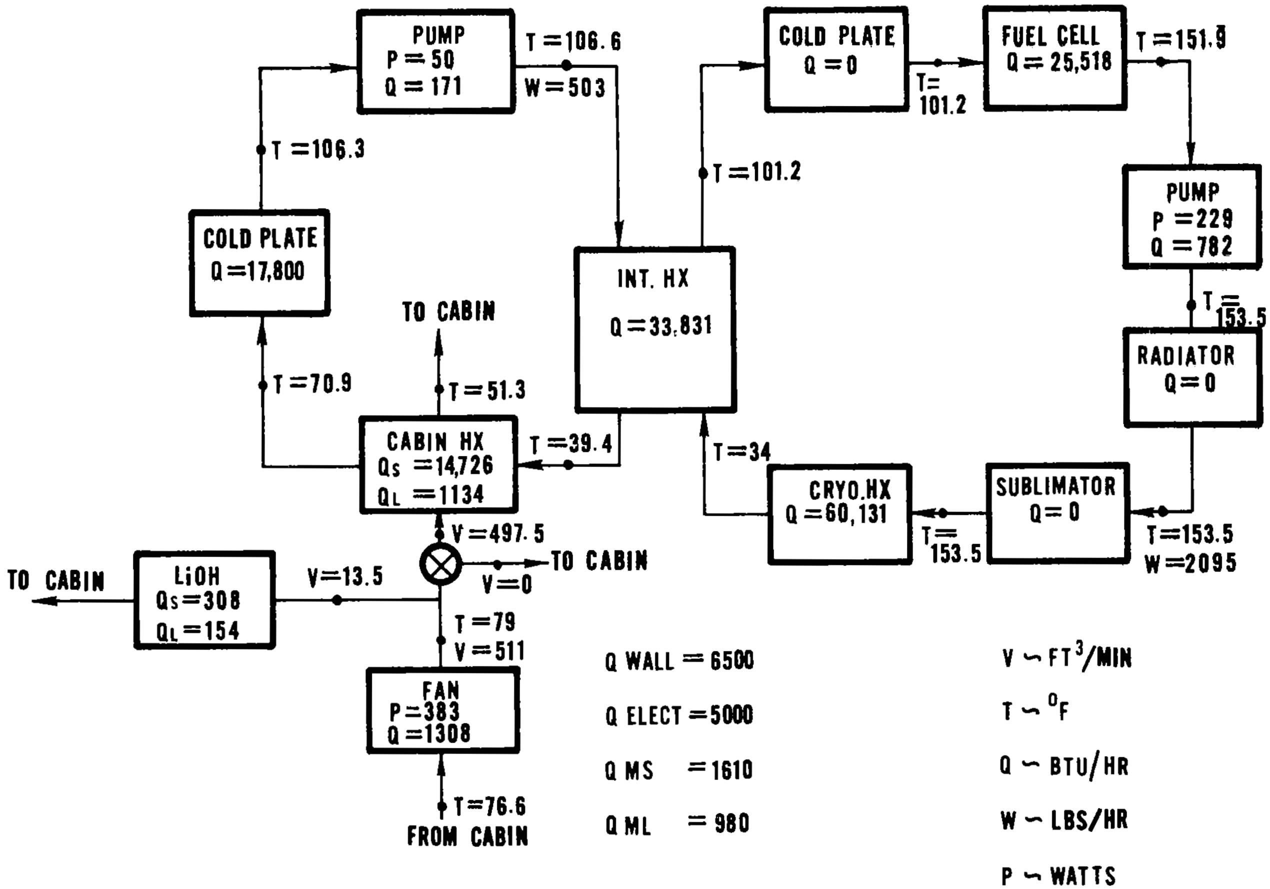

FIGURE 89. FLOW CHART, REENTRY AND ATMOSPHERIC FLIGHT PHASE

This subsystem interfaces with the cabin coolant loops and the water and waste management subsystem. Air enters the system through a combination inlet silencer and particulate filter (item 191). The inlet silencer reduces the fan noise to acceptable levels. The debris trap removes particles larger than 100 microns.

A process flow fan (item 151) supplies a pressure rise of 2.25 in H_2O at a flow of 511 cfm. Three parallel fans are required to meet the fail operational-fail safe requirement. A controller (item 181) senses marginal fan performance and automatically switches to a standby fan. Two check valves (item 101) are placed downstream of each fan to prevent backflow through the non-operating fans. Dual check valves are required to meet the failure criteria. The check valves have a small built-in leakage to permit the valves to be checked out on the ground to determine that both valves are in operational condition. During checkout, if both valves are "checking" properly the pressure drop across each valve will be approximately 1/2 the pressure rise of the fan. If one of the check valves has failed open, more of the pressure drop is taken across the operating check valve.

For CO_2 control approximately 13.5 cfm is drawn from the fan outlet plenum through a solenoid shutoff valve with a manual override (item 102), through a quick disconnect (item 103) into the LiOH canister (item 172). Each LiOH canister contains four man-days of LiOH. Seven cartridges, changed daily, are required for the nominal four man,seven day mission. The LiOH in the canister must be isolated from normal atmospheric water vapor and CO_2 prior to use or its capacity will be diminished. A built-in check valve and self-sealing disconnect are part of each canister. Dual LiOH canisters are installed in parallel. When the active canister is expended, the standby canister is activated by opening the solenoid shutoff valve. The spent canister is valved to the "off" position and can be replaced at the crew's convenience. Replacing LiOH canisters is the only normal in-flight maintenance required.

The temperature control valve (item 104) is a flapper type bypass valve driven by dual actuators and a manual override. To control cabin temperature the valve diverts flow from the condensing heat exchanger (item 161), through a bacteria filter (item 171). A temperature controller (item 182) senses cabin temperature and sends a signal to the actuator to position the bypass flapper. An internal stop is provided to insure that a minimum flow (200 cfm) through the heat exchanger will always be available.

The condensing heat exchanger (item 161) transfers the heat from the cabin air to the cabin coolant loop. This is a three circuit heat exchanger having an air circuit capable of transfering heat to either of two cabin coolant circuits. Water vapor condenses on the cold heat exchanger walls and is then blown off the walls into the discharge air duct. Momentum change causes the water droplets to collect along the duct wall. A gutter collects this water and transfers it with about 5 cfm of air to the liquid-air separator in the water and waste management subsystem.

As air is bypassed around the cabin condensing heat exchanger (due to low heat loads), the humidity level in the cabin decreases due to higher heat exchanger effectivness. The heat load range over which the relative humidity will not exceed the maximum specification level is from 1/4th to full load at 65°F and 1/8th to full load at 75°F cabin temperature.

Atmospheric Contaminant Control

The contaminant control function is provided by a minimum of equipment, located in different portions of the system, and all working in unison to complement each other in the removal of anticipated specific contaminants.

- The charcoal contaminant control canister (item 173) contains activated charcoal, and copper sulfate on sorbeads. It performs the lion's share of the contaminant control function, by controlling odors, both throughout the cabin as well as at the urine/water separator gas outlet, and by absorbing the major organic trace contaminants anticipated. The copper sulfate on sorbeads is included for ammonia control.

- The cabin condensing heat exchanger (item 161), besides controlling cabin humidity and temperature, serves a subtle tertiary function as a contaminant control device. The condensing cabin moisture will dissolve pyruvic acid, which is completely soluble in water, and this contaminant will then be disposed of with the waste water. Control of pyruvic acid (and other acid gases) is also accomplished by the LiOH included in the primary LiOH used for CO_2 removal.

- Bacteria filters (items 171 and 771) are included both in the water separator gas discharge flow path, and in the main cabin ventilating circuit, to maintain a low bacteria count in the cabin. The location of the main bacteria filter (item 171) in the temperature control bypass line results in no power penalty, since only "excess" flow is normally routed through the filter. During periods of maximum heat loads, virtually no flow passes through the filter. For the overall mission however, sufficient bypassing through the filter will occur (due to averaging of heat loads) to maintain an average flow consistent with average bacteria filtration requirements.

A particulate filter (item 191) is located upstream of the CO_2, humidity and temperature control package to prevent particulate contaminants from entering the package. It is replaced after each mission.

Heat Rejection

The heat rejection subsystem consists of two liquid cabin coolant circuits. Both circuits are completely contained within the cabin, and circulate water as the heat-transfer medium. Water is used because of its unmatched efficiency as a heat transport fluid, and its low toxicity. A leak into the cabin can be handled through the normal condenser/water separation equipment, with minimum system upset. The water coolant could even be replenished from the potable supply in an emergency, although no provisions have been made for this in the light of the installed redundancy. The primary loop contains redundant pumps (item 251), accumulators (item 271), and switchover controls to select the backup unit in the event of a failure. The accumulators are bladder-type tanks, with dead-ended gas pressurization, and are provided with pressure sensors and low-level indicators. External leaks are sensed by a drop in both pressure and liquid level while an internal leak (bladder failure) is sensed by a low level indication combined with a steady pressure. The bladder is driven to the low-level position by a light spring load or by a molded-in bias. It is important to sense a bladder failure (leak) before gas enters the coolant circuit, so the particular accumulator can be isolated before the pumps "vapor-lock". Otherwise, the redundant accumulator (and the redundant pump) cannot correct an air-bound loop, and the value of the redundancy is lost. A redundant circuit is provided with one pump and one accumulator. The redundant loop is considered a fail-safe backup; its use means an emergency abort. The circuit absorbs heat, primarily from the cabin condensing heat exchanger (item 161) and from equipment cold plates within the cabin, and rejects this heat to the interface heat exchangers, item 261.

The heat rejection loop transports the heat from the interface heat exchangers, fuel cells, and electronic cold plates to the radiator, porous plate sublimator (item 263), the Ground Support Equipment (GSE) heat exchanger (item 561) and the cryogenic heat exchanger (item 661). Refrigerant-21 ($CHCl_2F$) was selected as the heat rejection loop heat transport fluid. Selection was based on its good thermal heat transport properties, low freezing point, and low cost. This fluid is not used within the cabin due to its possible breakdown into toxic gases. Only water is used within the cabin area. Due to its high freezing temperature (32°F) and expansion on freezing, water cannot be used as the heat rejection loop fluid.

The radiator is the primary means of rejecting heat on orbit. The radiator and its controls are considered to be part of the vehicle. As the size of the radiator is influenced by the heat rejection loop flow rate and temperature requirements, a penalty for radiator weight was used when optimizing the EC/LSS. The radiator is considered to be a deployable panel radiating from both sides and was limited to 900 ft^2 (1800 ft^2 of radiating surface). For the nominal design condition (4 man-nominal heat loads) the radiator weight penalty is 996 lbs. The radiator is designed to reject 52,831 BTU's/hr with an inlet temperature of 147.1°F and an outlet temperature of 42° F. The heat rejection loop flow rate is 2095 lbs/hr.

A porous plate sublimator (item 263) is used to supplement the radiator during the orbit phase. It uses excess fuel cell water and can reduce the radiator outlet fluid temperature an additional 5°F and the EC/LSS total equivalent weight by 240 pounds. A temperature controller (item 283) senses the radiator fluid outlet temperature. When the temperature exceeds 37°F the controller opens dual solenoid valves (item 201) which allows flow to the sublimator. A pressure regulator (item 205) controls the water inlet pressure to 5 psia to prevent water "breakthrough" of the porous plate sublimator during startup. When the radiator fluid outlet temperature falls below 37°F, the solenoid valves are shut. In order to meet the fail operational requirement two solenoid valves in series are required. If a valve fails closed, the controller switches to a parallel circuit containing a pressure regulator and two solenoid valves. If the parallel circuit fails closed, the fail-safe provision is met by manual overrides of the solenoids valves. The sublimator is utilized only on the primary heat rejection loop. It can only be used above 120,000 ft. altitude as below this the ambient pressure is above the triple point, and too high for the water to freeze. A sublimator is not required for the secondary heat rejection loop since use of this loop is a fail-safe condition, and the mission will be aborted when this loop is activated.

The Ground Support Equipment (GSE) heat exchanger (item 561) is used to remove the heat generated during ground checkout, prelaunch, and post landing operations. To minimize the heat exchanger weight, very cold GSE fluid must be used. It has been assumed that the GSE can supply 0°F fluid. The weight advantage (30% lighter) of a three fluid heat exchanger resulted in its selection rather than two separate heat exchangers. Failure or leakage of the quick disconnects (item 504) is not a problem, as this does not affect the integrity of the heat rejection loops. Preflight checkout requires the GSE to transfer heat from both circuits.

Two cryogenic heat exchangers (item 661), one in each heat rejection loop, are used to reject heat during the reentry mission phase. They can also be used for ferry flight and all ground mission phases if cryogenics are available. The cryogenic heat exchanger is sized to handle the reentry heat load of 60,131 BTU's/hr with a heat transport fluid outlet temperature of 34°F. Liquid hydrogen enters the heat exchanger in the primary heat rejection loop through one of the two parallel solenoid shutoff valves (item 601). If the operating valve fails closed, the other valve can be opened. Heat transport fluid temperature is controlled by modulating the outlet cryogenic flow (item 602). A temperature controller (item 681) senses the heat transport fluid temperature and transmits a control signal to the cryogenic modulating valve (item 602). A solenoid shutoff valve (item 603) is placed upstream of the modulating valve to protect against a failed modulating valve. Parallel controllers, modulating valves, and shutoff valves are used to meet the fail-operational requirement. A single controller, modulating valve and two shutoff valves are required with the cryogenic heat exchanger in the secondary loop.

Two three fluid interface heat exchangers (item 261) are required to allow either cabin coolant loop to operate with either heat rejection loop. In this manner, a failure of one cooling circuit permits the remaining cooling circuit to operate with either of the loops.

The interface heat exchanger is designed to be 92% effective with a "mass flow ratio" of one. The water, being less dense than the Refrigerant-21, requires dual passages and a single passage is used for the R-21.

The heat rejection circuit has two redundant paths, or loops, using the same design concepts as the cabin coolant circuit. Again, redundant pumps and accumulators are provided in the primary circuit, while a single pump and accumulator are provided in the secondary circuit. Switchover operation is similar to the operation previously described for the cabin coolant circuit.

Water Management

Potable water from the fuel cells is fed to the water management subsystem. Manual shutoff valves (item 401) are used to isolate the water management subsystem from the fuel cells for ground sterilization.

The potable water storage tanks (item 471) hold the potable water in an uncontaminated state until use. Two bladderless tanks are used, one on line and the other for standby use. Dual electrical heaters (item 492) and heater controllers (item 481) maintain the water temperature at 160°F in the on-line tank for bacteria control. Manual shutoff valves (item 401) are used to isolate each tank from the loop. The standby tank is filled on the ground with potable water and iodine (for bacteria control) and would be required if contamination or leakage of the operational tank occurs. The tanks are pressurized with oxygen and nitrogen from the pressure control subsystem. Manual shutoff valves (item 301) are used to isolate the tanks from the pressurization system in case of failure. Although the tank shells and capacities are identical, the primary on-line tank is fitted with electric heaters, insulation, and separate inlet and outlet ports. In this way, the inflowing fuel cell water must circulate through the tank prior to use, minimizing the possibility of local stagnation of the potable water, thus insuring good thermal mixing and simplifying ground flushing of the tank. GSE quick disconnects (item 202) are used to fill and sterilize the tanks while on the ground. In the event the on-line tank becomes full, a water dump controller (item 483) senses the condition and allows a fixed amount of water to flow into the urinals where it is then transferred to the waste storage tanks. In this way, direct plumbing between potable and waste water circuits is avoided.

