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Spacecraft Life Support Systems

RATIONALE

The technical committee which originally created this document no longer exists. The documents provides good basic information on making calculations in spacecraft life support systems. This document is one of 14 documents that were part of the original SAE Applied Thermodynamics Manual, most of which have already been stabilized.

STABILIZED NOTICE

This document has been declared "Stabilized" by the SAE AC-9 Aircraft Environmental Systems Committee and will no longer be subjected to periodic reviews for currency. Users are responsible for verifying references and continued suitability of technical requirements. Newer technology may exist.

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PREFACE

This document is one of 14 Aerospace Information Reports (AIR) of the Third Edition of the SAE Aerospace Applied Thermodynamics Manual. The Manual provides a reference source for thermodynamics, aerodynamics, fluid dynamics, heat transfer, and properties of materials for the aerospace industry. Procedures and equations commonly used for aerospace applications of these technologies are included.

In the Third Edition, no attempt has been made to update material from the Second Edition nor were SI units added. However, all identified errata were corrected and incorporated and original figure numbering was retained for the first ten sections.

The SAE AC-9B Subcommittee originally created the SAE Aerospace Applied Thermodynamics Manual and, for the Third Edition, used a new format consisting of AIR1168/1 through AIR1168/10. AIR1168/11 through AIR1168/14 were created by the SAE SC-9 Committee.

The AIRs comprising the Third Edition are shown below. Applicable sections of the Second Edition are shown parenthetically in the third column.

AIR1168/1	Thermodynamics of Incompressible and Compressible Fluid Flow	(1A,1B)
AIR1168/2	Heat and Mass Transfer and Air-Water Mixtures	(1C,1D,1E)
AIR1168/3	Aerothermodynamic Systems Engineering and Design	(3A,3B,3C,3D)
AIR1168/4	Ice, Rain, Fog, and Frost Protection	(3F)

AIR1168/5	Aerothermodynamic Test Instrumentation and Measurement	(3G)
AIR1168/6	Characteristics of Equipment Components, Equipment Cooling System Design, and Temperature Control System Design	(3H,3J,3K)
AIR1168/7	Aerospace Pressurization System Design	(3E)
AIR1168/8	Aircraft Fuel Weight Penalty Due to Air Conditioning	(3I)
AIR1168/9	Thermophysical Properties of the Natural Environment, Gases, Liquids, and Solids	(2A,2B,2C,2D)
AIR1168/10	Thermophysical Characteristics of Working Fluids and Heat Transfer Fluids	(2E,2F)
AIR1168/11	Spacecraft Boost and Entry Heat Transfer	(4A,4B)
AIR1168/12	Spacecraft Thermal Balance	(4C)
AIR1168/13	Spacecraft Equipment Environmental Control	(4D)
AIR1168/14	Spacecraft Life Support Systems	(4E)

F.R. Weiner, formerly of Rockwell International and past chairman of the SAE AC-9B Subcommittee, is commended for his dedication and effort in preparing the errata lists that were used in creating the Third Edition.

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1. INTRODUCTION

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SECTION 14 - SPACECRAFT LIFE SUPPORT SYSTEMS

1. INTRODUCTION

In the years since manned space flight began, some of the new developments have been successfully demonstrated on only a few actual flights. Much has been written about man's new environment in space and the technology required to support him safely. In this AIR much of this technology will be discussed and summarized, although the scope here is restricted to the then current state of the art (circa 1965) in order to concentrate on fundamentals and at the same time avoid the more advanced concepts that have yet to be proved.

An attempt has been made to avoid, as much as possible, reference to the Mercury, Gemini, and Apollo systems, since much has been included in the literature about these specific designs. Rather, the attempt has been to describe objectively and discuss the fundamental variations that were used in their design conception so as to permit the most valid extrapolation to future spacecraft.

1.1 Scope

A life support system (LSS) is usually defined as a system that provides elements necessary for maintaining human life and health in the state required for performing a prescribed mission. The LSS, depending upon specific design requirements, will provide pressure, temperature, and composition of local atmosphere, food, and water. It may or may not collect, dispose, or reprocess wastes such as carbon dioxide, water vapor, urine, and feces.

It can be seen from the preceding definition that LSS requirements may differ widely, depending on the mission specified, such as operation in Earth orbit or lunar mission. In all cases the time of operation is an important design factor. An LSS is sometimes briefly defined as a system providing atmospheric control and water, waste, and thermal management.

The major subsystems required to accomplish the general functions mentioned above are:

1. Breathing and pressurization gas storage system.
2. Temperature and humidity control system.
3. Carbon dioxide control system.
4. Trace contaminant control system.
5. Water management system.
6. Waste management system.

1.2 Nomenclature

c_p = Specific heat capacity, constant pressure, Btu / lb-°F
D = Diameter, ft, in.
$E.T.$ = Effective temperature, °F
g = Gravitational acceleration, ft / sec^2
h = Enthalpy, Btu / lb
L = Length, ft, in.
M_g = Molecular weight, lb / mol
Δp_d = Pressure differential, lb / ft^2
p = Pressure, psia, mm H_g
P_{amb} = Ambient pressure, psia
P_c = Cabin pressure, psia
Pm = Promethium
Po = Polonium
P_{02} = Oxygen partial pressure, mm H_g
P_t = Total atmospheric pressure, mm H_g
Q = Energy, Btu / sec-ft^3
q_s = Body heat storage rate, Btu / ft^2-°R
R = Ratio of end cap thickness to cylinder annulus thickness, dimensionless
S = Entropy, Btu / °F
SA = Surface Area, ft^2
Sr = Strontium
t = Temperature, °F
t_{cr} = Critical temperature, °F
t_r = Rectal temperature, °F
t_{sk} = Skin temperature, °F
T = Temperature, °R
v_{gas} = Gas velocity, ft / min
W = Body mass, lb
w_g = Weight flow of gas (air), lb / man-day
$\overline{w}_{H_2 0}$ = Weight flow of water, lb / man-day
Y = Mole fraction, dimensionless
η_{SEP} = Efficiency of water separator, dimensionless
μ = Absolute viscosity, lb / sec-ft, lb / hr-ft
ρ = Mass density, lb-sec^2 / ft^4
ρg = Specific weight (density), lb /ft^3
τ = Relative burning time, dimensionless
ψ = Relative power penalty parameter (fluid heat flow transport parameter), dimensionless
ψ = Power penalty parameter defined by Eqs. 14-3 and 14-4, dimensional

Subscripts

g = Gas
l = Laminar
t = Turbulent
1 = Inlet
2 = Outlet

1.3 Common Abbreviations

AC — Alternating current
AFOSR — Air Force Office of Scientific Research
AIAA — American Institute of Aeronautics and Astronautics
Air Force — United States Air Force
amb — Ambient, or local (surrounding) conditions
AMRL — Aerospace Medical Research Laboratories (USAF)
anti-g — Capable of support (restraint) under high acceleration (anti-gravity)
approx — Approximate
ARS — American Rocket Society
ASD — Aeronautical Systems Division (USAF)
ASHRAE — American Society of Heating, Refrigeration, and Air Conditioning Engineers
ASME — American Society of Mechanical Engineers
ASTIA — Armed Services Technical Information Agency (now Defense Documentation Center)
atm — Atmosphere
av — Average
Btu (BTU) — British Thermal Units
°C — Degrees Centigrade
cap. — Capacity
cat — Catalytic
cc — Cubic centimeters
cfm — Cubic feet per minute
clean room — Room with controlled air cleanliness and environment
Co. — Company
Conc. — Concentration
contam. — Contamination
Dacron — Trade name for woven synthetic produced by Dupont
DC-200, DC-550 — Trade names for heat transport fluids produced by Dow Corning Co.
DC — Direct current
deg — Degree

Dowtherm A Dowtherm E	—	Trade names for heat transport fluids produced by Dow Chemical Co.
ed.	—	Editor
ELF	—	Electrolysis cell / fuel cell system
E. T.	—	Effective temperature, °F
et al	—	And others
etc.	—	And so on
°F	—	Degrees Fahrenheit
FC-75	—	Trade name for fluorinated hydrocarbon heat transport fluid produced by Minnesota Mining and Manufacturing Co. (3M)
Fig. (Figs.)	—	Figure(s)
fpm (FPM)	—	Feet per minute
fps	—	Feet per second
Freon 21	—	Trade name for Refrigerant 21 produced by Dupont
ft (FT)	—	Feet
GARD	—	General American Research Division (GATC)
GATC	—	General American Transportation Association
g	—	Gravity
gm	—	Gram
Hg	—	Mercury
hr (HR)	—	Hour
in. (IN.)	—	Inch
kcal	—	Kilocalorie
kg	—	Kilogram
kW	—	Kilowatt
lam	—	Laminar
lb (LB)	—	Pound
LSS	—	Life support system
m	—	Meter
Max	—	Maximum
mg	—	Milligram
min (MIN)	—	Minute
ml	—	Milliliter
mm (MM)	—	Millimeter
mol	—	Mole
mol.	—	Molecular
Mol. Wt.	—	Molecular weight
mrem	—	Millirem
NASA	—	National Aeronautics and Space Administration
No.	—	Number
p. (pp.)	—	Page(s)

Par.	—	Paragraph
perm	—	Permeation
pH	—	A measure of the acidity of an aqueous solution
ppm	—	Parts per million
PRESS	—	Pressure
psi	—	Pounds per square inch
psia (PSIA)	—	Pounds per square inch absolute
psig	—	Pounds per square inch gage
P4SR	—	Predicted four-hour sweat rate
Ref. (Refs.)	—	Reference(s)
REG	—	Regulator
RH	—	Right hand
RH	—	Relative humidity
°R	—	Degrees Rankine
S.A.	—	Surface area
SAM	—	School of Aerospace Medicine (USAF)
sea level	—	760 mm Hg
sec (SEC)	—	Second
TEMP	—	Temperature
Trans.	—	Transactions
TR	—	Technical Report
turb	—	Turbulent
USAF	—	United States Air Force
UV	—	Ultraviolet
U-238	—	Uranium 238
V	—	Volts
Vol.	—	Volume
W	—	Watts
WADD	—	Wright Aeronautical Development Division (USAF)
WADD TR	—	Wright Aeronautical Development Division Technical Report
Wt. (WT)	—	Weight
zero-g	—	Zero Gravitational acceleration (zero gravity)
%	—	Percent
α	—	Alpha
μ	—	Micron (10^{-6} meters)

2. DESIGN CRITERIA

Under the general heading of design criteria for a spacecraft LSS, many things must be considered during the preliminary design phase: the various spacecraft restraints, mission parameters, reliability and mission safety requirements, and of course the physiological and psychological requirements of man himself.