Hot (160°F) water, directly from the potable water tank, is used in food preparation. A manual shutoff valve (item 401) is used to control hot water flow to the sink. A heat exchanger (item 262) is used to reduce the hot water temperature to 60° to 100°F. This intermediate temperature water is required for urinal flushing and as evaporator feed water. The heat exchanger rejects the heat to the primary cabin coolant loop downstream of the cabin condensing heat exchanger, item 161. A water chiller (item 461) reduces the intermediate water temperature to 50°F or below. This chiller is only in the primary cabin coolant loop as once the secondary loop is actuated, the mission is aborted. The cold water is used for drinking and food preparation. Sink water temperatures (45 to 160°F) can be obtained by modulating the hot and cold manual shutoff valves (item 401) at the sink. It is also possible to run full hot water (160°F) through the sink "faucet" to control bacteria buildup in the water dispenser nozzle. Water flow is cycled through the water chiller (item 461) first in one direction, and then in the reverse direction, such that the cold water and hot water lines are interchanged. This is accomplished by a timer (item 484) operating latching solenoid valves (item 201) in unison. Thus the cold potable water circuit, a potential breeding ground for bacteria, becomes the hot (160°F) water circuit the next day, and vice-versa. This cyclic pasteruization process eliminates the bacteria growth potential in the cold water lines.

Waste Management

The Waste Management Subsystem collects and stores solid wastes and collects, transfers, stores and dumps liquid wastes overboard. Waste water from the sink. urine and urinal flush, and condensate are collected, separated from air, stored, and expelled. Solid wastes are stored and vacuum dried.

The waste collector (item 772) collects both urine and feces. The urinal and solid waste collector require approximately 20 cfm of air each to direct the urine and feces into the collectors. When the waste collector is used, the sink and standup urinal are shut off automatically as not enough air is provided by the fan/water separator (item 751) to operate all of the waste water collectors at the same time. To dry the fecal wastes, a gate valve under the seat is manually closed. The waste system control (item 781) simultaneously closes the dual solenoid valves (item 102) which isolate the collector from the urine/gas separators and opens the dual solenoid valves (item 102) to vacuum. Manual overrides are provided to the solenoid shutoff valves (item 102) to allow operation if they both fail closed. To use the commode, the vacuum valves are closed and the repressurization valve (item 712) opened to allow the pressure in the commode to equalize with the cabin. The manual gate valve and solenoid shutoff valves (item 102) are opened to allow air flow through the unit. A backup mode of operation allows for the injection of bactericide with a manual dispenser (item 791) into the commode. A manual shutoff valve (item 715) prevents loss of bactericide during vacuum drying operations. This valve normally remains closed since bactericide injection at this point is a backup system, and only occurs after a gross failure of the vacuum system, preventing normal drying of the wastes.

Operation of both the standup urinal (item 792) and the urinal in the waste collector is identical. The solenoid shutoff valve (item 202) is opened allowing approximately 20 cfm of air flow through the unit. The air directs the urine and flush water in the collector. The air entrains the liquid droplets down the duct to the liquid-air separator. Subsequent to micturation, the bactericide is injected into the urinal from the manual dispenser (item 791), signaling the waste system controller (item 781) to open the water solenoid shutoff valve (item 402) for a predetermined length of time. The urinal is then flushed with 0.33 lbs of 60° to 100°F clean water.

The bactericide is stored in a bladder tank (item 773). Tank pressure is kept slightly below cabin pressure by a relief valve to prevent the bactericide from leaking into the cabin air. Self-sealing quick disconnects are used to assure that no spillage of bactericide will occur when the tank is replaced during ground refurbishment.

A combined fan/centrifugal water separator (item 751) is utilized to separate the liquid and gas, pump the liquid into the waste storage tank, and pump the air from the collectors through the required filters. A concept of this unit is shown in figure 70. The fan is designed to flow 45 cfm of air at a pressure rise of 4.0 inches of water. Dual check/relief valves (item 403) are used at the liquid outlet to slightly pressurize the pitot pump. prevent air inclusion and to prevent liquid backflow when the unit is not operating. Two valves are used to meet the fail-operational - fail-safe requirement. Air check valves (item 714) are located at the fan inlet and outlet to prevent backflow when non-operating. Three separators are placed in parallel to meet the fail operational - fail safe requirement.

All of the air flow leaving the separator passes through a bacteria filter (item 771) and a charcoal canister (item 173) before reentering the cabin. The air flow rate is sufficient to provide for odor control for the entire vehicle. A fan/water separator controller (item 782) automatically switches to a backup unit should the performance of on-line separator/fan be marginal.

The same fan/centrifugal water separator also serves as the second stage of the main cabin humidity control water separator, and so must operate continuously.

Two waste water storage tanks (item 472) serve to collect waste water and store it prior to venting to space. A bladder tank is used because of the variable nature of the stored liquid (varying mixtures of water, urine, bactericide, and condensate) which would make a zero gravity capillary tank unpredictable. Each tank is sized to hold all of the waste water generated during a 24-hour period, 100 pounds of liquid. Only one tank is on line at a time. The other tank is redundant in case of tank failure. The liquid in the tanks is stored at cabin pressure and vented downstream of the fan/centrifugal water separator to prevent liquid leaks to cabin and to obviate the need for a separate pressurization scheme. A manual water shutoff valve (item 401) is used to isolate the waste water tanks from the waste system. Manual gas shutoff valves (item 301) are used to isolate the tanks from the cabin atmosphere in case of bladder failure.

A liquid GSE quick disconnect (item 202) is used for flushing the tanks and the dump system during ground refurbishment. When the water in the waste tank reaches a predetermined level, the dump control (item 483) actuates the system to initiate the dump procedure. The fan/water separators are simultaneously isolated from the storage tanks by a solenoid shutoff valve with a manual override (item 201). In order to meet the fail operational - fail safe requirement, four valves in a series parallel arrangement are used. The dump nozzle (item 491) is heated to ensure that it is not blocked by ice. The nozzle temperature controller (482) sends an inhibit signal to the dump control (item 483) until the nozzle temperature reaches 60°F. To dump, dual solenoid valves (item 402) are opened allowing the waste water to flow to space. Dual nozzles and shutoff valves are used to enable the system to fail operational. If both solenoid valves fail open, a manual shutoff valve (item 401) is used to isolate the dump system and the mission is aborted. Manual dumping is still possible, but is not recommended because it requires similtaneous manipulation of two or more valves in response to waste tank level and/or water line pressure. The solenoid shutoff valves (item402) are located close to the nozzle to limit the amount of water trapped in the nozzle and lines, thereby minimizing heater power. The timed dump signal can be inhibited by either flushing a urinal or by an excess potable water dump (into a urinal). In this case, the waste tank returns to its filling mode until the next timed cycle.

INSTRUMENTATION

One of the major integrators between the EC/LSS and the crew is the instrumentation. The instrumentation must provide for monitoring fault isolation and controlling of the EC/LSS by both crew and the Onboard Checkout System (OCS). The two types of instrumentation, which are identified in the system schematic (figure 82), are as follows:

Type A - Control or Operational Instrumentation

Type B - Warning/Fault Isolation/Monitoring or Maintenance Instrumentation

Control

Type A instrumentation provides the OCS and crew with the feedback necessary to control the EC/LSS both automatically and/or manually. For shuttle application, it is assumed that the computer will be self-analyzing.

Monitoring/Fault Isolation

Type B instrumentation provides the OCS and crew with the information necessary to accomplish fault isolation down to the hardware level and must be capable of verifying a fix has been properly accomplished. It must also provide an early warning so that adequate maintenance time exists before real crew or system danger results. Each "black box" control shown on figure 82 has inputs and outputs monitored by the OCS such that a malfunction of the controller is detectable, and overrideable at the control panel by the crew.

The instrumentation required for control, fault detection and isolation was determined employing the following criteria:

- Wherever possible utilize the instrumentation for both prelaunch checkout and during the various mission phases.

- The Onboard Checkout System will provide, in conjunction with the EC/LSS control scheme, the capability of automatically transferring functions to redundant hardware, if required, and analyze, with the proper input, the equipment status on a display panel.

- Recalibration of the instrumentation will not be required after every mission unless a malfunction was identified during the mission or the performance of the instrument is considered to be critical to crew safety.

- Additional instrumentation required for subsystem/component checkout will be provided but will not function during the various mission phases.

Table 36 specifies the type of instrumentation required for each subsystem in the EC/LSS. The table contains a brief description of the possible component failure(s) that could have produced the failure indication. In many instances, one instrument is capable of isolating a failure within a loop without specifying which component has failed to operate properly. For this circumstance, the incorporated prelaunch checkout instrumentation provides the necessary information to assure that the malfunctioned component can be identified and replaced quickly with a minimum of difficulty during ground refurbishment.

The type of presentation (display) that the instrumentation yields along with the procedure for prelaunch checkout are also identified in the table.

Controllers shown as "black boxes" in figure 82 all have redundant internal circuitry, and provide input and output signals to the OCS so that controller faults may be isolated. In this way, equipment may be kept operating after a controller failure by manual panel control switches. In point of fact, all the "black boxes" could eventually very well be integrated into a single master controller, with a substantial weight savings and only minor degradation of control flexibility.

Valve position indicators on all electrically powered valves, also transmit a signal to the OCS, to allow correlation between valve input signal and valve position.

TABLE 36

SHUTTLE INSTRUMENTATION

Category/Subsystem	Function					Prelaunch Checkout		
	Instrument	Req'd Amount	Control	Fault Isolation	Presentation (Display)	Function	Calib.	Verif. Not Req'd
Cabin Input	P_{Total} Sensor	3		Total Cabin Press. Press Reg (1st Stage) Leakage, Cabin Press Regulator Failure	Gages - Normal warning and emergency levels Visual - Warning and emergency Audio - Emergency			X
	P_{O_2} Sensor	1		O_2 Partial Press. Controller Backup Cabin Press Reg Failure, check valves failed closed	Same as Above		X	
	CO_2 Sensor	3		CO_2 Partial Press. LiOH cartridge failure or life cycle completed	Same As Above		X	
	Dew Point Sensor	3		Cabin Dewpoint Condenser, Hx Failure, Water Separator fail., Coolant Loop failure, temp. Control Valve failure.	Same As Above			X
	Temperature Sensor	1		Cabin Temperature Temp Control Valve Controller, Coolant Loop, Cond. Hx Failures.	Same As Above			X
	Gas Chrom/ Mass Spect.	1		Contaminant Control - Degradation of charcoal, depletion of Bactericide, Hx or Coolant Loop failure	Same As Above			X
Atmospheric Storage, Pressure and Comp. Control	Pressure Sensor			N_2 Primary and Em. O_2 Lines Pressure - Leakage	Gage - Warning Light		X (dur. fill)	
				N_2 - Downstream First Stage Regulator Reg. Failure, failed closed upstream solenoid, controller failure etc.	Gage - Warning Light	X	X	
				O_2 - Downstream First Stage Regulator - (both Circuits) Failed Open check valve, failed open regulator, failed closed solenoid	Gage - Warning Light	X	X	
				Checkout only O_2 Circuit - Between solenoid and regulator (both circuits)			X	
				N_2 Loop (both circuits) between each side of regulator			X	
				Airlock Total Press.	Gage		X	
	PO_2 Sensor and Control	3	O_2 Sensor	Integrated into controller is voltage sensor.	Warning light visual indication - secondary controller operational	X		

TABLE 36 (Continued)

SHUTTLE INSTRUMENTATION

Category/Subsystem	Instrument	Req'd Amount	Control	Fault Isolation	Presentation (Display)	Prelaunch Checkout Function	Calib.	Verif. Not Req'd
Water and Waste Management								
Potable Water Supply	Quantity Sensor	1 per tank	Signal to dump control	Failed controller, urinal solenoid failed closed	Gage, Visual Indication			X
	Temp. Sensor	1 per con- troller circuitry	Heater Control	Failed heater or controller	Gage, WarningLight - Visual Indication that redundant control circuitry is functioning	X (Conti- nuity)		
	Pressure Sensor	1		Pressure Relief Valve (308) Failure	Same as above			X
	Temp. Sensor	1		Water/Tank Temp.	Gage			X
	pH Sensor	1		Water Quality	Gage			X
	Conduct. Meter	1		Water Quality	Gage			X
Collection Loop	Quantity Sensor	1		Bactericide Quant. - Dispenser flowing excessive amounts per cycle, leakage	Gage		X (Dur- ing fill)	
	Valve Position Indicator	9		Urinal - Inlet/Outlet solenoid failed closed	Warning Light Inlet - Open Outlet - Closed	X		
				Commode - Failed Open/Closed Overboard Dump Valves or Repress. Solenoid	Series Solenoid and Repress. Solenoid- Open Dump Valves - Closed	X		
	Pressure Sensor	1	Signal to Controller	Pressure Upstream of Dump Valve - Waste collector seal failure, solenoid failure (leakage) over- board valve failed open/closed	Gage - Warning Light			X
		1		Pressure between series solenoid valves	Gage			X
	Speed Sensor	1		Slinger Failure	Gage	X		
Urine Separator Loop	ΔP Transducer	1 per separator		Fan - Water side	Gage, Warning Lights that redund. fans are functioning	X		
		1		Bacteria, Charcoal Cartridge - Check valve failure (leakage) or failed bacteria filter clogged	Gage - Warning Light	X		
	Speed Sensor	1 per separator		Failed closed check or back filter.	See ΔP Fan	X		
Waste Storage	Pressure Sensor	1		Line Pressure - (between 201 solenoid and waste water tanks) failed open dump solenoids		X		
	Quantity Sensor	1 per tank	Signal to dump Control	Initiates Dump Sequence - failed controller, failed solenoids (two loop) open/closed	Gage		X (Dur- ing fill)	

TABLE 36 (Continued)