In this AIR it is impossible to treat with any degree of completeness the spacecraft restraints or mission parameters. Similarly, a detailed treatment of reliability concepts cannot be included. A few general items involved in some of these considerations are applicable, however, and include weight, power requirements, volume, reliability, development status, interfaces, and physiological requirements. For any given application it will be necessary to consider all these criteria, since no single one can be assumed to control the selection of the optimum system, nor is any criterion independent of another.

2.1 Weight

Weight includes the weights of fixed equipment, ducts and connecting fixtures, all supplies (such as activated charcoal) necessary to the operation of the system, and related control mechanisms and instrumentation. In addition, the power requirement is often considered in terms of the weight required for the power sources.

2.2 Power Requirements

Power requirements include mechanical or pneumatic power for circulation of the atmosphere, heat power for use in a catalytic burner, mechanical or pneumatic power for the water separator, and pneumatic or electric power for operation of control elements and instrumentation. Mechanical power may come from electric motors, and heat power may come from electrical resistance elements; that is, the entire power supply may be electrical. Pneumatic power is customary in capsule pressure controls and pressure relief valves.

The preferred type of power will depend upon the design of the equipment and on the relative availability of the different types. For continuously rotating devices such as compressors, electric power may be better than pneumatic, while for periodically actuated devices such as control valves, pneumatic power may have distinct advantages.

Both the maximum rate at which power will be used and the average rate must be considered. The penalty imposed by any power source will be a combination of the influences of the maximum rate and the average rate of power utilization.

2.3 Volume

The volume of an atmospheric control system is relatively difficult to determine at an early stage of a program because a substantial percentage of the total volume is necessarily devoted to ducts and fittings, the actual sizes of which are dependent upon the layout or arrangement of components. The total volume includes:

1. Core volume or volume of heat exchanger element, or volume of a reacting substance such as lithium hydroxide.

2. Volume of the supports for the core.
3. Volume of the pans and manifolds.
4. Volume of associated or integral ducts.
5. Volume of auxiliary items, spare parts, tools, and replacement chemicals such as lithium hydroxide.
6. Volume of space clearance necessary for access to equipment and for repairs, on the ground or in flight.

It is essential that a layout (or, better, a mockup) be used to arrange system components for minimum volume.

2.4 Reliability

LSS studies must include realistic considerations of reliability, serviceability, and life for each component and subsystem. Component reliability must be emphasized in design together with failure modes and effects analyses, which must be used to establish redundancy and spares concepts for the systems in the comparison and selection stages.

Existing LSS designs should be examined for suitability. Wherever adequate reliability margin is not evident, the equipment designer must analyze new designs that offer the greatest promise of improvements required to meet the mission requirements.

The relative reliability of components is important to the various system and subsystem designs that are to be analyzed and compared. Mean time between failure values of most components are presently known with reasonable confidence. Besides ensuring that the weakest reliability links are adequate, the standard practice of redundancy for all weak links must be judiciously followed.

In particular, all continuously rotating equipment essential for either mission completion or crew safety must be redundant. In addition, certain spares should be recommended wherever a weight or volume advantage might thus result and where this is physically feasible. The reliability analysis should include reliability logic diagrams for each subsystem, to show the applicable failure rate anticipated and to complement the failure modes and effects analysis.

2.5 Development Status

The development status of each component and subsystem should be determined to provide an evaluation as to the probability that the total system can be developed within the known limitations of time and budget. For example, the design of some components such as heat exchangers and ducts is so well advanced that they may be assumed to perform as required, with little or no development.

On the other hand, a regenerative chemical system for space application will require extensive development, together with some risk that it will not be possible to reach the goals at the desired time. A closely related problem is the adaptability of the system to different mission profiles, a requirement which is becoming essential.

2.6 Interfaces

There are numerous interfaces between the atmospheric control system and the other vehicle systems. All must be taken into consideration in arriving at conclusions relative to the advantages and disadvantages of competing systems. These include:

1. Thermal loads to and from other vehicle systems, including vehicle structure.
2. Power requirements, including quality, type, amount, and variation of rate.
3. Supplies of oxygen, nitrogen, and any other gases required. This is especially important when the gases are stored remotely or depend upon another process, such as fuel cells. Each gas should be separately considered. Also, the energy connected with the storage and delivery of the gas must be taken into account.
4. Metabolic inputs from occupants, carbon dioxide, water vapor, odors, and similar contaminants.
5. Water from water separator and water to evaporators in the atmosphere control circuit.
6. Chemical process supplies such as lithium hydroxide, molecular sieves, activated charcoal, and catalysts.
7. Vibration and shock loads, including those generated within the system and those received from outside.
8. Noise generated by operation of the system.
9. Control linkages for operation of the life support system itself.
10. Space and relative location requirements within the vehicle. The resolution of this item usually requires the use of mockups and trade-off studies with other spacecraft systems.
11. The ground checkout system.
12. On-board display instrumentation.

13. Instrumentation providing information to be telemetered.

14. Provision for supplying an atmosphere for use in a portable backpack to provide atmospheric control for a pressure suit used for extravehicular operation.

15. Provision for use of an airlock to enable occupants in pressure suits to leave and reenter the space vehicle.

16. Detection of malfunctions within the system and the transmission of the information to the astronauts.

17. Interaction with operator; manual control required; extent and scheduling of operator's time; special skills required, if any.

2.7 Physiological Requirements

Table 14-1 presents the physiological requirements that are generally in current use. These values will usually be made more precise for a specific mission; however, the range of values shown is sufficiently accurate to support preliminary investigations.

3. ATMOSPHERE CONTROL

In space flight or atmospheric flight, man must be maintained in a comfortable environment if he is to work at his best. This does not necessarily mean that it is essential to duplicate exactly man's terrestrial environment in space, for it is evident that man can adapt

Table 14-1 - Physiological Requirements

Requirement	Value
Total Pressure, psia	3.5-7.0
Oxygen Partial Pressure, psia	3.5–5.0
Atmosphere Diluent (if any)	Nitrogen
Carbon Dioxide Partial Pressure, Nominal, mm Hg	4–7.6
Temperature,°F(nominal)	75
Relative Humidity, %	40-60
Oxygen Consumption (av), lb/day	1.9
Carbon Dioxide Production (av), lb/day	2.2
Respiration and Perspiration Water Output (av), lb/day	2.4
Metabolic Heat Load (Unpressurized Suit), Btu/hr	350-600
Metabolic Heat Load (Pressurized Suit), Btu/hr	1000-2000

satisfactorily to a fairly wide range of environmental conditions without detectable degradation in performance.

The conventional ASHRAE comfort criteria involving ambient air temperatures and humidities may not be applicable to space systems because of the entirely different relationships among the various heat transfer processes that may be obtained in manned spacecraft as compared with a terrestrial environment. Since it is not possible at the present time to adopt the statistical empirical methods employed by ASHRAE to determine comfort zone conditions, it will be necessary to establish the design criteria in terms of thermal and pressure adequacy. Heat transfer models may be used to determine the heat removal rates for particular conditions, and the available physiological data must be used to determine the required pressure.

Man normally dissipates waste heat by a combination of heat transfer processes, including natural convection, forced convection, radiation, and evaporation of moisture. The energy balance for the body is given by

$$Q_{metabolic} = Q_{work} + Q_{latent} + Q_{sensible} + Q_{stored} \tag{14-1}$$

Any deficit in body cooling is accompanied by heat storage, an undesirable condition that can be tolerated for only a limited time. Although heat storage in amounts up to approximately 600 Btu can be tolerated before physical collapse occurs, it should be assumed intolerable as a design condition for normal operation. That is, the condition for thermal adequacy requires zero heat storage under design operating conditions.

It is reasonable, however, to allow a certain amount of heat storage (up to 275 Btu) for short duration emergencies, as long as the cooling deficit rate does not exceed 15 Btu / min. Figs. 14-1, 14-2 and 14-3 show available data on comfort and heat storage permissible.

In Ref. 23, from which these illustrations are taken, supplementary information relative to the figures is as follows: For Fig. 14-1:

> "Human thermal comfort is defined by air temperature and humidity in the area enclosed by the heavy solid line. Note the stipulations of normal street clothing, seated resting individuals, and minimal air movement. An increase in air velocity to 200 fpm, which is a common level in high performance aircraft, extends the comfort zone into higher temperatures as shown. If impermeable clothing is worn, comfort (indefinite tolerance) for seated men moves toward the cold side. Partial coverage with rubberized cloth, as found in anti-g suits and partial pressure suits, calls for drier, cooler conditions as shown in the cross-hatched area. Complete coverage with impermeable material, as found in anti-exposure suits and full pressure suits, calls for

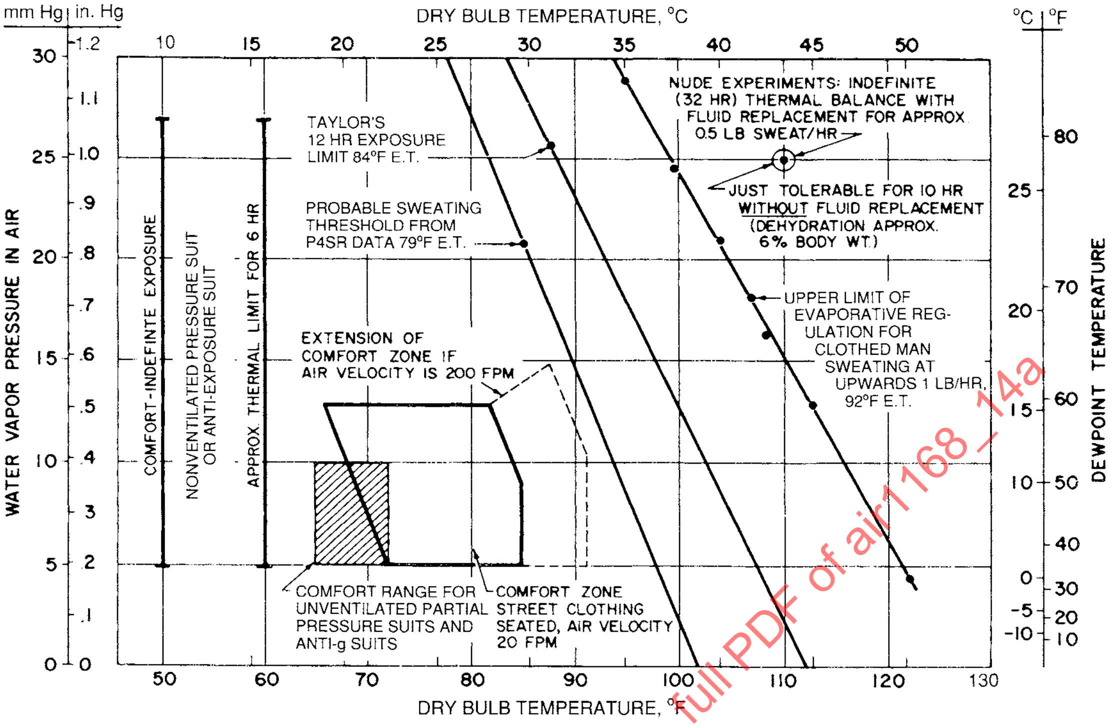

Figure 14-1 - Thermal comfort zone (Ref. 23)

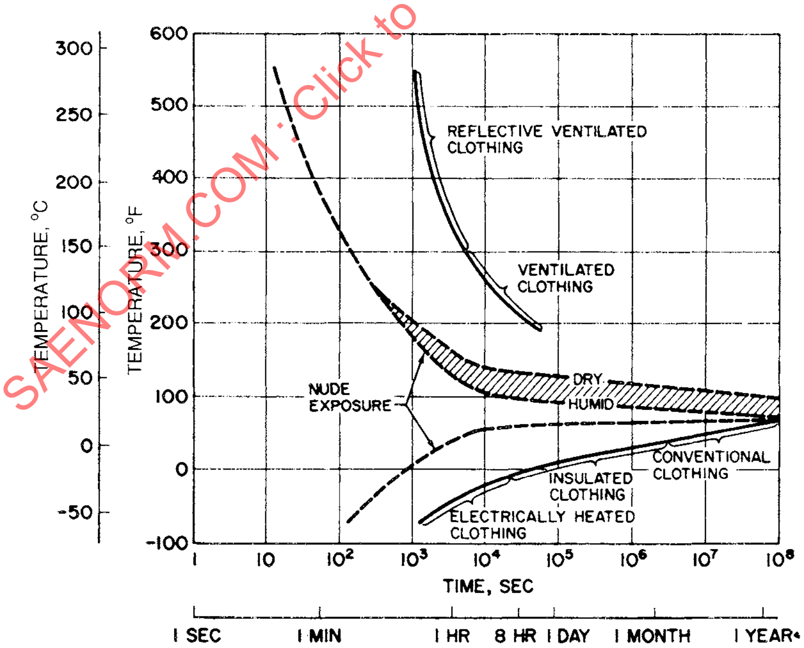

Figure 14-2 - Range of temperature experience (Ref. 23)

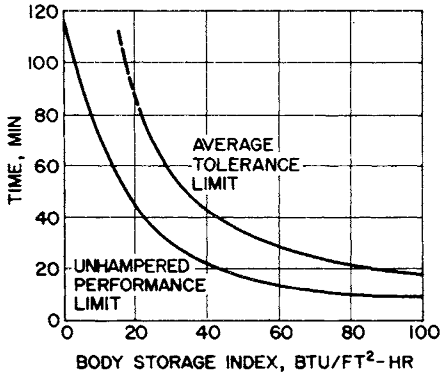

Figure 14-3 - Thermal tolerance limits (Ref. 23)

cooler temperatures, but no special humidity, since evaporation cannot take place. Activity in such assemblies produces critical thermal loading, solved only by forced clothing ventilation to permit removal of water vapor.

"Several reference points are shown for warm conditions above the comfort zone, again for normally clothed resting men, where air velocity is low. The sweating threshold falls at about the line labeled 79°F E.T., as derived from a prediction method called the Predicted Four-Hour Sweat Rate (P4SR). Exposures up to 12 hours can be tolerated, but with the cost of physiological adaptation, up to 84°F E.T. Thermal balance (at a higher-than-normal body temperature) can be maintained for hours up to the line shown fitting solid dot data points, and corresponding to about 92°F E.T. Finally, a set of experiments is shown with nude men at rest at 110°F and 25 mm Hg vapor pressure, wherein those who had fluid replacement maintained thermal balance for 32 hours, and those deprived of fluid became severely dehydrated and lost thermal control in 10 hours."

From the same source, for Fig. 14-2:

"Experimentally determined range of human thermal tolerance are shown for resting men without protection, and also protected with the best clothing for each zone of heat or cold. The environments used in establishing the curves were all characterized by low air movement (less than 100 fpm) and approximately equal air and wall temperatures. Tolerance limits for nude subjects are: surface pain above 250°F; body heat storage from 140°F – 250°F; fatigue and dehydration from 100°F – 140°F; fatigue, shivering and general body cooling, with increasing discomfort from 65°F – 0°F; and cold pain and increasing danger of frostbite below 0°F. The improvement in thermal tolerance times caused by properly chosen clothing is depicted by the two solid curves, one in the hot zone and one in the cold zone."

Ref. 23 also supplements Fig. 14-3 as follows:

> “Tolerance limits are shown which define impairment in performance and the physiological endpoint for severe heat exposures which produce storage of body heat. Body storage rate (q_s) is computed from the change in average skin temperature (t_{sk}), rectal temperature (t_r), and the body mass (W), surface area (S.A.), and specific heat (=0.83) according to the formula
>
> $$q_s = 0.83\frac{W}{\text{S.A.}} \times \frac{0.33\Delta t_{sk} + 0.67\Delta t_r}{\text{hr}} \tag{14-2}$$
>
> English units (lb, ft^2, °F) give the answer in Btu / ft^2-hr, and metric units (kg, m^2, °C) give the answer in kcal / m^2-hr. Storage of heat occurs in those severe exposures (usually above 120°F) where the body’s physiological mechanisms are unable to compensate for the heat load and metabolic heat. The tolerance limit in storage is reached when approximately 80 kcal / m^2-hr has been stored, and the subject is on the verge of clinical heat stroke. (Adapted from Blockley *et al.*, WADD TR 53-346, 1953).”

A second design criterion, for which it is more difficult to establish limits, involves the sweat rates at given environment and specified activity levels. Because of the impairment or reduction in certain of the important heat transfer processes, it appears that high latent heat loads will result in both pressure suit and shirtsleeve environments, where ventilating cooling serves as the primary cooling method.

It is known that the sweat mechanism apparently undergoes fatigue after 4 or 5 hr at the high latent heat load requirement. Thus, even with ventilation cooling, the body will start storing heat. The recovery period for restoration of normal function and replenishment of water lost from the body fluids is relatively long. These factors pose significant difficulties, particularly when combined with the other physiological and psychological stresses imposed by the space environment and mission. For example, the reduced work capacity anticipated after exposure to weightlessness may accelerate the onset of these deleterious effects. Therefore it appears highly desirable to reduce sweat rates to a minimum level, although it will probably not be practical to eliminate all sensible perspiration at high metabolic rates.

3.1 Atmosphere Pressure and Composition

Currently, almost all United States manned spacecraft programs employ the same atmospheric pressure and composition, which is 5.0 psia with pure oxygen. Emergency operation in the pressure suit is at the reduced pressure of 3.7 psia. Russian spacecraft, on the other hand, have used an oxygen and nitrogen mixture at sea level pressure.

There are advantages and disadvantages to both concepts. A brief summary of the various considerations is given below:

1. Alveolar Pressure - It is desirable to maintain the alveolar oxygen pressure at normal values of approximately 100 mm Hg at all times, including emergency. This requires a varying amount of oxygen pressure above 100 mm Hg, depending on the diluents and contaminants such as nitrogen, water vapor, or carbon dioxide. This is shown by Fig. 14-4, where the oxygen limits are also shown.

2. Atelectasis, or Lung Collapse - The application of high *g* forces or bronchial restrictions tends to promote atelectasis, whereas the presence of nitrogen tends to prevent it.

3. Aeroembolism - This is caused by the formation of expanding gas bubbles in the body tissues during rapid decompression. These bubbles are almost entirely the result of the diluent nitrogen, since the oxygen is held chemically bonded to the blood constituents. The probability of aeroembolism increases with the concentration of nitrogen.

4. Weight - Various factors affect weight. As the total pressure of the cabin is increased the cabin leakage is increased proportionately. Also, the structural weight is increased as the cabin pressure is increased above a nominal 6 or 7 psia. It is possible, however,

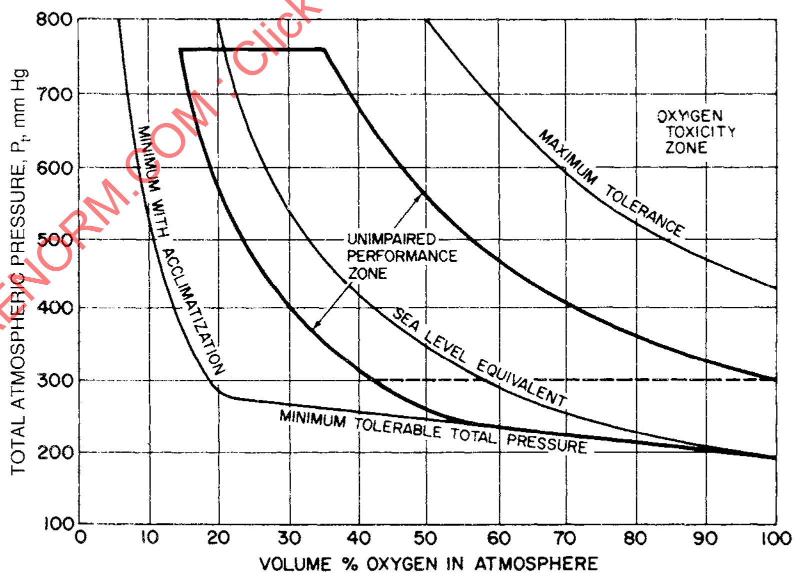

Figure 14-4 - Physiological performance chart, oxygen pressure effects; sea level = 760 mm Hg that the cabin air pumping power could be decreased by the increased cabin pressure if the flow requirements were set by minimum volume flow circulation rates.