SHUTTLE INSTRUMENTATION

Category/Subsystem	Function					Prelaunch Checkout		
	Instrument	Req'd Amount	Control	Fault Isolation	Presentation (Display)	Function	Calib.	Verif. Not Req d.
	Valve Position Indicators	8		Failed Open Dump and (201) Solenoid Failed Closed Dump and (201) Solenoid	Warning Light (2) - Open Warning Light (2) that redundant loop is functioning	X		
	Temp. Sensor	1	Dual Nozzle Control	Nozzle Temp. (in conjunction with Temp. sensing control) - heater failure	Gage - Visual indicator that redundant heater is functioning and if secondary loop has actuated	X Cont.		
CO_2 Humidity and Temper. Control	ΔP Transducer	3		Fan failure, LiOH plugging, solenoid valve failed closed, check valve leak	Gage, warning light that redundant fan(s) is functioning	X Fan		
	Valve Position Indicators	2		LiOH solenoid failed closed, redundant loop solenoid failed open	Warning Lights - Visual Indication that redundant loop is on line.	X Without LiOH Cart. On Line		
	Temp. Sensor	1 per controller circuitry	Temp. Control	Failure of Controller or Temp. Cont. Valve	Gage - Warning Light that Redundant Cont. is operating	X Cont.		
	Pressure Sensor	3		Checkout Only - One per fan between series check valves.				X
Coolant Loop	Temp. Sensor	2		Coolant Loop(s) Downstream Interface Hx - Hx failure, heat rejection loop failure	Gage			X
		1		Cold Plate Outlet	Gage			X
	Quantity Sensor	1 per accum.		Bladder Failure, immediately verify operational status of secondary loop	Warning Light			X
	Valve Position	1 per loop accum. line		Failed Closed Solenoid	Warning Light - Visual Indication when redundant accumulator is on line. Light if redundant valve failed closed.	X		
	ΔP Transducer	3		Pump Performance - failed pump failed controller, failed closed check valve subsequent to visual indication, check secondary loop pump.	Gages, Warning Light - Visual Indication that redundant pump has actuated, light when secondary loop has actuated.	X		
	Pressure Sensor	1 per accum.		Gas Side of Bladder - Loop leakage, failed closed solenoid	Gage		X (During fill)	

TABLE 36 (Concluded)

SHUTTLE INSTRUMENTATION

Category/Subsystem	Function					Prelaunch Checkout		
	Instrument	Req'd Amount	Control	Fault Isolation	Presentation (Display)	Function	Calib.	Verif. Not Req'd
Heat Rejection Loop	Temp Sensors	1 and 1 per cont. circuitry	Temp. Cryog. Hx outlet	Controller Failure, Regulating Valve or Solenoid Valve Failure (Closed)	Gage, Visual Indication that redundant controller is operational	X Cont.		
		1 per circuit		Temp. cryog. Hx Inlet radiator performance cryog. Hx perform. Primary Loop - Sublim. performance	Gage			X
	Temp Sensor	1	Temp. Second Loop Cryog. Hx outlet		Gage, Warning Light that secondary controller is operating	X Cont.		
		1 each (2)		Elec. Cold Plate and Fuel Cell Outlet Failed	Gage Warning Light			X
	Valve Position Indicators			Failed closed solenoid (H_2 Cryogenic Outlet)	Warning Light that redundant loop is operational and sep. light that redundant solenoid failed	X		
		1 per accum. line	Accum. Solenoid Valve	Failed Closed Solenoids or failed controller	Warning Light that redundant loop has actuated and separate light if failed closed	X		
	Quantity	4		Failed Closed/Open sublimator inlet valves	Warning Light	X		
	Sensor	1 per accum.		Bladder Failure subsequent to signal, verify operational status of secondary loop	Warning Light			X
	Pressure Sensor	1 per accum.		Gas Side of Bladder - Tank leakage failed open solenoid, failed controller, solenoid failed closed.	Gage		X (During fill)	
		2		Pressures Between Solenoids and Sublimator - Sublimator failure failed closed solenoids, failed controller	Gage			X
	ΔP Transducer	3		Failed Pump, failed controller, failed closed check valve. Check secondary loop status	Gages, Visual Indication that redundant pump is operational, light if second loop pump has actuated	X		

GROUND SUPPORT EQUIPMENT

An integral part of any successful space activity is the Ground Support Equipment (GSE). The following section identifies the GSE required to accommodate and support prelaunch checkout and monitoring for flight assemblies of the space shuttle vehicle.

The Ground Support Equipment identified for the various subsystems which constitute the shuttle EC/LSS is summarized as follows:

- Multipurpose Test Rig for post installation, refurbishment and prelaunch checkout.
- Water and Waste Management Supply Rig for charging water storage tanks (including coolant loop accumulators).
- Trace Contaminant Monitoring Rig for calibration of the gas chromatograph and mass spectrometer.
- Heat Rejection Loop Supply Rig for charging the heat rejection loop and accumulators with Freon 21 and to provide coolant fluid for the GSE heat exchanger.

Additional test rigs used internally for component assembly, development, qualification and performance testing will also be required but are not identified at this time.

The GSE would be capable of monitoring system/subsystem status and provide a backup to the onboard checkout systems during all checkout, functional and flight readiness testing and launch operations.

Multipurpose Test Rig

Requirements. - Pre-installation and prelaunch checkout of the space shuttle EC/LS system components and subsystems, requires that identical test rigs be provided at the facilities of the EC/LSS subcontractor, the prime vehicle contractor and at the launch site. The tests which will be conducted prior to installation in the vehicle, constitute a functional and continuity evaluation and will not necessarily require actual simulation (i.e., dry). In addition, the rigs will be capable of functioning as a monitoring device, during vehicle checkout, for onboard instrumentation and performing a continuity check of all power consuming components.

Functional description. - It is proposed that a single test rig be provided to satisfy the requirements for pre-installation checkout and prelaunch monitoring. The rig will be capable of performing the following tests for pre-installation checkout:

- Leakage - subsystems and components
- Functional ΔP - components (fans, pumps, filters, valves etc.) subsequent to assembly installation; expendable cartridges will not be subjected to this test
- Proof Pressure - components (Freon 21 accumulators, relief valves etc.)
- Electrical Continuity - subsystem and components (fans, pumps, controllers, solenoid valves, sensors etc.)

After vehicle installation the system will be functionally checked utilizing the vehicle onboard checkout system, system instrumentation and the GSE test rig. The multi-purpose test rig functions as a monitoring device for fault isolating onboard instrumentation. The test rig will have facility interfaces for power and it will be capable of performing independent continuity checks on all power consuming components prior to vehicle installation.

Water and Waste Management Supply Rig

Requirements. - A rig capable of charging the subsystem's tanks (4 tanks including the coolant loop accumulators) with sterile water, which meets the requirements of the Requirements/Guidelines (appendix A), is required. In addition, the rig will be capable of draining and sterilizing the waste water tanks subsequent to each mission. The rig will incorporate the necessary instrumentation and hardware to assure that the tanks are fully charged and that the flight quantity sensors, spring loaded bladders and valving are functioning properly.

Functional description. - It is proposed that the subject rig be provided to satisfy the charging requirements for the space shuttle. The portable rig will require a pressurant source, the water supply and a vacuum pump for the initial charging of bladder tanks. Subsequent to the initial charging procedure, the water quantity will be verified after each mission with the necessary steps taken to assure the tanks are full. To assure that the charging water meets the rigid potability standards, the rig should be capable of being sterilized and provide for testing for pH, conductivity and bacterial level.

Atmospheric Contaminant Monitoring Rig

Requirement. - A rig capable of calibrating and monitoring the onboard atmospheric contaminant monitoring assembly during prelaunch checkout is required.

Functional description. - It is proposed that a rig be provided to verify during pre and post installation, and prelaunch checkout the accuracy of the flight contaminant monitoring assembly. A commercial mass spectrometer and gas chromatograph will provide contaminant measurement and the control required. Furthermore, the rig is required to perform electrical continuity test.

Heat Rejection Loop Supply Rig

Requirements. - A rig capable of charging the heat rejection loop and accumulators with Freon 21 and supplying the coolant fluid to the vehicle installed GSE heat exchanger is required. The rig will incorporate the necessary instrumentation and hardware to assure that the accumulators are fully charged and that the flight quantity sensors, spring loaded bladders and valving are functioning properly.

Functional description. - It is proposed that a rig be provided to satisfy the charging requirements of the space shuttle heat rejection loop and to provide the required coolant for heat rejection during prelaunch and pre-installation. The rig will also be capable of draining the loop of all coolant and any gas that may have entered the loop via leakage. In addition to the pressurant source and coolant supply, the rig will require a vacuum pump to evacuate the loop prior to initiating the charging procedure. With the capability of performing the draining operation, the rig will also provide a means of detecting leakage paths within the loop.

GSE fluid connectors are configured differently to minimize the possibility of wrong connections during the ground refurbishment checkout operations. An itemized list of these different connectors and their respective functions is shown in table 37. In general, these GSE connectors are located near the outer skin of the vehicle, in a common area, for ease of access during ground maintanance. Two exceptions, as shown on table 37, are the LiOH canister connectors, and the bactericide tank connector, which are located within the cabin.

The general philosophy used in the design of the connector-related circuits is that the ground support equipment is provided with sufficient control and safety devices (i.e., flow regulators, temperature controllers, pressure relief valves) to obviate the need for corresponding controls and safety devices on the flight vehicle itself. Thus, there are no pressure relief valves on the atmospheric storage tanks, for instance, since they are protected during fill by the GSE itself.

TABLE 37

GROUND SUPPORT EQUIPMENT CONNECTORS

ITEM NO.	FLUID	FUNCTION
202	Water	Coolant and Potable Water drain, flush and fill
203	Inert Gas	Accumulator Pressurization
310	Oxygen	3000 Psi Gaseous O_2 Fill
311	Nitrogen	3000 Psi Gaseous N_2 Fill
502	Refrigerant-21	Coolant Drain, Flush and Fill
504	GSE Coolant	Primary Ground Cooling
*103	Air	Quick Change Connector for Lithium Hydroxide Canisters
*716	Silver Nitrate Solution	Bactericide Tank Connector

*Internal to Cabin

QUIESCENT PERIOD

Introduction

During the operation of future spacecraft, it may become desirable or necessary for the crew to leave the spacecraft. These periods of non-occupancy might last from several hours to several days. During these periods, the question of how or if the EC/LSS equipment should be operated becomes of paramount importance.

This study section was undertaken to investigate the possible environmental conditions that effect the selected EC/LSS equipment, to consider the resultant equipment problem areas, to determine ways of surmounting the problems, and to recommend procedures that will eliminate or minimize these potential difficulties.

Summary

The selected EC/LSS equipment was examined to determine the impact of extended periods of unoccupied, dormant operation. Of the many environmental conditions possible, only two significantly affect the EC/LSS equipment; low temperature (less than 32°F) and space vacuum.

The results of this study show that the nature of the problems likely to be encountered by an advanced type space vehicle, during a quiescent period, are not as severe as might at first be expected. Indeed, they reduce to the problems of microbiological contamination and water freezing. These problems, in the selected shuttle EC/LS subsystems are readily amenable to solutions by simple and straightforward procedures that include the overboard dump of fuel cell water and line water throughout the water management subsystem.

Environmental Conditions

In space the environmental factors affecting spacecraft equipment are: pressure, temperature, humidity, atmospheric content, vibration and radiation. During normal operation in a manned craft, most of these (temperature, pressure, humidity, and atmospheric content) are actively controlled although vibration and radiation are not. This does not imply that these last two factors are ignored, rather, they are passively controlled; i.e., their potential effect is diminished to satisfactory levels by proper design or operation. During unmanned operation, passive control of vibration and radiation remains unchanged but passive control of the other environmental factors may or may not be satisfactory. In fact, to assess this point and its effect on the EC/LSS equipment requires consideration of the environments that would exist in what may be termed a passively controlled mode of operation. Thus, each environmental factor must first be examined to determine its range of values under this passive operating mode.

Pressure. - The nominal actively controlled cabin pressure for the shuttle vehicle is 14.7 psia. In a quiescent or uncontrolled mode of operation, the pressure will decay with time from the nominal pressure level, as determined by the prevailing leakage rate. Figure 90 shows the pressure decay for the cabin as a function of temperature and leakage rate (3.5 lbs/day and 10.0 lbs/day). At 3.5 lbs/day, the cabin pressure level is above 10 psia during a week of uncontrolled operation. Even at 10 lbs/day leakage, the pressure is significant (>5 psia) after one week. Thus, with the pressure uncontrolled, significant pressure levels can be maintained for extended periods even with leakage rates greatly in excess of the nominal.

Of course, there are situations under which hard vacuum conditions cannot be avoided, and indeed, there may be conditions under which a hard vacuum may prove desirable. The latter may occur if the unmanned cabin is purposely exposed to vacuum for microbiological control.

Temperature. - In view of the previous discussion, it is plain that temperature must refer to equipment temperature rather than cabin temperature because the latter infers an atmosphere and there may not be one. The normal actively controlled cabin temperature range is 65°-75°F ± 2°F.

If there is no temperature control, equipment temperatures become a function of the cabin wall temperature which, in turn, is a function of the exterior coatings, spacecraft orbit and orientation. When these factors are properly controlled, the wall heat leak can be brought to nearly zero. Because of this, and the fact of a large mass-to-surface area ratio of the vehicle, it is anticipated that the interior wall temperatures could vary between 30° and 120°F. It is thus possible for some of the equipment to achieve below freezing temperatures, either as a steady-state condition or as a result of some particular vehicle orientation.

Humidity. - Humidity is dependent on having a cabin atmosphere, so the following discussion does not apply to the possible vacuum condition. The normal actively controlled relative humidity in the pressurized cabin is held to between 50% and 65%. In the uncontrolled mode of operation, the amount of water vapor in the air will vary with cabin temperature and the amount of water available for evaporation.

With the selected carbon dioxide control configuration, a condenser/separator is required. The water that remains in the heat exchanger and the elbow separator will be available for evaporation into the cabin, having a direct effect on the relative humidity. The lowest relative humidity would occur at the highest temperature (120°F) after all the free water in the equipment has evaporated. This relative humidity has been roughly estimated to be 16%.

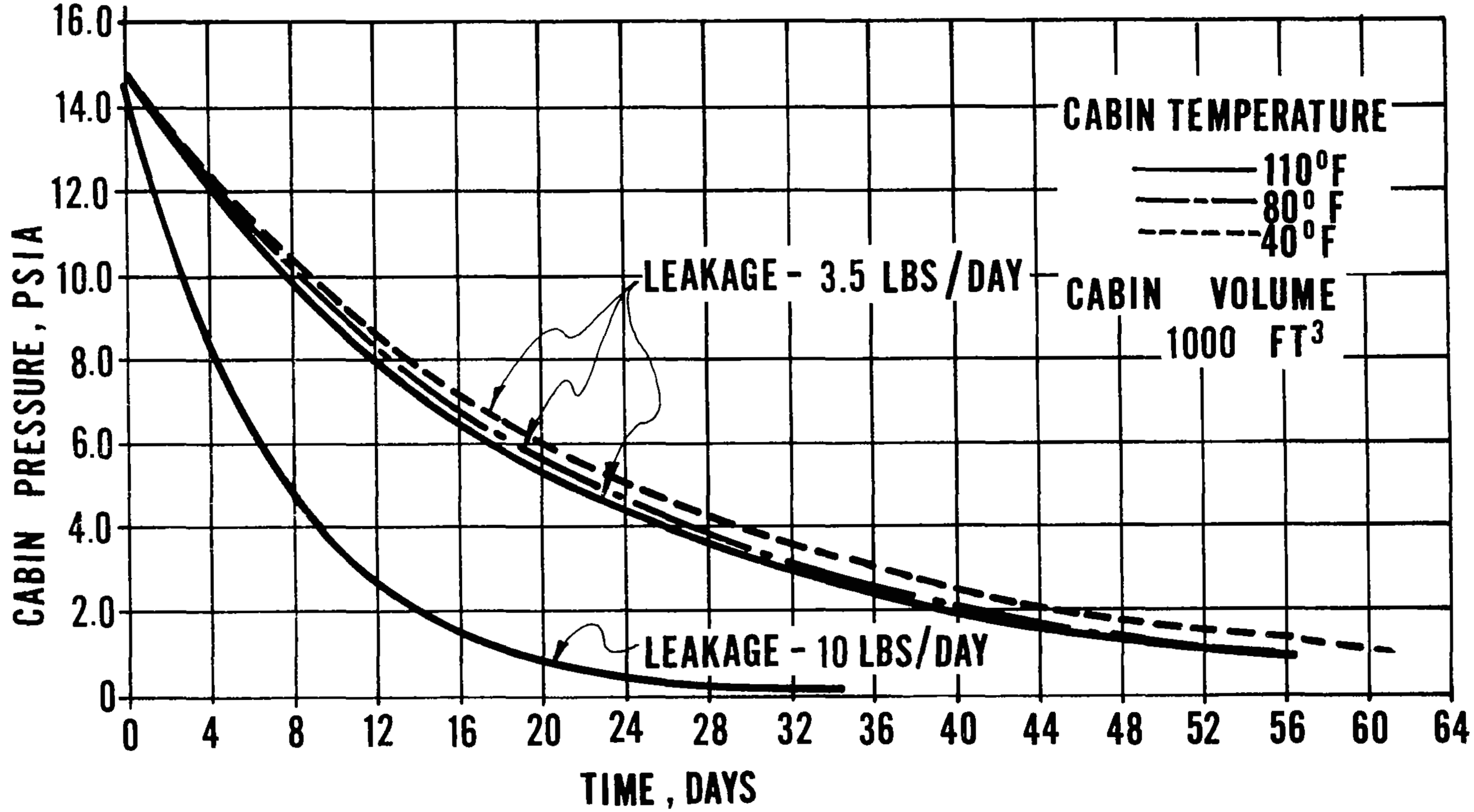

FIGURE 90. CABIN PRESSURE VERSUS TIME

Therefore, at any temperature between 30°-59°F water vapor will condense on any surface, such as the cabin walls or equipment in good thermal contact with the wall that might be below this temperature.

If the temperature of the equipment surfaces fall below 32°F, a film of ice would form on them, and if the cabin temperature fell below 32°F, ice crystals would form in the atmosphere. Interestingly enough, this phase change would greatly increase the thermal capacity of the spacecraft possibly preventing the freezing of bulk water within the coolant loops and water management subsystem.

Atmospheric composition. - The normal shuttle atmosphere is a mixture of roughly 20% O_2 and 80% N2 at 14.7 psia. As has been pointed out, the pressure, if uncontrolled, will decay with time depending on the cabin leakage rate. Within the range of significant pressures (14.7 to 0.1 psia), the atmospheric composition is a function of the type of flow associated with the leak. For large leakage rates, bulk flow will occur and the composition of the cabin atmosphere will remain unchanged as the pressure drops. For small elastomer seal type leaks, the flow will approach capillary-free molecular flow. In this case, the loss of oxygen will be about 2.6% greater than with bulk flow. Only at very small cabin pressures will the cabin air composition depart significantly from a 20-80 mixture of O_2 and N2. Thus, changes in atmospheric composition from an actively controlled to uncontrolled environment should have no effect on the shuttle equipment.

Impact on Subsystems

For this investigation it was assumed that the fuel cells are operated powered down (2.7 kW) and the electrical equipment associated with the fuel cell is a part of the electrical cold plate package.

In view of the above discussion, there are four uncontrolled cabin environments that are anticipated. They are listed below:

- Above freezing temperatures and significant pressures (0.1 to 14.7 psia)
- Above freezing temperatures and cabin vacuum
- Freezing temperature and significant pressure (0.1 to 14.7 psia)
- Freezing temperature and cabin vacuum

Solution

From the foregoing discussion and analyses of the vehicle and cabin conditions, two potential problems emerge: microbiological growth and freezing of water in numerous components on exposure to temperatures below 32°F. The recommended solutions to the potential problems are based on the following assumptions:

- Cooling of the powered down fuel cell is required, i.e., the heat rejection loop must be operative during the quiescent period.

- The electrical equipment associated with fuel cell operation is located within the electrical cold plate package and therefore, requires cooling from the EC/LSS coolant loop.

- Overboard dump is permitted.

Freezing water. - The requirement for the fuel cell to be operative during the quiescent period necessitates that the heat rejection and coolant loops be functioning. As a result of these two circuits being operative the condition of temperatures below 32°F presents no significant impact to the water in the coolant loop because the minimum temperature in the loop is estimated to be 36°F. To prevent potential freezeup in the potable water subsystem lines, an overboard dump procedure will be performed (through normal operation of the water dump section) to drain the lines. The potable water outlet solenoid valves would be closed and remain in that position until startup is initiated. Connecting the GSE fill connectors of the potable water tanks to the corresponding connectors in the water dump section will allow for the continuously processed hot fuel cell water to be collected and dumped overboard by the normal sequence of operation of the dump control. A bacteria filter will be placed in the line to prevent possible back contamination. The thermal capacitance of the redundant potable water tank and the condensing heat exchanger will prevent total water freezeup. Small ice formation may form on the perimeter of the potable water tank or along the walls of the condensing heat exchanger.

Microbiological contamination. - The survival of bacteria is determined by the environmental conditions or relative humidity, temperature and food availability. In the event the equipment temperature drops below the dewpoint, water vapor will condense on the surface and present a breeding ground for microbiological growth. It is anticipated however, that the potential environmental conditions that will exist will not present a significant problem for the following reasons. First, under low temperature conditions bacterial growth is inhibited. Hence, little if any growth will occur during the expected duration of the quiescent period. Secondly, under a high cabin temperature, water will evaporate and diffuse towards the coldest point in the system, the condensing heat exchanger, which itself being at a low temperature will inhibit microbial growth. Therefore, it is concluded that microbiological contamination for the time duration considered (maximum 30 days) will not present a problem for crew reentry to the vehicle or system startup.

It should be noted that low cabin pressures would require the fuel cell water outlet to be back pressurized to insure proper fuel cell performance.

In conclusion, the solutions to the potential problems of water freezing and microbiological growth are simple and straightforward and result in a minimum penalty to the shuttle vehicle.

SHUTDOWN AND STARTUP

This section deals with suggested shutdown and startup procedures appropriate to the problem solutions previously discussed during the quiescent period. These procedures are stated in table 38 by subsystem, somewhat generally because sufficient hardware detail does not exist at this time to allow a detailed sequence of operations to be made. The listing also includes operations indigenous to the overall system operations not covered by one of the subsystems.

SHUTTLE EC/LSS INTERFACES

Inherent in the Shuttle Environmental Control/Life Support System are the interfaces with various Shuttle subsystems and with subsystems of other external vehicles. Specifically, Shuttle EC/LSS interfaces with other vehicles can exist under the following circumstances:

- Ground Support Equipment (GSE) hookup (subsystem to subsystem)
- Booster hookup (subsystem to subsystem)
- Orbiter (cabin to payload module subsystems)
- Space Station hookup (subsystem to subsystem)

During hookup with another vehicle, the Shuttle's EC/LS subsystems will either operate independently, or be discontinued for the mated duration.

The nominal seven day Shuttle mission for Space Station support may be broken down into the time periods shown in table 39. These periods are nominal, and may be extended or contracted depending on space station orbit, time of launch, etc. It is

TABLE 38

RECOMMENDED SHUTDOWN, STARTUP PROCEDURES

EC/LS Subsystem	Shutdown Procedures	Startup Procedures
Atmospheric Storage	Close Solenoid valves	Open solenoid valves*
Pressure and Composition Control	No action	
CO_2, Humidity and Temperature Control	Turn off main fan Remove Lithium Hydroxide canisters Remove particulate filter	Replace Lithium Hydroxide canisters Replace particulate filter Turn on main fan
Atmospheric Contaminant Control	Sorbents removed as part of the water and waste management subsystem	
Heat Rejection Loops	Both the coolant and heat rejection loops are operating Close evaporator inlet solenoid valves	Open evaporator inlet solenoid valves
Water and Waste Management	Turn off heaters in potable water tank Open inlet solenoids (outlets should be normally open) to sink and urinals (standup and urinal section of commode). Override controller to initiate dump procedure of potable water tanks Upon completion of dump, close potable water tank outlet valve Mate flexible hose (with built-in back pressure relief valve and bacteria filter) between potable water tank connector to mating connector in overboard dump section. Turn off fan/centrifugal water separator Close shutoff valve for the potable water pressurant source Open waste collector overboard solenoid valve (normally open) and verify other subsystem valves (repressurization of commode etc.) are closed. Remove activated charcoal (copper sulfate on sorbeads included) canister and bacteria filter. Dump control and nozzle heaters remain operational	Open potable water tank outlet valve Open potable water tank pressurant source shutoff valves Turn on potable water tank heaters Replace activated charcoal canister and bacteria filter Turn on fan/centrifugal water separator Disconnect flexible hosing
Crew Provisions	Remove frozen food from refrigerator Turn off refrigerator	Turn on refrigerator
Instrumentation	All instrumentation except the following will be - Overboard dump section and controllers - Coolant loop and heat rejection loop sensors controllers	Turn on all instrumentation*

*To be performed first during startup

TABLE 39

SPACE STATION SUPPORT MISSION PROFILE

Prelaunch	2 Hours
Booster Ascent	6 Minutes
Orbit	24 Hours
Docking Procedure	2 Hours
Docking Period	110 Hours
Orbit	28 Hours
Reentry	18 Minutes
Atmospheric Flight	30 Minutes

quite obvious therefore, that interfaces could exist during prelaunch, space station docking, and within the orbiter cabin and payload module. Booster - orbiter integration is so short that no interfaces would exist between these two. Each vehicle operates using its own EC/LSS. Table 40 lists the anticipated EC/LSS interfaces with other vehicle subsystems and with other external equipment.

Prelaunch

The EC/LSS interfaces required with the GSE during the two hour prelaunch is minimal. During this period only the GSE Heat Rejection Loop Supply Rig is used to provide coolant fluid for heat rejection. It is equipped with flyaway disconnects. It is expected that during this period, power will be supplied by the fuel cell. If not, an electrical hookup will be required.

Boost

No EC/LSS interfaces with the booster are contemplated because of the short time that the two vehicles are joined together. Each vehicle system will be self-sufficient.

Orbit

The EC/LSS interfaces during orbit are all internal to the shuttle vehicle. These can be as many as five (Cryogenic O_2, Vacuum Vent, Fuel Cell Water, Radiator and Electrical) interfaces during this period. These items have been discussed previously in this report. Every attempt has been made to make the interfaces with the vehicle very basic so that the EC/LSS has little impact on the vehicle configuration. The expendables utilized, oxygen, nitrogen, hydrogen and fuel cell water and electrical power requirements are minimal and are readily available with little impact to the vehicle. The radiator requirement is a necessary and efficient heat sink. The vacuum vent is required for venting the waste management subsystem commode and overboard liquid dump nozzles.

The question of interfaces between the cabin and payload module arises during orbital flight. It is far more advantageous to have few, if any, interfaces between the two EC/LSS for autonomy, safety , and simplicity considerations. It is therefore recommended that each compartment have its own independent EC/LSS. This allows for some redundancy if either cabin or payload module EC/LSS fails. Also, intricate piping and large subsystem components are not required if independent systems are used. The configuration of the payload module and connecting tunnel is an important consideration, because this might determine whether one oxygen supply, CO_2 removal, pressurization subsystem, etc. would suffice in place of two. It may be generally

TABLE 40

EC/LSS INTERFACES

Mission Phases	Sea Level		Space Station		Booster	With Vehicle					
	Electrical	GSE Hx Coolant	Pressure & Composition	Water Transfer		Cryogenic O_2	Cryogenic H_2	Fuel Cell Water	Vacuum Vent	Radiator	Electrical
Prelaunch	X*	X	-	-	-	X	-	X	-	-	X
Boost	-		-	-	-	X	-	X	-	-	X
Orbit	-	-	-	-	-	X	-	X	X	X	X
Space Station Docking	-	-	X	X	-	X*	-	X	-	X	X
Reentry	-	-	-	-	-	X	X	X	-	-	X
Atmospheric Flight	-	X*	-	-	-	X	X	X	-	-	X

*When Required

agreed that an independent EC/LSS study of the payload module would bring out the problems and interfaces, if any, that result with the Shuttle cabin. It is conceded that the fuel cell power supply is shared between the two areas. For this study, no internal orbiter interfaces shall exist, except for the common power source.

Space Station Docking

Interfaces will exist between the Shuttle and space station. These interfaces however, should be kept at a minimum in order to conserve man-hours, maintain subsystem simplicity, etc. The Shuttle, while docked, operates on reduced power (approximately 2.70 kW); thus the basic Shuttle EC/LSS may still operate under normal modes. It is recommended that the Shuttle employ the space station s pressure and composition control subsystem, only because the latter's subsystem is larger. When the hatchway between the Shuttle and space station is opened, the Shuttle's atmospheric pressure and composition control subsystem should be shut down; likewise, turned on when the door is closed. The mixing of contaminants will occur when the space station atmosphere migrates into the Shuttle. It is desirable to continue to operate the Shuttle contaminant and humidity control subsystems, the heat rejection subsystems, and the water and waste management subsystems while the shuttle is docked.

The largest interface problems between the Shuttle and space station are due to the shadowing effect on the radiator and the dumping of liquids and gases to space while the two vehicles are docked. The shadowing effect on the radiator is a function of the vehicle size, orientation and relationship to the sun and earth; factors which are not known at this time. It is assumed that some provisions will be made so the fuel cells can be operated at half power while docked because they cannot be restarted if shut down.

If fuel cell water is not used in the evaporator for cooling, the 60 lbs H_2O/day generated (at a power output of 2.70 kW) must be stored in the waste water storage tanks or transferred to the space station. If stored, it will result in large (400 lb H_2O) storage tanks to handle six days of water. If, however, 60 lbs H_2O/day is used by the evaporator while in the docking mode, the presently recommended 100 lb H_2O storage tanks are sufficient for the docking period. The transfer of waste water from the Shuttle to the space station does not seem practical, because of the potential difficulties inherent in hooking up, pumping, providing proper transfer lines, etc. for the task. The entire problem of Shuttle dumping liquids and gases in the vicinity of the space station should be more exactly defined and resolved in a later follow-on Shuttle study. Interfaces such as operating the waste management subsystems, concurrently or independently, operating the waste water storage system, and humidity, and trace contaminant subsystems should be kept to a minimum. This especially holds true, since the Shuttle will be bringing back to Earth, various wastes and debris from the space station.

Reentry

The EC/LSS interfaces with the vehicle during reentry are limited to four; cryogenic oxygen and hydrogen, fuel cell water, and electrical power. The hydrogen is used as the heat sink for reentry as discussed in the Heat Rejection section of this report. No venting of the commode or liquid waste is contemplated during this phase.

Atmospheric Flight

During atmospheric flight after reentry the use of the fuel cell for generating power will continue. Hydrogen will be used as the coolant heat sink as the radiator will be inoperative. The selection was discussed in detail in the Heat Rejection section of this report. No overboard venting of the waste liquids or the commode is contemplated during this mission phase. However, these items could be vented if deemed necessary.