5. Fire Hazard - The relative fire hazard is a strong function of the oxygen concentration. It has been shown that the burning rate in a 5.0 psia pure oxygen atmosphere is greater than for a 7.0 psia mixture of oxygen and nitrogen. Figs. 14-5 and 14-6 show the effect of oxygen partial pressure on the burning rate for two series of tests, from Ref. 15.

6. Operational Complexity - Although the controls for a mixed gas atmosphere are not particularly complex, there are additional operational problems introduced by its use,

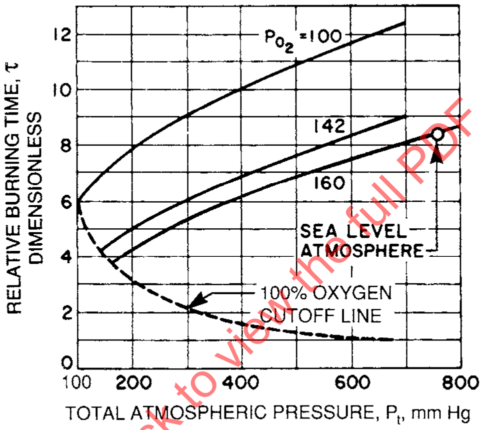

Figure 14-5 - Effect of oxygen partial pressure on relative burning time; P_{O_2} in mm Hg (Ref. 15)

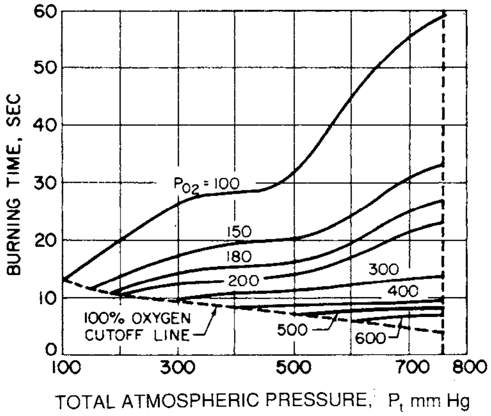

Figure 14-6 - Effect of oxygen partial pressure on burning time; P_{O_2} in mm Hg; (Ref. 15)

since a two-gas system must also have a single-gas capability for emergency conditions. This also requires a capability for reduction in the total pressure.

From the preceding considerations, it is apparent that both medical and nonmedical factors affect the choice of atmospheric content. Sufficient data exist to justify the 5 psia pure oxygen for the present missions, but insufficient data exist for longer missions. It is expected, however, that new and more complete data presently being obtained by intensive study and testing will aid materially in the final optimization of the selection of spacecraft atmosphere.

3.2 Thermal Control

Three simple thermal control systems are shown in Fig. 14-7. In the expendable evaporant system the heat to be rejected is used to change a fluid from a liquid to a vapor, which is then vented overboard. This system utilizes to advantage the latent heat of vaporization of the liquid (usually water).

In the cryogenic fluid system the heat load is released through the heat exchanger to a stored cryogenic fluid. The heated fluid is either vented overboard (if it is an expendable) or directed to other on-board systems for further use.

The third basic cooling system shown in Fig. 14-7 is the radiator system, in which the heat load to be rejected is transported to a radiating surface, that takes advantage of the heat sink characteristics of space.

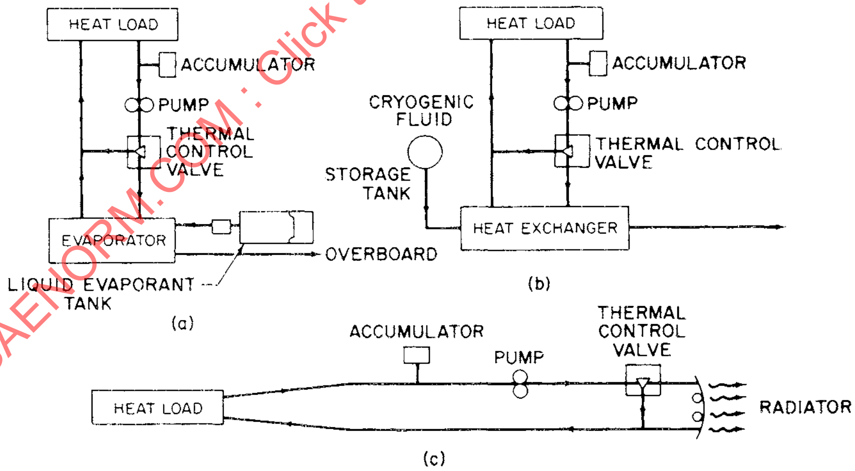

Figure 14-7 - Typical cooling systems; (a) expendable evaporant, (b) cryogenic fluid, (c) radiator

In determining which of these three systems is most suitable for any given application, the duration of the expected space mission is of prime importance. Both the evaporating system and the cryogenic fluid utilize an expendable cooling source and therefore have a large time penalty. The heat sink characteristics of space in reasonable proximity to a planetary body are such that the heat loss by radiation is small. Consequently the radiator weight is large in comparison with that of the components of an expendable system. Time is therefore a most important factor in determining which system should be utilized for any given design.

3.2.1 Shirtsleeve Considerations

Figs. 14-8 and 14-9 illustrate the use of simple heat transfer models to show the effects of certain basic environmental design parameters on heat rejection from the body by radiation and by forced convection. The radiative heat loss (Fig. 14-8) assumes a body surface area of 19.5 ft^2, 80% of which is effective for radiation with a thermal emissivity of 0.94.

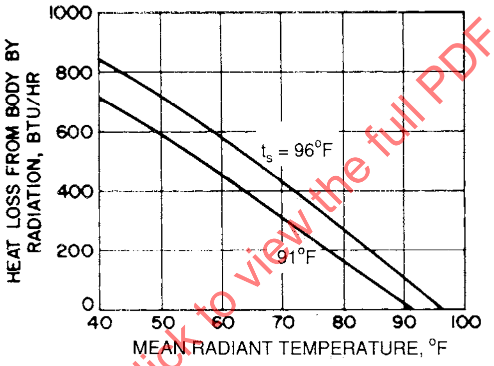

Figure 14-8 - Estimated radiant heat loss from body; effective body area = 15.6 ft^2, thermal emissivity = 0.94

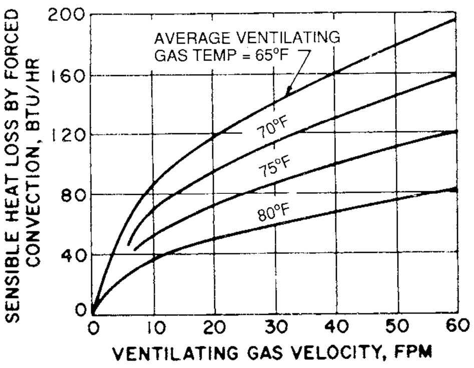

Figure 14-9 - Estimated convective heat loss from body; average t_{sk} = 91°F, P_{amb} = 7.35 psia

The convective heat loss (Fig. 14-9) assumes the ventilating gas flow normal to a cylinder with a surface area of 19.5 ft^2 and a height of 5.8 ft. Ventilating gas velocities greater than approximately 40 fpm are generally held unacceptable for long duration exposures because the body has a sensation of uncomfortable drafts at high gas velocities.

The criteria may not be applicable under conditions of high work rates or of thermal inadequacy, since limiting gas velocities will be imposed by the penalty of providing the ventilating power and the gas distribution. It will usually be difficult to provide average gas velocities in space cabins much in excess of 10 fpm without excessive power penalties and heat exchanger installation problems.

It can be seen from Fig. 14-9 that the sensible heat loss from the body by forced convection will be on the order of 100 Btu / hr for a ventilating gas velocity of 40 fpm and the usual design cabin average temperature of 75°F. Assuming a mean radiant sink temperature of 75°F, the radiant heat loss from the body will amount to approximately 230 Btu / hr for an average skin temperature of 91°F (Fig. 14-8). For an environmental temperature of 75°F, the total sensible heat loss from the body is then 330 Btu / hr, which suggests that high sweat rates may occur in shirtsleeve environments for high work rates.

Fig. 14-10 shows the total sensible heat loss from the body as a function of environmental temperature for the shirtsleeve environment. The minimum latent heat load, represented by the insensible perspiration from the body, though varying with metabolic rate, will be greater than 100 Btu / hr. It is apparent in Fig. 14-10 that cabin areas characterized by high work rates should be designed for low environmental temperatures, in order to minimize sweat rates.

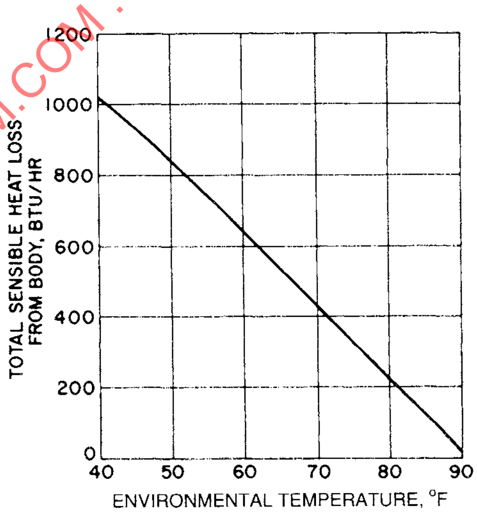

Figure 14-10 - Total sensible heat loss from body for shirtsleeve environment; $t_{sk} = 91°F$, $v_{gas} = 40$ fpm

Conversely, rest and recreation areas and other sedentary activity level areas should be designed for higher environmental temperatures for comfort.

3.2.2 Pressure Suit Considerations

The highest metabolic rates will be obtained in pressurized suits because of the increase in metabolic rate resulting from restricted mobility in the pressurized suit. This may represent a 100% increase in energy expenditure over that required for performance of the same task in an unpressurized suit or in a shirtsleeve environment. Present space suits represent an extension of aircraft full-pressure suits in which the pilot is restricted in motion and limited to more or less sedentary activity levels, with suit ventilation providing adequate cooling.

However, in future extravehicular suits, greater mobility will be required, since man will perform fairly extensive physical tasks such as walking on the lunar surface. It is reasonable to expect that this will require design to permit continuous activity at high metabolic rates.