IMPACT OF MISSION PARAMETERS

The impact of mission parameters were discussed under each of the subsystem concepts. This is a summary of the effect of the following parameters on the selected system:

- Mission Length

- Crew Size

Mission Length

For the selected system and assuming no hardware changes, increases in mission length increase the usage of expendables. Variations in the selected subsystem weight as a function of mission length are shown in figures 91, 92, and 93.

As mission length increases, The Atmospheric Storage subsystem will require an additional nitrogen supply tank to provide for additional vehicle leakage. It is assumed that the same size tank will be used and therefore, for longer than seven days, a second nitrogen tank must be added. As both tanks contain sufficient gas for a 48-hour emergency reserve and a cabin repressurization, a second N_2 tank will provide for nearly 50 additional days to the mission length. As oxygen is normally drawn from the OMS tank, no additional emergency tank will be required, although the OMS must provide the additional oxygen, which is a penalty.

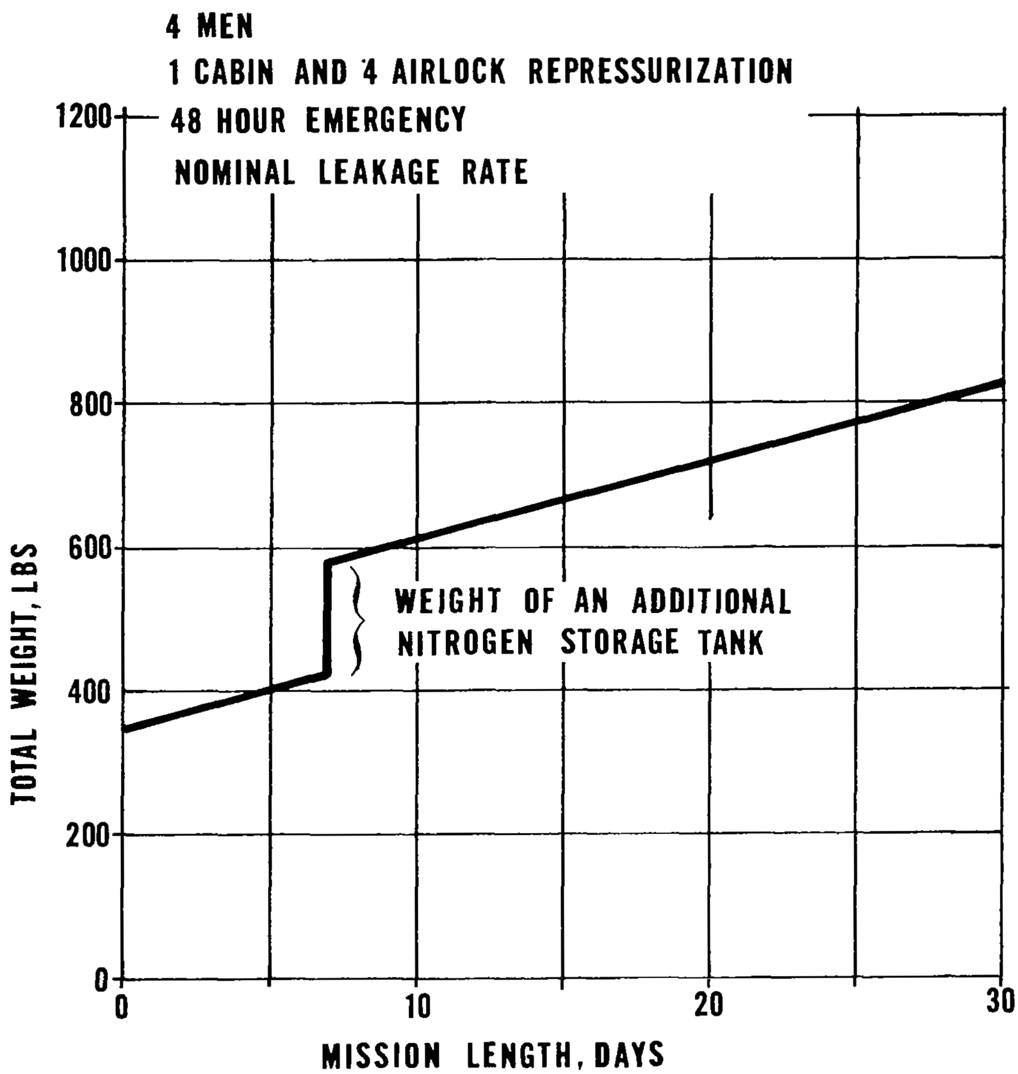

FIGURE 91. ATMOSPHERIC STORAGE TOTAL WEIGHT VERSUS MISSION LENGTH

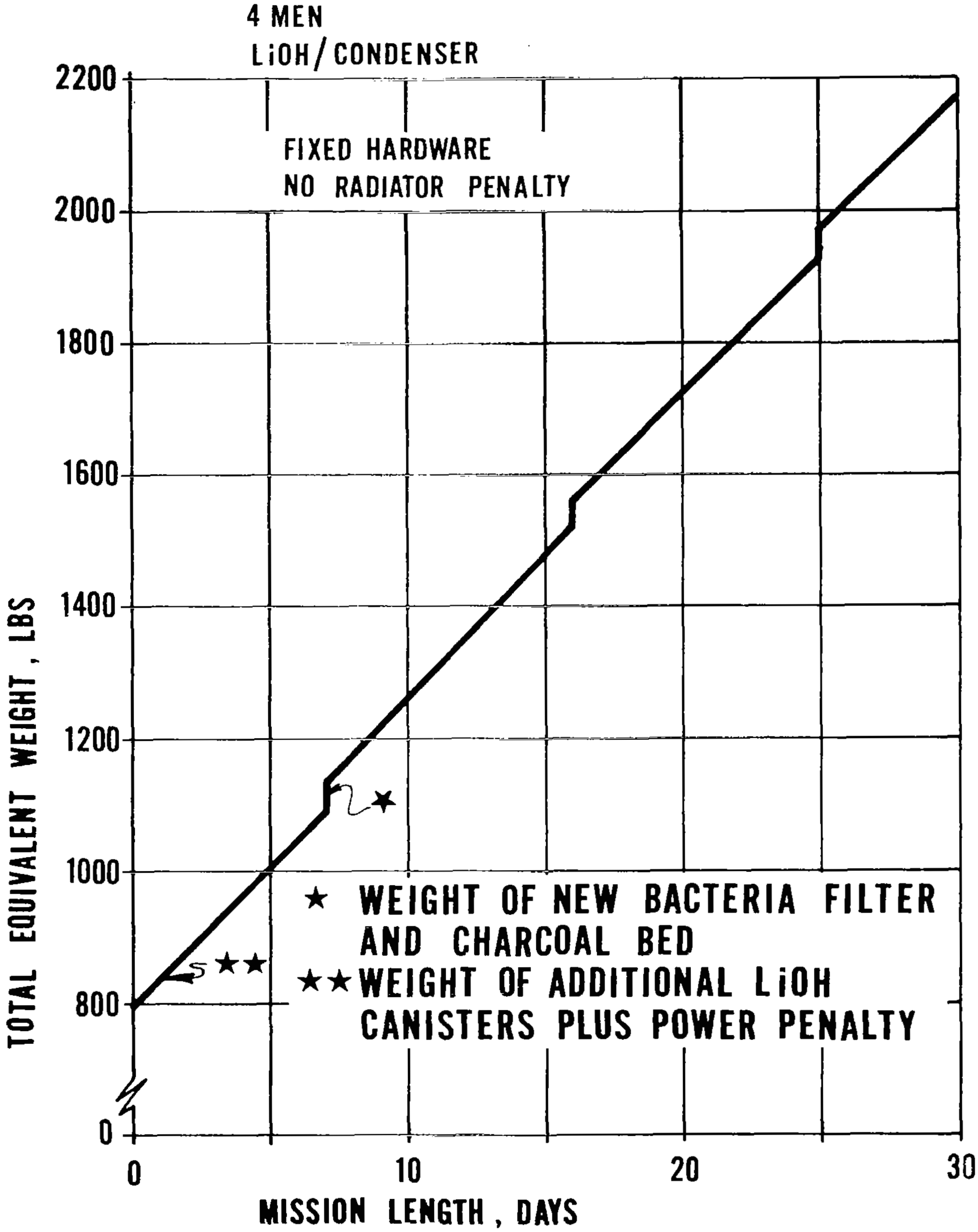

FIGURE 92. LiOH/CONDENSER WEIGHT VERSUS MISSION LENGTH

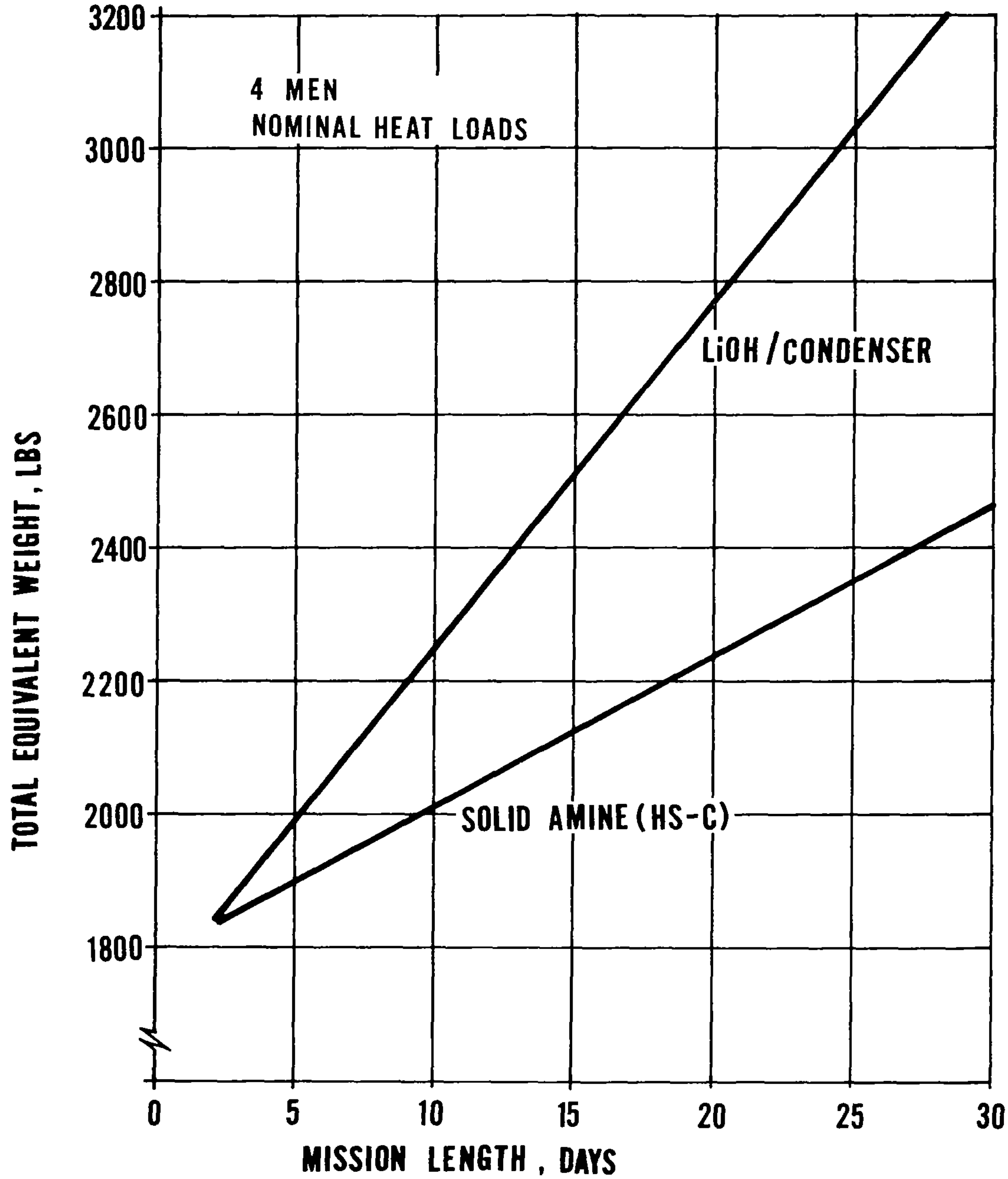

FIGURE 93. LiOH/CONDENSER AND SOLID AMINE WEIGHT VERSUS MISSION LENGTH

For the CO2 Humidity, and Temperature Control subsystem, the LiOH, charcoal, and bacteria filters must be replaced to extend the mission length. However, this results in an additional weight penalty (figure 92) for the additional LiOH canisters relative to the solid amine (HS-C) concept. If mission lengths greater than seven days with a crew size of four men are contemplated, CO_2, humidity and temperature control can be accomplished much more efficiently and is less costly using the solid amine (HS-C) concept (figure 93).

Pressure and Composition Control and the Heat Rejection subsystems are not affected by an increase in mission length. The Heat Rejection subsystem uses excess fuel cell water to reduce the radiator outlet temperature and cryogenic hydrogen for the reentry phase of the mission. Therefore, on orbit mission length does not affect subsystem weight. Since the waste management system has a large enough capacity to handle a 120 man-day mission, an extra or larger commode is not required. Only gas ullage, makeup gas anu tissue wipes are required as mission length increases.

Crew Size

With increases in crew size, location of the additional personnel becomes significant. Table 41 defines the EC/LSS equipment changes as the crew size increases to six men in the crew compartment, an independent payload module is used, to carry up to 10 additional men, and when up to 14 men, including the crew, are located within a single compartment.

The atmospheric storage nitrogen tank size or number must increase as a function of compartment volume as shown in figure 94. An additional emergency oxygen tank must also be added or the existing one enlarged for crew sizes above four men.

The Pressure and Composition Control subsystem is capable of handling the larger crew sizes in the same compartment with no increase in weight. It is recommended that a separate and identical Pressure and Composition Control Subsystem be used for the payload module, however, to reduce the vehicle interfaces.

The size of the CO_2, Humidity, and Temperature Control subsystem is related to the crew size and associated cabin heat loads. It is possible that with a separate payload compartment that the baseline LiOH subsystem could handle the requirements by operating both LiOH cartridges at the same time and that the condensing heat exchanger size could be adequate. Another alternative with increased crew size and increased heat loads would be to use the solid amine concept which would then become more advantageous and not require an interface with the waste management subsystem.

For the CO_2, Humidity, and Temperature Control subsystem, the installed system can handle up to six men by using more expendables. Increased temperature and humidity control are accomplished by using the cryogenic heat exchanger to reject the additional heat. This requires an additional cryogenic weight of 250 lbs. for a

TABLE 41

IMPACT OF CREW SIZE AND PAYLOAD MODULE

Major Subsystem	Crew Compartment 2-6 Men	Independent Payload Module 1-8 Men	Single Compartment With > 6 Men (7-14)
Atmospheric Storage and Pressure and Composition Control	Per baseline system. Above 4 men additional emergency oxygen is required.	Install additional N_2 storage. Recommend independent pressure & composition subsystem per baseline system to reduce compartment interfaces.	No change to baseline pressure & composition control. Increase nitrogen & emergency oxygen storage capacity as appropriate.
CO_2, Humidity, and Temperature Control	Per baseline system. Above 4 men change LiOH cartridge more often.	Resize subsystem approx. 2 times baseline system & add ventilation fans.	Same as independent payload module.
Atmospheric Contaminant Control	Per baseline system. Above 4 men add catalytic oxidizer.	Resize subsystem approx. 2 times baseline system. Add catalytic oxidizer.	Resize and add catalytic oxidizer.
Heat Rejection	Per baseline system. Above 4 men use cryogenic heat exchanger for add'l heat sink for peak heat loads.	Resize radiator, interface heat exchanger, etc., for resultant heat loads.	Same as independent payload module.
Water Management	Per baseline system.	Recommend installing independent system per baseline system.	Per baseline system, may add additional dispenser.
Waste Management	Per baseline system.	Recommend installing independent urinal & split-commode per baseline system.	Suggest adding additional split-commode.

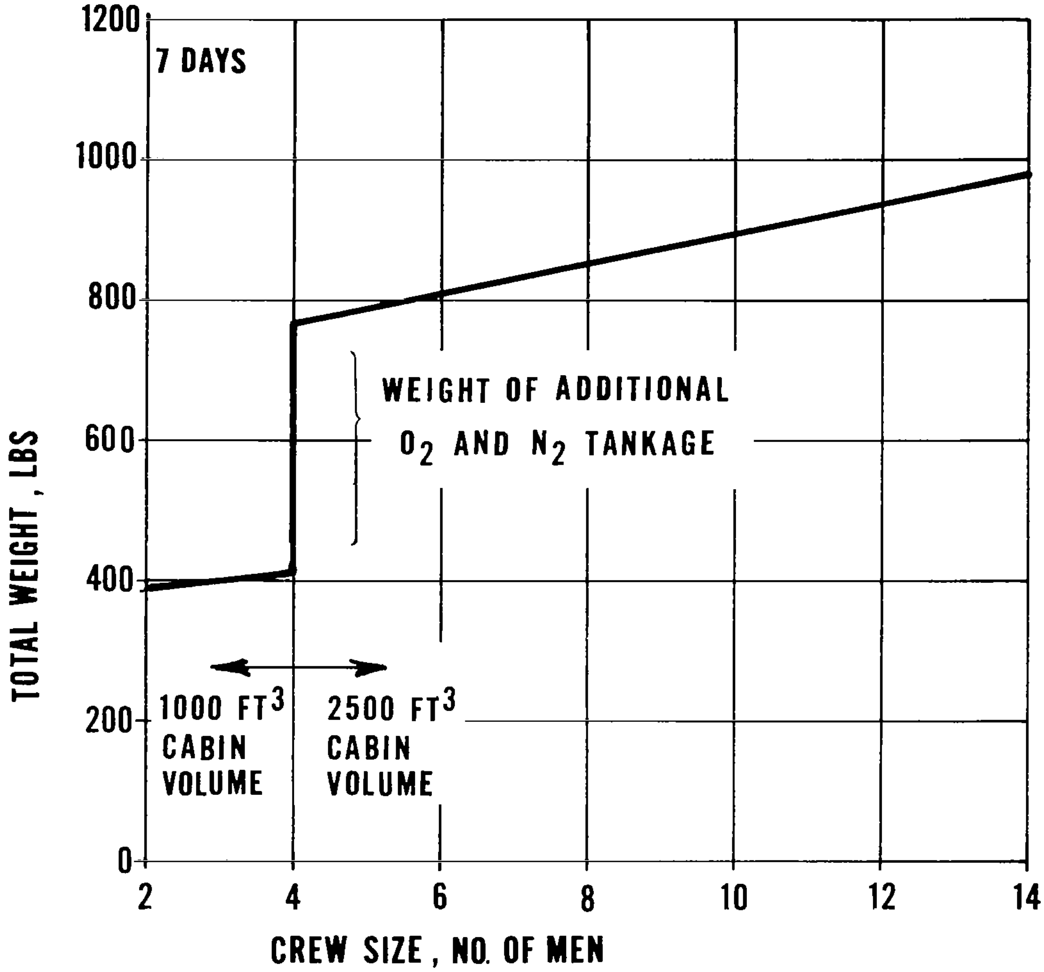

FIGURE 94. ATMOSPHERIC STORAGE TOTAL WEIGHT VERSUS CREW SIZE

six man crew under peak heat load conditions. At nominal loads cryogenics are not required for a heat sink. At crew sizes greater than six men, the cryogenic heat exchanger would have to lower the radiator loop temperature below 32°F which would then have a possibility of freezing the water coolant loop and therefore require the system to be redesigned for this condition. The redesign would require higher coolant flow rates and a larger radiator.

CO_2 levels can be maintained by either increasing the flow rate through the LiOH canisters or by running both canisters at the same time and changing cartridges more frequently. Odor and bacteria control would suffer as there is no way to increase these flow rates without system redesign. Short missions (less than 28 man-days) should present no problem. Actually, if operation with more than four men is anticipated for seven days or longer, a desiccant solid amine (HS-C) should be used since it is much lighter (figure 95) and is regenerative. In addition, its weight advantage increases with increased radiator heat influx and cabin heat loads.

Heat rejection requirements are also directly dependent on the crew size and compartment and vehicle heat loads. Since the vehicle appears to be radiator limited, additional cooling would require use of the evaporator supplemented with the cryogenic heat exchangers for adequate heat rejection.

The Waste Management subsystem is capable of handling up to fourteen men. It would be desirable to add a second commode for 12 men or more but it is not required. If a payload module is used to house the extra men, it is possible for them to use the Waste Management subsystem in the cabin or add a separate Waste Management subsystem can be added in the payload module. The addition of an additional Waste Management subsystem is recommended to reduce the number of compartment interfaces and for personnel consideration.

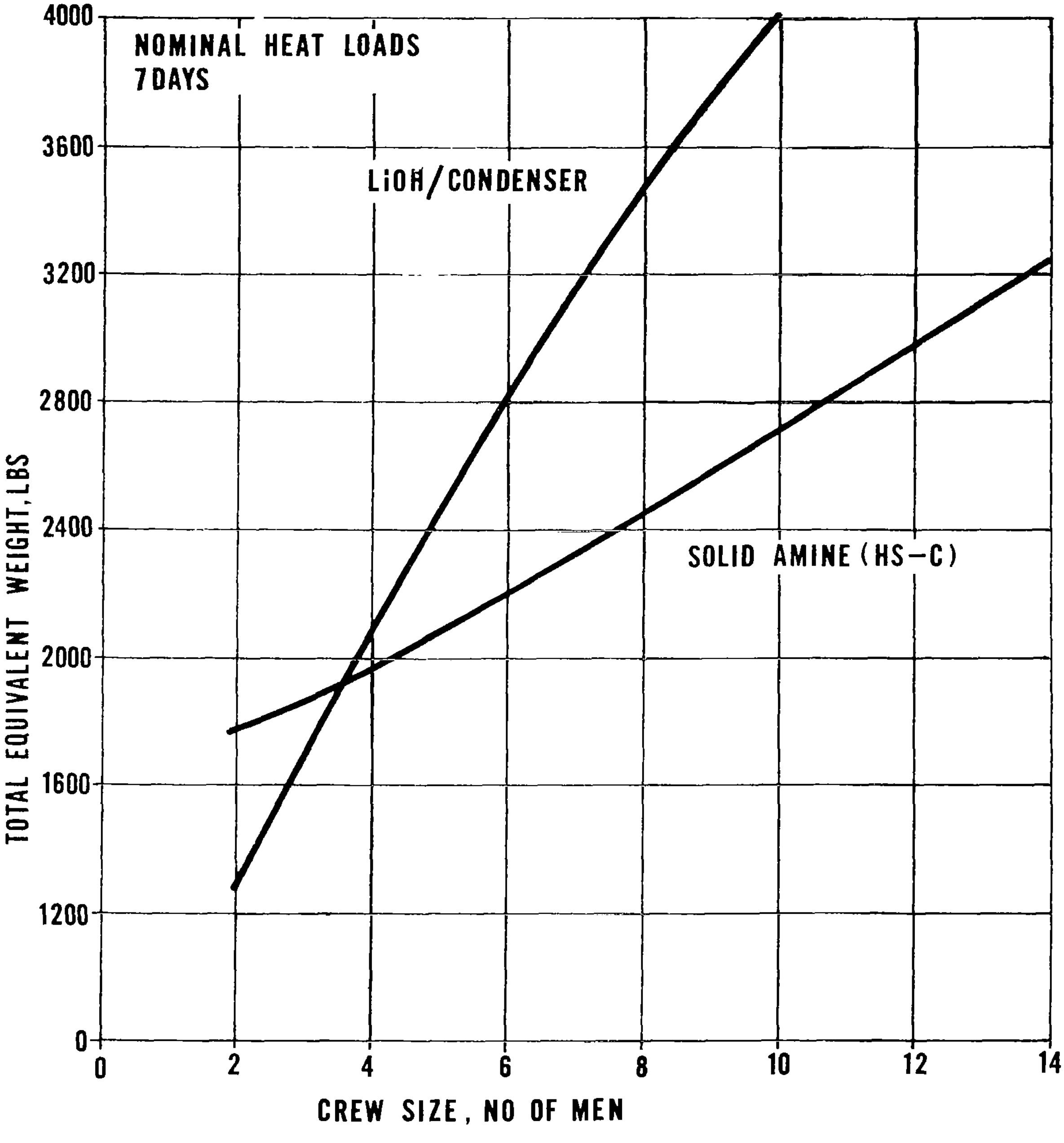

FIGURE 95. LiOH/CONDENSER AND SOLID AMINE WEIGHT VERSUS CREW SIZE

PACING TECHNOLOGY

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PACING TECHNOLOGY

As with all new vehicles, certain areas of Environmental Control and Life Support can be improved or enhanced by resolving particular technological problems. As noted in the introduction, one of the primary objectives of the study program was to identify pacing technology areas of the Environmental Control and Life Support System. Advancements in these areas offer the potential of reduced total program cost, better performance, longer life and less crew time requirements both in-flight and on the ground during the course of the space shuttle program. As a result, these items are worthy of consideration at this time.

This section of the report identifies two types of technology improvement areas (table 42): those that are requirements to permit the mission as now planned to be completed without compromising the crew or the mission, and second, those that offer the potential for improved performance, lower weight, and more mission flexibility.

For each required technology item noted, the recommended approach is listed together with an estimate of the time and funds required to bring the concept to the point where operation is proved and sufficient parametric data is obtained for initiation of a flight design with a high level of confidence. The schedules shown are based on funding the effort as Research and Development contracts prior to phase "C" shuttle effort. Work would continue in parallel with the phase "C" effort until completed. The results would then be phased into the shuttle program.

REQUIRED ITEMS

Effort on the following items, is required to assure ability to complete the shuttle mission without compromising the crew or mission.

Contaminant Model Definition

The contaminant control model is the basis for determining the need for and effectiveness required of all control methods. An adequate definition will permit accurate sizing of the contaminant control hardware thereby reducing the weight, power penalty and cost.

This definition may be obtained by conducting manned tests in an environment with equipment representative of an actual vehicle and by utilizing data gathered from the Apollo and Skylab programs.

TABLE 42

TECHNOLOGY RECOMMENDATIONS

Subsystem	Required Items	Recommended Items
Atmospheric Storage and Pressure and Composition Control	Partial Pressure Sensors (O_2 & CO_2)	Composite Material Tanks
CO_2, Humidity and Temperature Control		Solid Amine (HS-C)
Atmospheric Contamination Control	Contaminant Model Definition	Purafil
Heat Rejection	Evaporators Cryogenic Heat Exchanger	
Water and Waste Management	Liquid Quantity Sensor	Zero Gravity Tanks
	Urinal	Water Potability Sensor
	Split-Flow Commode	Chemical Water Control
Crew Provisions		Noise Control

Task schedule and cost. -

Task	Schedule, years from start (0 1 2 3 4)	Preliminary estimate (millions of dollars)
Conduct manned test	0 to 2.4	1.3

Liquid Quantity Sensor

An important part of any water use system is the ability to measure accurately the water available for use and, ideally, the quantity used for various operations. At the moment an accurate quantity sensor is not available.

The first step in this area would be to develop a quantity sensor for use in a bladderless tank and also one for use in a bladdered tank. The sensor should be accurate (±3%), reliable, and not interfere with delivery or storage of the water.

Task Schedule and cost. -

Task	Schedule, years from start (0 1 2 3 4)	Preliminary estimate (millions of dollars)
Evaluate promising concept	0 to 0.7	0.4
Develop selected concept	0 to 2.1	1.5

Urinal

To improve crew acceptance, a new, more conventional, wall-mounted urinal utilizing an air stream to facilitate urine collection is recommended for use by the male crew members. This would be much more acceptable for a multi-man use as it would not require body contact with the urine collection device. This task would include determination of the proper bowl design to eliminate splash back and to prevent aerosols from entering the cabin, efficient method of flushing and determination of the optimum quantity of air flow required for zero gravity operation.

Task schedule and cost. -

Task	Schedule, years from start (0 1 2 3 4)	Preliminary estimate (millions of dollars)
Development	0 to 1.5	0.9

Split-Flow Commode

Present methods of collecting feces are not psychologically acceptable to the crew particularly when both male and female crew members will be aboard the vehicle. A zero gravity commode, "earth-like" in use, consisting of a split collector, one side of which contains a directed air flow urinal so urine can be stored or processed independently is required. The remaining portion collects feces using an air stream to direct the bolus into the collector and to control odors. This device should be as conventional and "earth-like" as possible for crew acceptance and convenience. Primary emphasis will be placed on the human interface operation, reduction of operational time and zero gravity operation.

Task schedule and cost. -

Task	Schedule, years from start 0 1 2 3 4	Preliminary estimate (millions of dollars)
Development	0 to 1.5	0.6

Partial Pressure Sensors

To provide a spacecraft with a specified atmospheric composition and pressure requires utilization of accurate and reliable carbon dioxide and oxygen partial pressure sensors. To date, partial pressure sensors have an inherent limited operational life, are susceptible to atmospheric as well as self contamination and exhibit an inherent drift which causes inaccurate readouts. Particular effort in this area is recommended in light of the shuttle structural environment and multiple reuse requirements.

This task requires extensive study of available instrumentation techniques and development and fabrication of selected instruments under representative operating conditions.

Task schedule and cost. -

Task	Schedule, years from start 0 1 2 3 4	Preliminary estimate (millions of dollars)
Development	0 to 1.5	1.0

Cryogenic Heat Exchanger

Heat rejection methods other than the space radiator are of prime importance for the space shuttle particularly during the reentry and atmospheric flight and ground cooling phases.

Of the many methods of heat rejection considered for shuttle atmospheric operation (reentry, atmospheric flight, and ferry phases), the cryogenic heat exchanger appears to be most competitive. The concept offers to the shuttle a simple, versatile and low cost method of heat rejection. Beside possessing the lowest total equivalent weight penalty of all the expendable heat sink approaches, the cryogenic heat exchanger's attractiveness is enhanced by the availability of the cryogenic source (required for the Auxiliary Power Unit). The technology advancements required for optimum design of the cryogenic heat exchanger are control of thermal stress and shock.