Suit ventilation performance is frequently given in terms of "suit efficiency," which relates the actual moisture pickup to that theoretically possible for the given suit inlet and outlet conditions. Fig. 14-11 relates the suit efficiency and outlet relative humidity with the suit outlet dewpoint temperature, which is a somewhat more basic parameter because it does not involve use of an arbitrary reference.

Ventilating efficiency will vary somewhat with suit design, particularly with regard to internal flow distribution; that is, not all ventilating flow passes over the same body area before returning to the suit outlet. A commonly specified suit outlet relative humidity of 70% corresponds to a suit efficiency of 60% and suit outlet dewpoint temperature of 79.5°F.

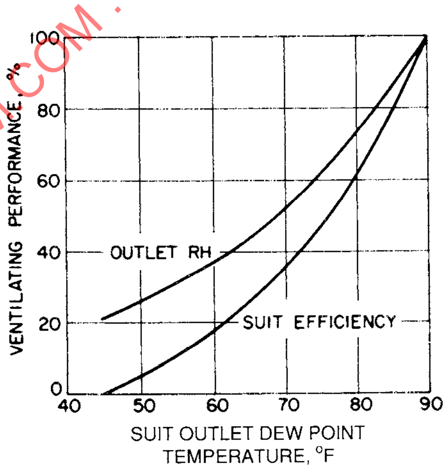

Figure 14-11 - Suit efficiency and outlet gas relative humidity versus outlet dewpoint for 45°F saturated inlet gas and 90°F outlet dry bulb temperature; suit pressure = 3.5 psia O_2

Fig. 14-12 shows the cooling capacity of the ventilating gas as a function of suit outlet dewpoint temperature, assuming an outlet dry bulb temperature of 90°F and an inlet dry bulb temperature of 45°F. It will be noted that, with the dry inlet condition, the cooling capacity of the ventilating gas is increased significantly.

In recirculating systems using water vapor removal by condensation, it will usually be impractical to provide ventilating gas inlet dewpoint temperatures below about 45°F. Where desiccants are used for humidity control, very low dewpoints can be readily obtained.

The gas obtained from cryogenic or gaseous storage containers will ordinarily have a very low moisture content, so that the vent flow in an open cycle system will provide a substantial cooling capacity in the form of the moisture being dumped overboard.

3.2.3 Heat Sink Selection

In addition to the three basic forms of heat sink mentioned above, it is also possible to utilize the thermal mass of the vehicle itself or to utilize the latent heat of fusion of a suitable material as a heat sink. In the first situation, advantage is taken of the thermal capacity characteristics of the vehicle structure material. Thus, an aluminum structure able to stand 50°F temperature rise is capable of absorbing 33 Btu / lb of structure.

In the second situation, heat is released to a solid which melts at a moderate temperature. The amount of heat accepted would depend upon the amount of solid present as well as the heat of fusion of the particular material. A distinct advantage of this type of heat sink is that at a later time the liquid may be cooled (solidified) and then be ready for re-use as desired.

The heat sink trade-offs of the foregoing systems are summarized in Fig. 14-13. This figure shows the thermal dissipation capacity as a function of the mission duration of the various

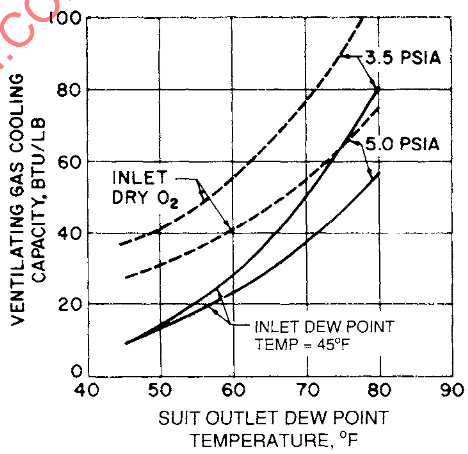

Figure 14-12 - Cooling capacity of suit ventilating gas, assuming 90°F outlet dry bulb temperature and 45°F inlet dry bulb temperature

systems. In obtaining the trade-off curve between passive radiator systems and active radiator systems that utilize solar cells as the power source, current optimistic data for solar cell performance were utilized. These data indicated that the value of 9 *W*/ lb of solar cell could be obtained and that these cells would degrade to approximately 75% of this value in a period of 6 months. The data, available from current space vehicles, also indicate that no further degradation occurs.

The curve shown in Fig. 14-13 assumes that 6.75 *W*/ lb (0.75 x 9 *W*/ lb) is obtainable from the solar cells throughout the entire time period shown.

3.2.4 Thermal Transfer

Thermal transfer can be accomplished by any of the three basic heat transfer processes: convection, conduction, and radiation. The thermal control system for any space vehicle may utilize all or any one of these processes. Conduction, while an inherently reliable form of heat transfer, is not particularly attractive for space vehicle applications except in very localized areas.

Radiation heat transfer coefficients are very low when compared with those obtainable by convection or conduction, and while useful in ultimately rejecting heat to space, do not form an attractive means of transporting heat within the vehicle. A forced convection fluid transport loop is therefore the most attractive means of transferring heat from one place to another within the vehicle.

A space radiator provides a very attractive means of rejecting to space itself the heat generated in the space vehicle. The determination of the effective space sink temperature constitutes only a small part of the problem of space radiator design. The actual evaluation of unit

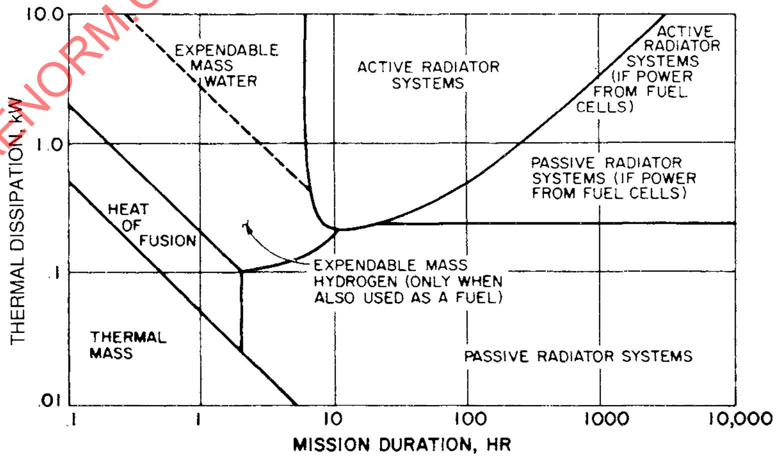

Figure 14-13 - Heat sink selection (summary) temperatures requires knowledge of vehicle location with respect to the Earth, Moon, and Sun and of the radiation characteristics of these bodies and the vehicle itself.

With the selection of a forced convection fluid transport loop, it is necessary not only to design minimum weight heat transfer components but also to select the fluid most suitable for the particular application. Figs. 14-14 and 14-15 show the plots of a relative power penalty parameter ψ for fluid flow versus temperature for both laminar and turbulent flow for various fluids. This parameter is defined by (μ = lb/ft-hr):

$$\psi_t = \frac{\mu^{0.25}}{c_p^{2.75}(\rho g)^2} \tag{14-3}$$

$$\psi_l = \frac{\mu}{c_p^{2}(\rho g)^2} \tag{14-4}$$

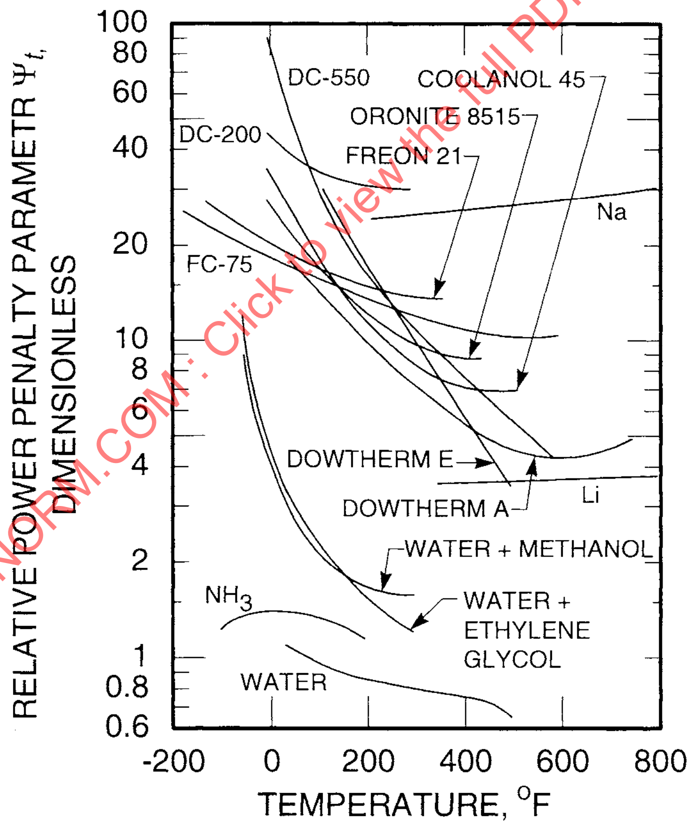

Fig. 14-14 - Relative performance of several fluids in turbulent flow. Parameter ψ_t equals ψ_t value of fluid in question divided by ψ_t value for water at 70°F (ψ_t = 0.3196 (10^{-3}) for water at 70°F).

The thermal properties of the fluids are combined into this parameter, which may be used to determine the suitability of any fluid as a heat transport fluid. Thus, not only is the thermal capacity considered but also its pumping power characteristics.

3.2.5 Heat Sources

Virtually all present-day conceptual designs of advanced life support systems are based on the availability of electric power as the sole source of supply in meeting all energy requirements. The ease in transport, variety in form, adaptability to control, and efficiency of use make electric energy well suited to the spacecraft energy demands.