Task schedule and cost. -

Task	Schedule, years from start 0 1 2 3 4	Preliminary estimate (millions of dollars)
Development		1.2

Evaporators

The use of an evaporator as a supplimentary heat rejection device to the vehicle radiator during the orbit mission is very desirable because it permits the vehicle radiator size to be reduced which is generally advantageous. Therefore, it appears desirable to further develop the life and performance characteristics of evaporators.

At the present time all evaporators types have some deficiencies which consist of either low load performance and startup problems such as water breakthrough, or life problems depending on the concept used. Resolution of the above mentioned problems for at least one type of evaporator is required for a reliable, low maintenance time vehicle.

Task schedule and cost. -

Task	Schedule, years from start 0 1 2 3 4	Preliminary estimate (millions of dollars)
Resolve control problems		1.8
Improve life		1.2

RECOMMENDED ITEMS

Effort on the following items is recommended because they offer the potential of improved performance, lower weight, and more mission flexibility.

Solid Amine (HS-C)

The solid amine (HS-C) CO_2, humidity and temperature control subsystem concept is considered very competitive for the space shuttle EC/LSS. Solid amine is an adsorbent material used to collect both CO_2 and water vapor and is regenerated by vacuum desorption. Since this concept is regenerative, no in-flight maintenance is required, while the selected concept, LiOH/condenser, which is an expendable system, requires daily in-flight replacement of the LiOH cartridges. In fact the overall subsystem review shows that the quantitative evaluation of these two concepts is almost equal. The LiOH/condenser system was selected since it has the immediate advantage of low cost through first flight and good availability for the baseline mission as now defined.

However, on a total program cost basis (ten years), the regenerative solid amine subsystem requires substantially less expendables and its cost becomes equal to that of the LiOH/condenser concept. While the solid amine concept has more parts and is less highly developed than the LiOH concept, its total equivalent weight is 149 pounds less than the LiOH/condenser concept for the baseline system. In addition, its weight advantages increases with increased: radiator heat influx, cabin air heat loads, crew size and mission lengths. While the solid amine subsystem has an acceptable shuttle flight availability it is recommended it be further evaluated on a full scale basis to verify its great potential for the shuttle application, particularly if the baseline mission requirements change to include a larger crew size or a longer mission length.

Purafil

A review of a model of the atmospheric contaminants contemplated for the shuttle cabin, indicates a number of trace contaminants whose level can rise to unacceptable limits if not controlled in some manner. However, if ammonia, carbon monoxide, (for longer missions) and pyruvic acid are controlled to acceptable levels, the remaining contaminants will also be controlled. Control of ammonia, carbon monoxide and pyruvic acid, at the present time, requires three different methods. However, one material, "Purafil", has the potential to control all three. Therefore, it appears desirable to establish a test program to determine the trace control capability of this material in view of its potential vehicle savings in terms of power, cost, weight and maintenance time.

Zero Gravity Tanks

Zero gravity liquid tanks are very desirable, since they eliminate the need for a bladder, thus improving mission life and eliminating the possibility of a bladder failure and its resultant system impact. To date little or no work has been done on zero gravity tankage for water storage. Since the capillarity properties of water can be affected by trace contaminants which might affect the operation of the tanks, it is recommended that effort be expended to explore this area.

Water Potability Sensor

A fast and reliable water quality and microbiological monitoring device is desired to verify the potability of the drinking water. Although not absolutely necessary for the shuttle mission, this device would indicate the acceptability of the potable water prior to use and preclude the possibility of any problems occurring due to contaminated water. It would also add a great deal to the crew's peace of mind.

Chemical Water Control

The use of pasteurization was selected in the shuttle for microbiological control of the water quality. A more flexible system, which should require less power, would be chemical control by using chlorine or iodine or some as yet undefined material. This control would require a device to measure the concentration of chemical in the water mixture and automatically add the chemical required, to maintain system sterility. It should be simple, reliable, acceptable to the crew and compatible with existing component materials.

Composite Material Tanks

Composite material (filament wound) tanks provide a significant weight advantage over the more conventional materials such as stainless steel, titanium, etc. However, to obtain the projected weight ratio of 0.8 pound of tank for each pound of stored gas at 3000 psi, a further development of manufacturing processes is required. It is, therefore recommended, in view of the weight savings projected, that development of tanks made of composite material for high pressure (3000 psi) gaseous storage of oxygen and nitrogen be expanded.

Noise Control

In a confined area, the problems of noise control become important. Although the traditional methods exist for noise control, which normally is to suppress noise after it occurs, it would be very desirable to incorporate low noise fans and other devices to eliminate noise at its source. Therefore, it is recommended that attention be given to developing low noise items.

APPENDIX A

LANGLEY SPACE SHUTTLE STUDY

REQUIREMENTS/GUIDELINES

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	b. Nominal Design Point (Passengers)	2
	c. Range	
	1. Crew	None
	2. Passengers	0-12
1.2	Metabolic Heat Generation (Btu/man-hr)	
1.2.1	Total Metabolic - Average	434
	a. Nominal Design Point	647
	b. Range	300 - 647
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	a. Nominal design point	402.5
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1.2.3	Latent Heat Generation	
	a. Nominal design point	244.5
	b. Range	30 - 244.5
1.3	O_2 Consumption (lb/man-day)	
1.3.1	Crewmen	
	a. Nominal design point (48 hour average)	1.84
	b. Range	1.69 - 2.20
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	a. Nominal design point (48 hour average)	1.84
	b. Range	1.69 - 1.93
1.4	CO_2 Produced (lb/man-day)	
1.4.1	Crewmen	
	a. Nominal design point (48 hour average)	2.20
	b. Range	1.92 - 2.68

1.4.2	Passengers		
	a.	Nominal design point (48 hour average)	2.20
	b.	Range	1.92 - 2.35
1.5	<u>Drinking Water and Food Preparation</u> (lb/man-day)		
1.5.1	Crewmen		
	a.	Nominal design point (48 hour average)	6.25
	b.	Range	3.44 - 12.09
1.5.2	Passengers		
	a.	Nominal design point (48 hour average)	6.25
	b.	Range	TBD
1.6	* <u>Water of Oxidation</u> (lb/man-day)		
	a.	Nominal design point	0.66
	b.	Range	0.61 - 0.72
1.7	* <u>Urine Produced</u> (lb/man-day)		
1.7.1	Water		
	a.	Nominal design point (48 hour average)	3.45
	b.	Range	2.54 - 4.48
1.7.2	Solids		
	a.	Nominal design point (48 hour average)	0.13
	b.	Range	0.10 - 0.18
1.8	* <u>Feces Produced</u> (lb/man-day)		
1.8.1	Water		
	a.	Nominal design point (48 hour average)	0.25
	b.	Range	0.22 - 0.37

* Crewmen and passengers.

1.8.2 Solids

a.	Nominal design point (48 hour average)	0.15
b.	Range	0.06 - 0.17

1.9 * Wash Water Required (lb/man-day)

1.9.1 Water

a.	Nominal design point (48 hour average)	2.2
b.	Range	1.5 - TBD

1.9.2 Solids

a.	Nominal design point (48 hour average)	0.0044
b.	Range	0.001 - TBD

2.0 MISSION DATA

2.1 Systems Life Requirement for Reliability Analysis -100 mission cycles

2.2 Mission Contingency Considerations

2.2.1 Substained Operation after System/Subsystem Failure (days)

a. Emergency life support for two-day operation must be provided after any complete system and/or subsystem failure except radiator failure. Twelve hour emergency must be supplied for radiator failure.

b. Sufficient supplies will be stored onboard to continue the mission for 2 days in excess of the nominal flight duration.

c. Supplies will be based on nominal daily crewmen/passengers shuttlecraft requirements.

2.2.2 Minimum Power

a. Mission and life support equipment essential for sustained crewmen sagety will be operational at all times.

* Crewmen and passengers.

2.3 Mission Length (Days)

a.	Nominal	7
b.	Range	2 - 30

2.4 Crew Size/Mission Length (See Figure 2.1)

2.5 Reliability

2.5.1 For the nominal mission the EC/LSS shall have minimum reliability of 0.9999 for crew safety

2.5.2 The subsystems shall meet the failure criteria of Table 2.1.

2.6 Power Penalty (Power Equivalent Weight)

PP = 0.16 lb/watt + 0.00133 lb/watt-hr.

2.7 Radiator Penalty (@ Ts = 492°R) - 1.35 lb/ft^2.
Maximum Area - 900 ft^2

3.0 VEHICLE DATA

3.1 Total Pressure (psia)

a.	Operational pressure will be selectable for any mission mode within the range shown.	10 to 14.7
b.	Nominal design point	14.7
c.	Emergency conditions (exposure to total pressures between the range shown shall not create hazards or damage).	TBD
d.	During quiescent periods in orbit.	TBD

3.2 Oxygen Partial Pressure

PO_2 shall be maintained between 3.1 and 3.4 psia under all conditions of cabin temperature and total pressure, except that, during atmospheric cruise, PO_2 shall not fall below 2.2 psia.

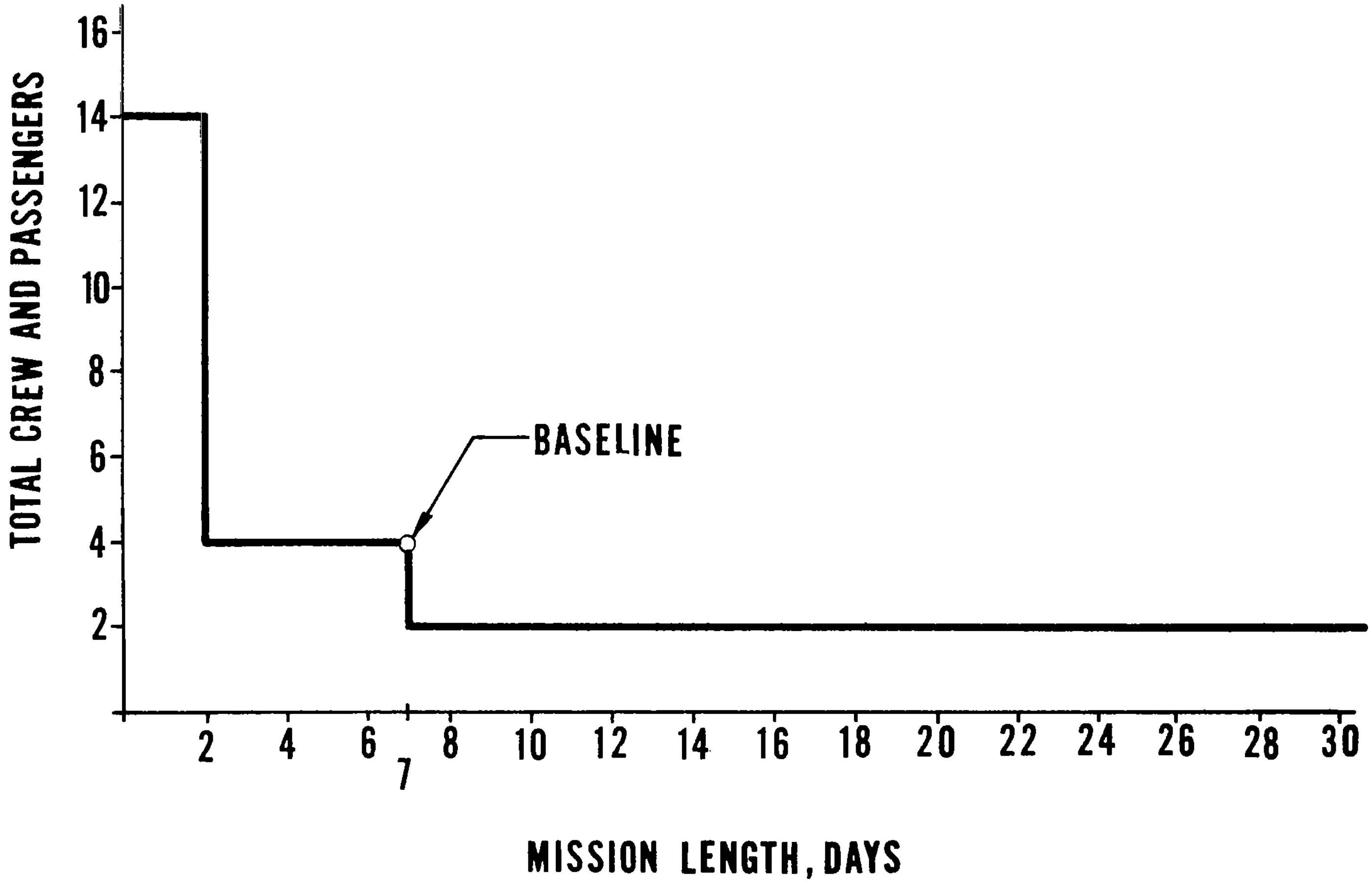

FIGURE 2-1 CREW SIZE VERSUS MISSION LENGTH

TABLE 2.1

MISSION SUCCESS DESIGN CRITERIA

- All critical equipment within the EC/LSS
    - Shall be designed to a fail operational - fail safe criterion except for static components such as pressure vessels, hydraulic and pneumatic lines, heat exchangers, and static line fittings. These will be designed to meet a fail safe criterion.
- All non-critical subsystems/components shall be FAIL SAFE

DEFINITION OF TERMS

Failure:	The inability of system, subsystem or component to perform its required function.
Critical Component:	A required functional element of a subsystem essential for mission success.
Critical Failure:	Any hardware failure which results in loss of life and/or which results in mission loss.
Fail Operational Capability:	Denotes no degradation of a mission critical function subsequent to a hardware failure.
Fail Safe Capability:	Denote no jeopardy of human safety subsequent to a hardware failure and safe return of crew and payload, i.e., intact abort.
Abort:	Premature termination of a mission because of existing or imminent degradation of mission success accompanied by the decision to make safe return of the crew and payload the primary objective.

3.3	Cabin Atmosphere Diluent (gas)	Nitrogen
3.4	Carbon Dioxide Partial Pressure (mm Hg)	
	a. Nominal	5.0
	b. Range	0 - 7.6
	1. During normal operation of the cabin PCO_2 shall not exceed 7.6 mmHg at any time.	
	c. Fail safe operation	10
	d. Emergency	
	1. Maximum partial pressure	15
	2. Maximum duration for crewman exposure (hr)	2
3.5	Trace Contaminants	
	a. Table 3.1 contains a listing of trace contaminants and their Maximum Allowable Concentrations.	
3.6	** Cabin Temperature ($^\circ$F)	
	a. Design Range	65 - 75
	b. Temperature control tolerance on selected temperature within above range.	±2
	c. Operational temperature will be selectable within the design range.	
	d. Range during quiescent period.	40 - 110
	e. Range during emergency, including during pressurization.	40 - 110
3.7	** Cabin Humidity (dew point temperature $^\circ$F)	
	a. Cabin dew point will be at least 12°F lower than T_{db} (dry bulb) at all times.	

b.	Maximum dew point for any Tdb.	57
c.	Minimum dew point during shirtsleeve	40

** Applicable to space occupied by crewmen/passengers, with measurement made more than one foot from any wall or equipment surface, and more than four feet from an air conditioning discharge or intake fitting.