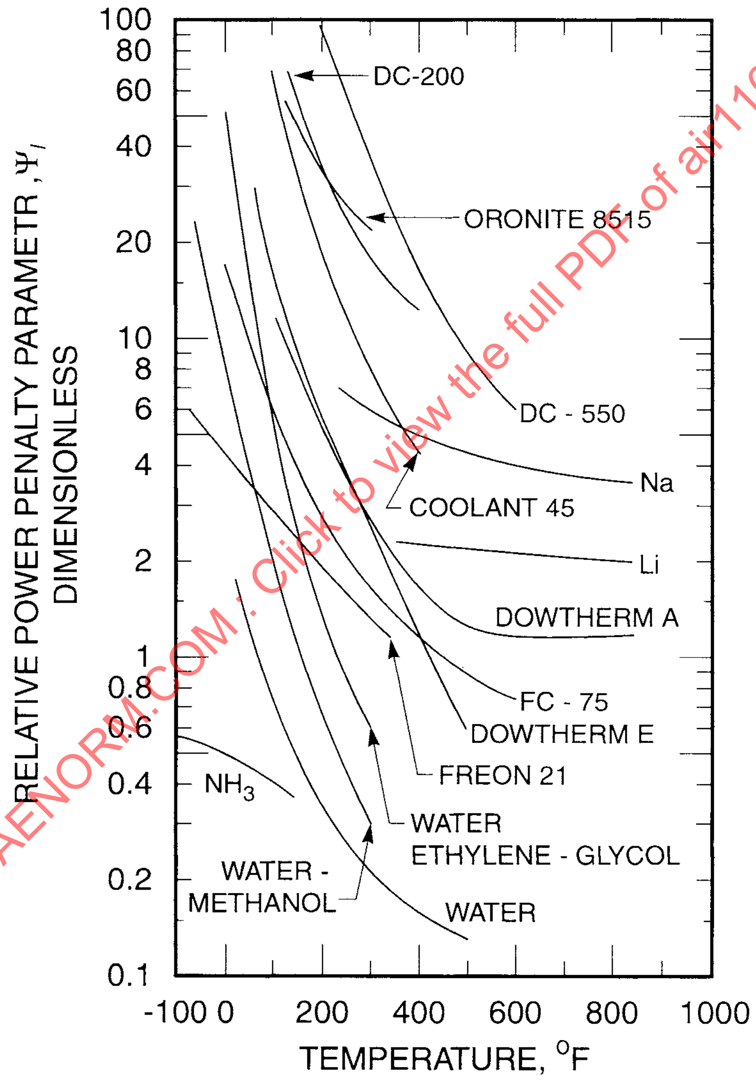

Figure 14-15 - Relative performance of several fluids in laminar flow. Parameter ψ_l equals ψ_l value of fluid in question divided by ψ_l value for water at 70°F ($\psi_l = 0.6163(10^{-3})$ for water at 70°F).

Many of the life support system energy requirements are met uniquely with electric power and could not be satisfied by another energy source. Important among these requirements is the electrolysis of water for the recovery of oxygen and (to only a slightly lesser degree) the operation of fans, pumps, and controls. The inherent adaptability of electric power has made it the overriding choice for all energy requirements in life support systems, even though many of these requirements are purely thermal in nature, and represent as much as 30%-40% of the entire life support system energy requirement.

The factors that militate against using other direct thermal sources, such as the Sun's energy, to satisfy the life support system thermal energy requirements are the temperatures at which the energy must be delivered and the ease of delivery. Typical temperature levels range from 600°F for the desorption of carbon dioxide collection systems, 1600°F for the operation of methane pyrolysis units for the recovery of hydrogen (or 4000°F if carbon dioxide pyrolysis is used). In the vicinity of Earth, operation of a simple solar absorber at 600°F is marginal; above 600°F, operation is impossible.

The use of solar concentrators may solve the temperature level problem, but it creates numerous other problems such as accurate Sun orientation, high-temperature energy storage for Earth shadow operation, and freezing of transport loops. The use of nuclear energy directly as a thermal source is possible. The problem of heat engine inefficiency is thereby avoided, but in its place the problem of using a heat transport loop with its lesser flexibility is substituted. The remaining obvious choice, which has only recently become available, involves the use of radioisotope fuels.

Radioisotopes, as a source of thermal energy, appear to have most of the important attributes of electric power, and none of the drawbacks of the alternate schemes; temperature level is not a problem, transport lines are not required, operation is not Sun dependent. This does not imply that there are no pitfalls in the use of radioisotopes. The five primary considerations bearing on the use of radioisotopes in long-duration manned spacecraft missions are availability, cost, shielding requirements, half-life, and waste heat rejection.

The cost and availability of radioisotopes will depend to a considerable extent upon future requirements. Since the data concerning cost and availability are in a high state of flux because of the uncertainty of future markets and because much of the information is classified, this discussion is limited to study of the applicability of radioisotope energy sources to the spacecraft life support systems.

Isotopes must be shielded to make them compatible with manned spacecraft requirements, although some of the α emitter requirements are minor. Fig. 14-16 shows the relative shielding weight as a function of the energy level required for three isotopes. The shielding material used on all cases was depleted U-238 and the geometry was that of a sphere of isotope material encased in a sphere of U-238. The allowable dosage rate was selected as

20 mrem / hr at 3 ft. The shielding requirements, of course, will vary as a function of the geometry and kind of isotope fuel used.

One possible disadvantage arising from the use of radioisotopes is that an initial oversupply of isotope must be stored aboard the spacecraft so that the mission design condition can be met. The excess storage is a function of the half-life of the isotope and the time at which the design condition occurs during the course of the mission.

Fig. 14-17 shows the relative weights of three isotopes as a function of mission time for a design capability of 1 kW. The weight shown includes the shielding required to reduce the dosage rate to the selected value of 20 mrem / hr at 3 ft.

It is possible that the space mission could be planned in such a way that the requirement for dissipation of excess thermal energy would be sequenced with the availability of excess space radiator area. While mission planning of this type is feasible, the possibility exists that the

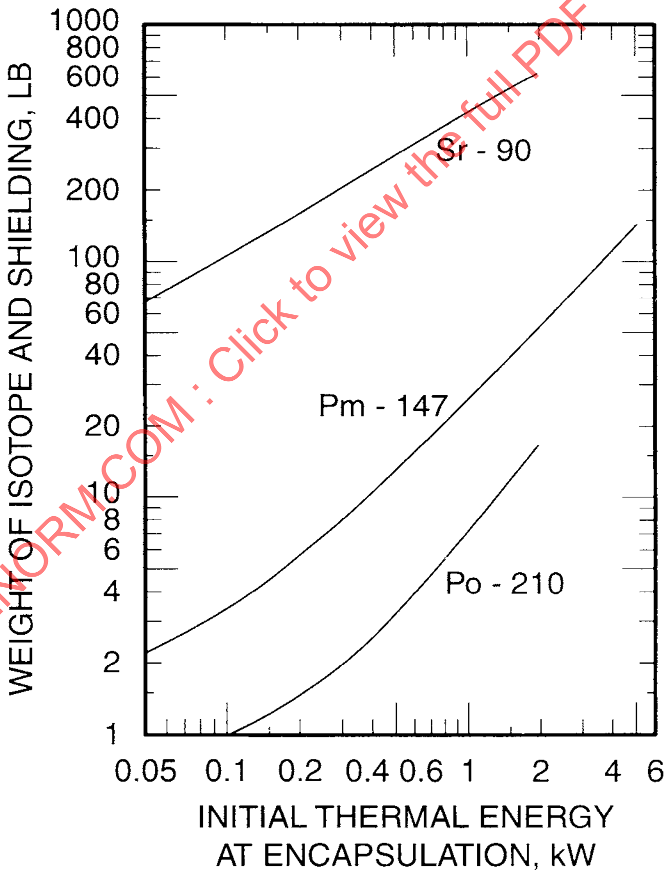

Figure 14-16 - Shielded isotope weights; shielding U-238, dose rate = 20 mrem / hr at 3 ft

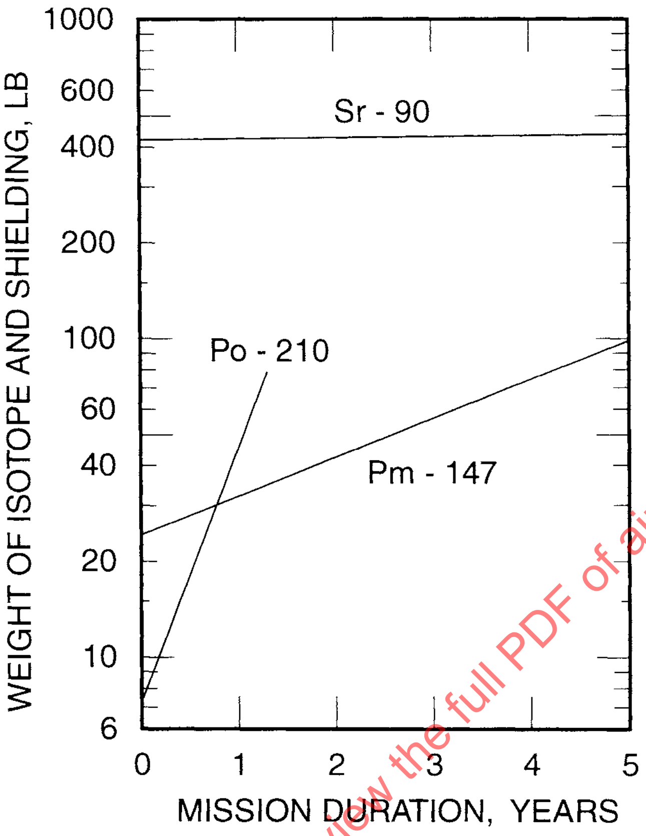

Figure 14-17 - Shielded isotope weights; 1 kW system, shielding U-238, dose rate = 20 mrem / hr at 3 ft

excess thermal energy of the radioisotope, manifested during the early phases of the mission, would have to be dissipated to space by means of a special radiator.

Fig 14-18 shows the resultant penalty as a function of mission duration for three isotopes when the weight of such a space radiator is included. The weight shown includes the weight of the isotope, shielding, and radiator. The radiator penalty number was taken as 6.8 lb / kW of dissipated energy. This number is typical for moderate temperature level space radiators in which the radiator panel is assumed to be part of the vehicle structure and only the radiator tube weight is used in deriving the penalty figure. The isotope design power level in this case was 1 kW.

The approach and penalties given above are conservative (i.e., maximum weight), since no alternate use for the initial excess energy of the isotope or for the isotope radiator during the latter phases of the mission was assumed. In missions where the excess isotope energy and / or the radiator can be used for other functions, penalty values can be lowered

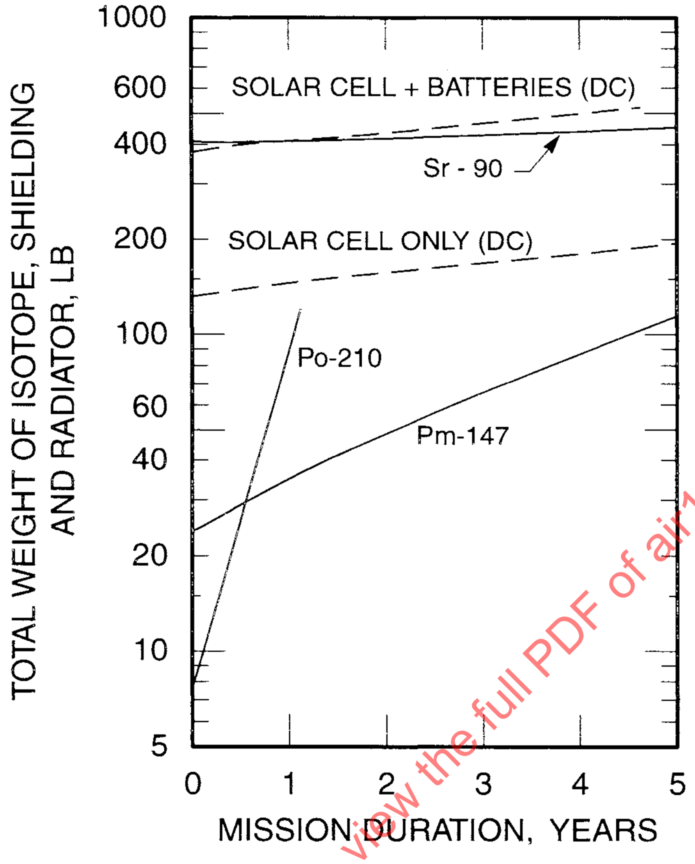

Figure 14-18 - Weight penalty comparison; 1 kW system

significantly. For example, consider the case of a lunar station. The following could be the sequence of use for the isotope and radiator:

1. During exposure to the Sun, the excess isotope heat is rejected by a radiator.
2. During shadow operation, the excess isotope energy is used for crew station heating, and the radiator is then used to subcool the cryogenically stored atmospheric breathing and make-up gases, thus reducing vent losses (direct weight penalty) due to heat leak.

Thus the "excess" isotope heat is really excess only part of the time, and the total radiator penalty to the system is reduced by the combination of radiator functions.

Fig. 14-18 also shows the weight penalties of two solar cell systems, one for operation in the Sun only and the other with auxiliary battery supply for Earth shadow operation. It will be noted that the weight of polonium-210 is well below that of solar cell systems for missions of short duration, while promethium-147 is competitive with solar cell systems as a thermal energy source for missions lasting up to several years, even with the conservative weight penalty procedure described previously.

3.3 Humidity Control

Humidity control of a space vehicle cabin atmosphere involves the removal of the water vapor produced by the crew members. The rate of production of water vapor by respiration and perspiration varies greatly, depending on the occupants' metabolic rate and also on their activity. The average rate of water vapor emitted is approximately 2.2 lb / man-day. If water is produced at a rate higher than average, the cabin relative humidity will rise slightly; this does not present any disadvantage, since the requirements for relative humidity are very broad.

3.3.1 Desiccant Water Removal

Moisture removal by the use of solid sorbents offers the advantage of providing additional usable heat for the system. Sorbents are classified according to the process by which they combine with water. With absorbents, water removal is achieved by means of a chemical reaction between water vapor and a solid. With adsorbents, water removal takes place as the result of physical attraction of water molecules to the surface of the solid, although capillary action is involved with some materials.

In view of the difference in reaction mechanics, the properties of absorbents and adsorbents differ radically. Absorbent water capacity at a given temperature is relatively independent of the water partial pressure in the process stream, but is fixed by stoichiometry. Thus the equilibrium water vapor pressure at a given absorbent water capacity is independent of the latter at any temperature. However, in the case of adsorbents, equilibrium vapor pressure and water capacity are directly related.

The heat available from the absorption process, then, is the heat of reaction that is derived from the energies associated with molecular interaction.

3.3.1.1 Absorption

Table 14-2 shows the ideal performance properties of a number of solid water absorbents that are commonly used as desiccants. Ideal water capacity and heat of reaction are given for each material. Physical properties are given for both the absorbent and the hydrated form, that is, the final product of the reaction of absorbent and water.

Although absorbents display greater water capacity and heat generation than do adsorbents, they have serious drawbacks. Those compounds which carry a large quantity of hydrated water exhibit low temperature stability, usually losing water of hydration at 200°F – 300°F. Hydrated forms falling into this category are: $Mg(ClO_4)_2 \cdot 4H_2O$; $Mg(ClO_2)_2 \cdot 6H_2O$; $CaSO_4 \cdot 2H_2O$; $CaCl_2 \cdot 6H_2O$; $Ba(OH)_2 \cdot 8H_2O$; and all the hydrates of lithium chloride.

The water capacity of the absorbents that produce these compounds is severely limited by bed temperature. Thus, in the case of calcium sulfate, a bed operating at 200°F would have a theoretical capacity of 0.265 lb-H_2O / lb-sorbent; at 270°F a capacity of 0.066 lb-H_2O / lb-sorbent; and at 350°F, no capacity for water. The reactions involved are:

$$\text{At } t = 200°\text{F: } CaSO_4 + 2H_2O = CaSO_4 \cdot 2H_2O \tag{14-5}$$

$$\text{At } t = 270°\text{F: } CaSO_4 + \frac{1}{2}H_2O = CaSO_4 \cdot \frac{1}{2}H_2O \tag{14-6}$$

or, upon heating an absorbed bed from 200°F to 270°F and 350°F,

$$\text{At } t = 270°\text{F: } CaSO_4 \cdot 2H_2O = CaSO_4 \cdot \frac{1}{2}H_2O + 1\frac{1}{2}H_2O \tag{14-7}$$

Table 14-2 - Properties of Common Water Absorbents

Absorbent	Physical Properties	Hydrated Form	Physical Properties	lb H_2O/lb Absorbent	Heat of Reaction, Btu/lb-H_2O
$Mg(ClO_4)_2$	Decomposes at 480°F; explosive organic materials deliquescent	$Mg(ClO_4)_2 \cdot 2H_2O$	Deliquescent	0.161	1725
		$Mg(ClO_4)_2 \cdot 4H_2O$	Deliquescent	0.324	1670
		$Mg(ClO_4)_2 \cdot 6H_2O$	Deliquescent		
			Decomposes 250 °F	0.486	1597
$CaSO_4$		$CaSO_4 \cdot \frac{1}{2}H_2O$	$-\frac{1}{4}H_2O$ at 325 °F	0.066	1040
		$CaSO_4 \cdot 2H_2O$	$-1\frac{1}{2}H_2O$ at 260 °F	0.265	1250
		$CaSO_4 \cdot 2H_2O$	$-2H_2O$ at 325 °F		
$CaCl_2$	Deliquescent	$CaCl_2 \cdot H_2O$	Deliquescent	0.162	1730
		$CaCl_2 \cdot 2H_2O$	Deliquescent, $-2H_2O$ at 390 °F,	0.324	1495
		$CaCl_2 \cdot 4H_2O$	Deliquescent, $-4H_2O$ at 100 °F	0.648	1475
		$CaCl_2 \cdot 6H_2O$	Melting point 86 °F $-4H_2O$ at 87 °F	0.972	1440
CaO	Absorbs CO_2	$Ca(OH)_2$	Absorbs CO_2 and releases water	0.322	2600
BaO	Absorbs CO_2	$Ba(OH)_2$	Absorbs CO_2 and releases water	0.117	3500
		$Ba(OH)_2H_2O$	Absorbs CO_2 and releases water	0.234	2500
		$Ba(OH)_2 \cdot 8H_2O$	Melting point, 170 °F	1.055	1621
LiCl	Deliquescent, absorbs CO_2	$LiCl \cdot H_2O$	$-H_2O$ at 210 °F	0.426	1480
		$LiCl \cdot H_2O$	Deliquescent, decompose 210 °F	0.850	1440
		$LiCl \cdot 3H_2O$	Deliquescent, decompose 210 °F	1.275	1413
P_2O_5	Very deliquescent	HPO_3	Deliquescent, highly corrosive	0.127	3160

$$\text{At } t = 350°\text{F: } CaSO_4 \cdot \frac{1}{2}H_2O = CaSO_4 + \frac{1}{2}H_2O \qquad (14\text{-}8)$$

Several of the sorbents show deliquescent properties, that is, atmospheric water is collected on the surface of the particles and forms a slime. The slime, which is the hydrated form of the sorbent, closes off pores and prevents further reaction. It also migrates through the sorbent bed, presenting serious problems in the downstream system, such as corrosion and blockage. Absorbents displaying deliquescent properties are $Mg(ClO_4)_2$, $CaCl_2$, LiCl, and P_2O_5.

Several of the compounds are undesirable for use as desiccants in the system because of their hazardous properties. P_2O_5 and its hydrated form, HPO_3, are highly corrosive materials. LiCl and $CaCl_2$ attack metal. The perchlorate, $Mg(ClO_4)_2$, is unstable and can react explosively with organic materials or under the influence of heat. Of the compounds listed in Table 14-2, the ones feasible for use in the system are BaO and CaO. Both compounds absorb carbon dioxide at a slow rate, thus reducing bed capacity for water. The hydrated forms will also react with carbon dioxide, releasing water:

$$Ca(OH)_2 + CO_2 = CaCO_3 + H_2O \qquad (14\text{-}9)$$

$$Ba(OH)_2 \cdot H_2O + CO_2 = BaCO_3 + 2H_2O \qquad (14\text{-}10)$$

The rate of reaction of CaO and water is dependent on the method of preparation, and preparation of particle size of the oxide; when prepared in a finely powdered form by calcining at 1000°C, it reacts rapidly. When prepared at 1300°C, the reaction proceeds slowly.

3.3.1.2 Adsorption

Humidity control by solid adsorbents such as silica gel or molecular sieves is more attractive than water removal by chemical absorbents. No heat of reaction is involved in the process, and the heat of adsorption released is roughly the heat of vaporization of the water. The saturated adsorbents can be regenerated by addition of heat to the bed at a much lower temperature level than required to regenerate the chemical absorbents; 250°F is usually quoted for silica gel.

Partial regeneration can be achieved by evacuating the bed to vacuum. Heat addition to the saturated bed, coupled with evacuation to vacuum, would be very satisfactory for systems in which water is dumped overboard. A desorption temperature of 150°F is sufficient in this case.