Table 3.1

MAXIMUM CONCENTRATION AND PRODUCTION RATE OF TRACE CONTAMINANTS

Contaminant	Production Rates		Maximum Allowable Concentration (mg/m^3)
	Non-Biological (gm/day)	Biological (gm/man-day)	
Acetone	1.02	0.0005	240
Acetaldehyde	0.02	0.0002	36
Acetic Acid	0.002		2.5
Acetylene	0.02		180
Acetonitrile	0.002		7
Aerolein	0.002		0.25
Allyl Alcohol	0.002		0.5
Ammonia	0.02	1.0	3.5
Amyl Acetate	0.002		53
Amyl Alcohol	0.002		36
Benzene	0.02		8
n-Butane	0.02		180
iso-Butane	0.002		180
Butene-1	0.02		180
cis-Butene-2	0.002		180
trans-Butene-2	0.02		180
1, 3 Butadiene	0.02		220
iso-Butylene	0.002		180
n-Butyl Alcohol	0.02	0.003	30

Table 3.1 (Cont.)

Contaminant	Production Rates: Non-Biological (gm/day)	Production Rates: Biological (gm/man-day)	Maximum Allowable Concentration (mg/m^3)
iso Butyl Alcohol	0.002		30
sec-Butyl Alcohol	0.002		30
sert-Butyl Alcohol	0.002		30
Butyl Acetate	0.002		71
Butraldehydes	0.002		70
Butyric Acid	0.002		14
Carbon Disulfide	0.002		6
Carbon Monoxide	0.02	0.0162	29
Carbon Tetrachloride	0.002		6.5
Carbonyl Sulfide	0.002		25
Chlorobenzene	0.002		35
Chlorofluoromethane	0.002		24
Chloroform	0.02		24
Chloropropane	0.002		84
Cumene	0.002		25
Cyclohexane	0.02		100
Cyclohexene	0.002		100
Cyclohexanol	0.002		20
Cyclopentane	0.002		100
Cyclopropane	0.002		100
Decalin	0.002		5
1, 1 Dimethyl Cyclohexane	0.002		120
trans 1, 2, Dimethyl Cyclohexane	0.002		120

Table 3.1 (Cont.)

Contaminant	Production Rates: Non-Biological (gm/day)	Production Rates: Biological (gm/man-day)	Maximum Allowable Concentration (mg/m^3)
2, 2 Dimethyl butane	0.002		93
Dimethyl Sulfide	0.002		15
1, 1 Dichloroethane	0.02		40
Di iso Butyl Ketone	0.002		29
1, 4 Dioxane	0.02		36
Dimethyl Furan	0.002		3.0
Ethane	0.02		180
Ethyl Alcohol	0.02	0.01	190
Ethyl Acetate	0.02		140
Ethyl Acetylene	0.002		180
Ethyl Benzene	0.002		44
Ethylene Dichloride	0.002		40
Ethyl Ether	0.02		120
Ethyl Butyl Ether	0.002		200
Ethyl Formate	0.02		30
Ethylene	0.02		180
trans 1, Methyl 3 Ethyl Cyclohexane	0.002		117
Ethyl Mercaptan	0.002		2.5
Freon 11	0.02		560
Freon 12	0.02		500
Freon 22	0.002		350
Freon 23	0.002		12
Freon 113	0.002		700

Table 3.1 (Cont.)

Contaminant	Production Rates: Non-Biological (gm/day)	Production Rates: Biological (gm/man-day)	Maximum Allowable Concentration (mg/m^3)
Freon 114	0.02		700
Freon 114 unsym	0.002		700
Freon 125	0.002		25
Formaldehyde	0.002		0.6
Furan	0.002		3
Furfural	0.002		2
Hydrogen	0.02	0.05	215
Hydrogen Sulfide		0.00006	1.0
Heptane	0.002		200
Hexene-1	0.002		180
n-Hexane	0.02		180
Hexamethylcyclotri-sihexane	0.002		240
Indole	0.002	0.1	126
Isoprene	0.002		140
Methylene Chloride	0.02		21
Methyl Acetate	0.02		61
Methyl Butyrate	0.002		30
Methyl Chloride	0.002		21
2-Methyl-1 Butene	0.002		1430
Methyl Chloroform	0.02		190
Methyl Furan	0.002		3
Methyl Ethyl Ketone	0.02		59
Methyl Isobutyl Ketone	0.002		41

Table 3.1 (Cont.)

Contaminant	Production Rates: Non-Biological (gm/day)	Production Rates: Biological (gm/man-day)	Maximum Allowable Concentration (mg/m^3)
Methyl Isopropyl Ketone	0.02		70
Methyl Cyclohexane	0.002		200
Methyl Acetylene	0.002		165
Methyl Alcohol	0.02	0.01	
3-Methyl Pentane	0.002		295
Methyl Methacrylate	0.002		41
Methane	2.96	0.6	1720
Mesitylene	0.002		2.5
Methyl Mercaptan		0.021	2
Naphthalene	0.25		5.0
Nitric Oxide			32
Nitrogen Dioxide			0.
Octane			235
Propylene	0.02		180
iso-Pentane	0.02		295
n-Pentane	0.02		295
Pentene-1			180
Pentene-2			180
Propane	0.02		180
n-Propyl Acetate			84
n-Propyl Alcohol	0.02		75
iso-Propyl Alcohol	0.02		98
n-Propyl Benzene			44
iso-Propyl Chloride			260
iso-Propyl Ether			120

Table 3.1 (Cont.)

Contaminant	Production Rates: Non-Biological (gm/day)	Production Rates: Biological (gm/man-day)	Maximum Allowable Concentration (mg/m^3)
Proprionaldehyde			30
Propionic Acid			15
Propyl Mercaptan		0.021	82
Propylene Aldehyde	0.002		10
Pyruvic Acid		0.377	0.9
Skatol		0.021	141
Styrene	0.002		42
Tetrachloroethylene	0.002		67
Tetrafluoroethylene	0.002		205
Tetrahydrofurane	0.002		59
Toluene	0.02		75
Trichloroethylene			52
1, 2, 4 Trimethyl Bezene	0.002		49
Valeric Acid		0.021	110
Vinyl Chloride	0.02		130
Vinyl Methyl Ether	0.002		60
Vinyldone Chloride	0.002		20
O-Xylene	0.02		44
m-Xylene	0.02		44
p-Xylene	0.02		44

Table 3.1 (Concluded)

Pertinent Chemical Synonyms
2-Butanone = Methyl Ethyl Ketone
Chlorodifluoromethane = Freon 22
Crotonaldehyde = Propylene Aldehyde
Decahydronaphthalene = Decalin
1, 2 Dichloroethane = Ethylene chloride = Ethylene Dichloride
Dichlorodifluoromethane = Freon 12
Dichlorofluoromethane = Freon 21
Dichlorotetrafluorethane = Freon 114
p-Dioxane = 1, 4 Dioxane
2-Methyl Butanone-3 = 3-Methyl 2 Butanone = Methyl Isopropyl Ketone
Methoxy Ethane = Vinyl Methyl Ether
Propene = Propylene
Propyne = Propine = Methyl Acetylene
Pentafluoroethane = Freon 125
Perchloroethylene = Tetrachloroethylene
Trichlorofluoromethane = Freon 11
Trichlorotrifluoroethane = Freon 113
Trifluoromethane = Fluoroform = Freon 23
1, 3, 5 Trimethyl benzene = Mesitylene

3.8 *Cabin Wall Temperature ($^\circ$F)

a. Wall inside temperature will be higher than the maximum dew point temperature for all pressurized compartments during all operational phases.

b. Inside surface temperature during reentry.

1.	Average	100
2.	Maximum	120

3.9 Cabin Potable Water Requirement

a. Bacterial and water sterility limits as defined in Table 3.2 Water Quality Specification, will be complied with. — See Table 3.2

3.10 Cabin Airborne Bacteria Requirements (microbes/ft^3) — 100

a. Airborne bacteria will be maintained below the level defined.

3.11 **Cabin Ventilation (fpm)

a.	Nominal design point	25
b.	Range	15 - 40

3.12 Cabin Acoustical Criteria (decibels)

a. Launch

1.	30 second maximum	125
2.	300 second maximum	115

b. Orbit

1. Work Area

a.	600 to 4800 cycles (maximum)	50
b.	4800 cycles (maximum)	75

*Crewmen/passengers shall not be exposed to direct contact temperatures greater than 105°F.

**Cabin ventilation rates apply to any free volume which the crewmen/passenger will inhabit while performing their daily duties.

TABLE 3.2

POTABLE WATER STANDARDS

Compound or Property	MSC-SPEC-SD-0020	Space Science Board
CHEMICAL (mg/l)		
Arsenic	—	0.50
Barium	—	2.00
Boron	—	5.00
Cadmium	0.01	0.05
Chloride	—	450.00
Chromium	0.05	0.05
Copper	1.0	3.00
Fluorine	—	2.00
Iron	0.3	Unobjectionable
Lead	0.05	0.20
Magnesium	—	—
Manganese	0.05	Unobjectionable
Mercury	0.005	—
Nitrate	—	10.00
Nickel	0.05	—
Selenium	0.05	0.05
Silver	0.05	0.50
Sulfate	—	250.00
Zinc	5.0	—
Alkyl Benzene Sufonates (ABS)	No Foam	No Foam
Chemical Oxygen Demand (COD)	100	100.00
PHYSICAL		
Turbidity (Jackson) Max.	11 units	10
Color (Pt-Co) Max.	15 units	15
Odor (TON)*	None at TON of 3	Unobjectionable
pH	6.0 - 8.0	—
Solids (ppm) ** Max.	500	1000
Taste	None at TON of 3	Unobjectionable
MICROBIOLOGICAL		
Coliform Test (MPN) ***	None	—
Total Count/ml	0	10

*Threshold Odor Number
**Parts per Million
***Most Probable Number

3.13 **Repressurization**

3.13.1 Air Lock (4/mission)

a.	Volume	250 ft^3
b.	Time (minutes)	
	1. Nominal	10
	2. Maximum	30
	3. Emergency (PO_2 from 0 - 3.1)	2

3.13.2 Main Cabin (1/mission)

a.	Volume	1000 ft^3
b.	Time (minutes)	60

3.13.3 Payload Compartment (1/mission)

a.	Volume	1500 ft^3
b.	Time (minutes)	60

3.14 **Waste Products**

a. Gases
   1. Gases unreclaimed by the onboard systems will be vented to space or utilized for spacecraft propulsion.

b. Solids
   1. Solid waste products will be stored onboard for return to earth.
   2. Microbiological and bacterialogically contaminated waste material will be disinfected as close as possible to its original source prior to storage, processing, or disposal.
   3. Microbiological and bacterial growth in organic waste products will be inhibited.
   4. Solid wastes will not be dumped to space.
   5. Waste generation rate (lb/man-day)

a.	Tissue wipes	0.11
b.	Food packaging	TBD
c.	Unused food	TBD
d.	Debris	0.09
e.	Facial and cranial hair	Negligible
f.	Vomitus	Occurs at infrequent intervals
g.	Others	TBD

3.15 Storage of Expendables

(Number of crewmen/passengers to be supported during a flight)

a. Nominal - Crewman/passenger total times nominal mission length.

b. Emergency - Crewman/passenger total times 2 days

3.16 Meteoroid Protection 0.99

3.17 EC/LSS Packaging

a. Functional packaging of the EC/LSS is desired within the vehicle.

b. Centralized packaging of the EC/LSS is desired.

c. Fluid lines will utilize a common entry and exit into and out of a package.

d. Electrical lines will utilize same general area for common entry and exit into and out of a package.

e. Redundant paths, such as fluid lines, electrical wiring, connectors, and explosive trains shall be located to insure that an event which damages one line is not likely to damage the other.

3.18 Heat Loads (excluding EC/LSS equipment)

3.18.1 On Orbit (Btu/hr)

a. Electrical air cooled	
1. Nominal	5000
2. Range	1130 - 10,000
b. Wall ambient	
1. Nominal	1700
2. Range	100 - 2400
c. Liquid cooled cold plates	
1. Nominal	17,500
2. Range	200 - 25,000
d. Fuel Cell	
1. Nominal (5.0 kW total)	23,000
2. Range	10,000 - 40,000

3.18.2	Reentry	TBD

3.19 Leakage

a.	Nominal (14.7 psia) (Main cabin)	3.5 lb/day
b.	Range	TBD
c.	Nominal (14.7 psia) (Payload Module)	5.0 lb/day

3.20 Redundancy

In addition to the normal reliability criteria, sufficient redundancy shall be provided to continue normal mission operation in the event of any single equipment failure, or to allow a safe abort in the event of any two equipment failures.

Sufficient redundancy shall also be provided to allow a safe abort in the event of a single failure of the following classes of equipment.

a. Structure

b. Pressure vessels

c. Lines and ducts, liquid or gas

d. Heat exchangers

e. Disconnects

3.21 Automatic Operation

Except for replacement of expendables, system operation will be completely automatic and "hands off". Automatic switchover of redundant equipment will be provided if the allowable equipment down-time is short and/or critical to system operation.

3.22 Ground Checkout

Insofar as practicable, ground checkout, including fault detection and isolation procedures, will be automatic. Manual operations will be held to an absolute minimum.

Sensors/transducers shall be included to support the automatic checkout requirement.

4.0 GENERAL SYSTEMS DATA

4.1 Water Usage

4.1.1 Crewman Wash Water

a. Quantity (lb/man-day)

1. Nominal design point	2.2
2. Range	1.5 - TBD

b. Delivered flow rate

1. Nominal design point (lb/hr.)	300
2. Range	90 - 105

4.1.2 Drinking

a. Quantity (lb/man-day)

1. Nominal design point	3.90
2. Range	1.04 - 9.69

b. Quantity stored and chilled (lb)

1. Nominal design point	TBD

c. Delivered flow rate (lb/hr)

1. Nominal design point	60

d. Temperature (°F)

1. Nominal design point (not to design temperature Control subsystem)	45
2. Range	40 - 50

4.1.3 Food Preparation

a. Hot

1. Quantity (lb/man-day)

a. Nominal design point	TBD

2. Stored quantity (lb)

a. Nominal design point	8

3. Temperature (°F)

a. Nominal Design Point	160
b. Range	155 - 165

b. Cold

1. Quantity (lb/man-day)

a. Nominal design point 1.0

2. Stored quantity (lb)

a. Nominal design point TBD

3. Temperature ($^\circ F$)

a. Nominal design point (not to design Temperature Control subsystem) 45

b. Range 40 - 50

4.1.4 Fecal Flush (If Used)

a. Quantity (lb/man-day) 3.3

b. Temperature ($^\circ F$)

1. Nominal design point 100

2. Range 90 - 105

4.1.5 Urine Flush

a. Quantity (lb/man-day) 2

b. Temperature ($^\circ F$)

1. Nominal design point 100

2. Range 90 - 105

4.2 <u>Heat Transport Fluid Circuits</u>

a. Nontoxic, nonflammable fluids should be used in pressurized areas.

APPENDIX B

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