The characteristic adsorption curves for silica gel and three types of molecular sieves are given in Fig. 14-19. Silica gel has a much higher capacity than molecular sieves at the water vapor pressures encountered in space vehicle humidity control systems. The two types of silica gel subsystems are described as follows:

1. Nonregenerable Silica Gel Subsystem - For missions of brief duration, a system in which the humidity is removed from the cabin air by circulating it through a silica gel bed is very attractive because of its simplicity. This system requires no valving, heating loops, or cooling. The weight of such a system is readily estimated from Fig. 14-19.

   Calculations show that the canister weight is only a small portion of the total subsystem weight. The weight of the system, neglecting secondary effects, is proportional to the number of crew members.

   It should be noted that, for high utilization efficiency, the length of the silica gel bed must be kept above a minimum length, which depends on the bed face area and on the process gas superficial velocity. Since the weight of this nonregenerable silica gel system is proportional to the mission duration, its field of application is severely restricted to short duration missions.

2. Regenerable Silica Gel Subsystem - For mission durations in excess of a few days, regeneration of the silica gel bed is required. A water removal system of this type is shown in Fig. 14-20. Two identical silica gel beds are used, one adsorbing and the other desorbing. When the process water concentration at the bed outlet reaches a certain preset value, all valves in the system are turned 90 deg from the position shown, and heat is applied to the saturated bed, which is then evacuated to vacuum.

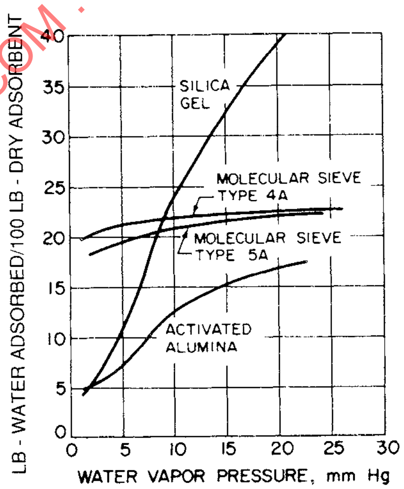

Figure 14-19 - Water adsorption isotherms at 77°F

The process air is routed through the other silica gel bed. Water from the saturated bed is dumped overboard. Switching of the valves is usually automatic at fixed time intervals.

The estimated weights of the components of a typical regenerable silica gel humidity control subsystem as depicted in Fig. 14-20 are listed in Table 14-3.

3.3.2 Cooler-Condenser Water Removal

A relatively simple method of controlling the humidity of the cabin air is to condense the moisture in a heat exchanger and to remove the condensate from the process air stream. Fig. 14-21 is a schematic diagram of such a system. Water from the moist air stream condenses on the surface of the cooler-condenser and is blown downstream by the air flowing through the heat exchanger. The liquid water droplets are separated from the main air stream in a water separator; the air is then returned to the cabin or to another subsystem for further processing.

Table 14-3 - Regenerable Silica Gel Subsystem Accessory Weight (3-Man System)

Component	Number Required	Total Weight, lb
Heater	2	0.6
Switching Valves	6	4.2
Valve Actuator and Drive	1	2.5
Flow Control Valve	1	0.6
Flow Controller	1	2.5
Sensor	1	0.1
Ducts	—	0.5
Total		11.0

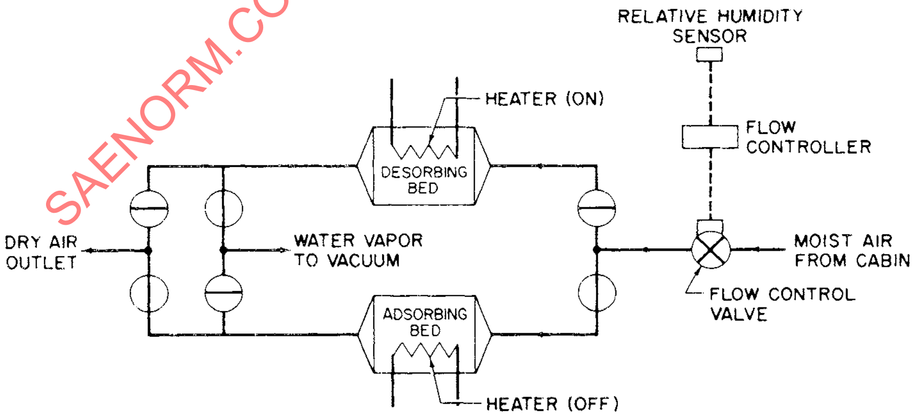

Figure 14-20 - Regenerable silica gel humidity control subsystem

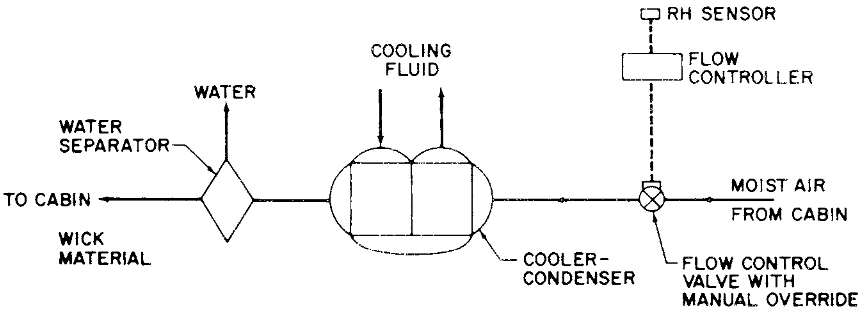

Figure 14-21 - Cooler-condenser humidity control subsystem

The flow required through the system for the removal of 2.2 lb-H_2O / man-day is a function of the inlet and outlet water concentrations in the process air stream, of the cabin pressure, and of the water separator efficiency. The expression for the flow requirement is given by

$$w_g = \frac{\overline{w}_{H_2O} M_g}{18\eta_{sep}} \left(\frac{1 - y_2}{y_1 - y_2} \right) \qquad (14\text{-}11)$$

where
M_g = Molecular weight, lb / mol
w_g = weight flow of gas (air), lb / man-day
$\overline{w}_{H_2O}$ = Weight flow of water, lb / man-day
y = Mole fraction, dimensionless
η_{sep} = Efficiency of water separator, dimensionless
Subscripts
1 = Inlet
2 = Outlet

Graphical solutions of this equation are shown in Figs. 14-22 and 14-23, where the flow requirement is plotted against the cabin relative humidity for cooler-condenser outlet temperatures of 40°F and 45°F and cabin pressures, P_c, of 5, 7, 10, and 14.7 psia. Also, the flow requirement for water removal is plotted against cooler-condenser outlet temperature in Fig. 14-24.

In Figs. 14-22 and 14-23 the humidity control system cooling requirements, which are obtained from the heat load, are also plotted as a function of the cabin relative humidity and cabin pressure. Fig. 14-25 shows the cooling requirements as a function of condenser outlet temperature.

The sharp rise in flow requirement and cooling load at low cabin relative humidity with a flattening characteristic at about 60% relative humidity points to the desirability of

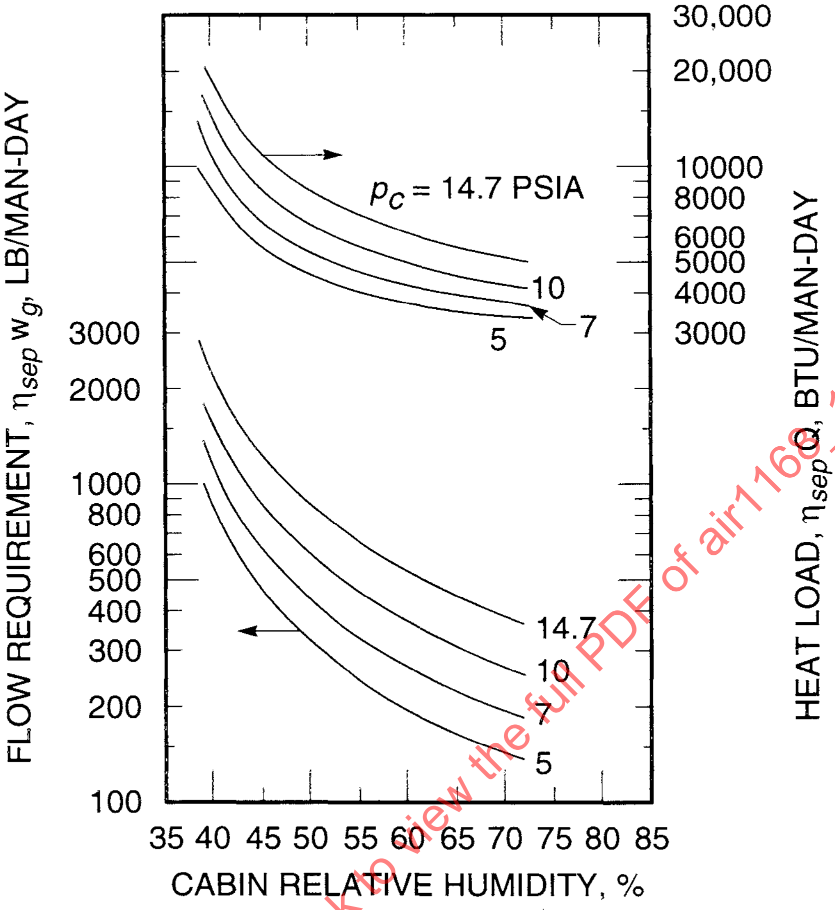

Figure 14-22 - Flow requirement and heat load for humidity control; condenser temperature 40°F

maintaining the cabin humidity as high as possible. The comfort zone inside the cabin extends over a wide range of relative humidities, with the maximum values compatible with unimpaired crew performance varying between 60% and 70%. These plots also indicate the savings that can be achieved by the use of low condenser outlet temperatures. This, however, is more difficult to satisfy than high relative humidity. Heat sink temperatures lower than about 40°F to 45°F normally impose very high weight penalties on space vehicle liquid cooling loops. These penalties result from the large radiator areas required to cool the heat transport fluid to the temperature level desired for operation of the humidity control system.

Temperatures on the order of 40°F to 45°F can, however, be achieved by evaporating water or another fluid at low pressure and dumping the vapor overboard. This process can be advantageously used aboard vehicles where material balance shows a surplus production of water.

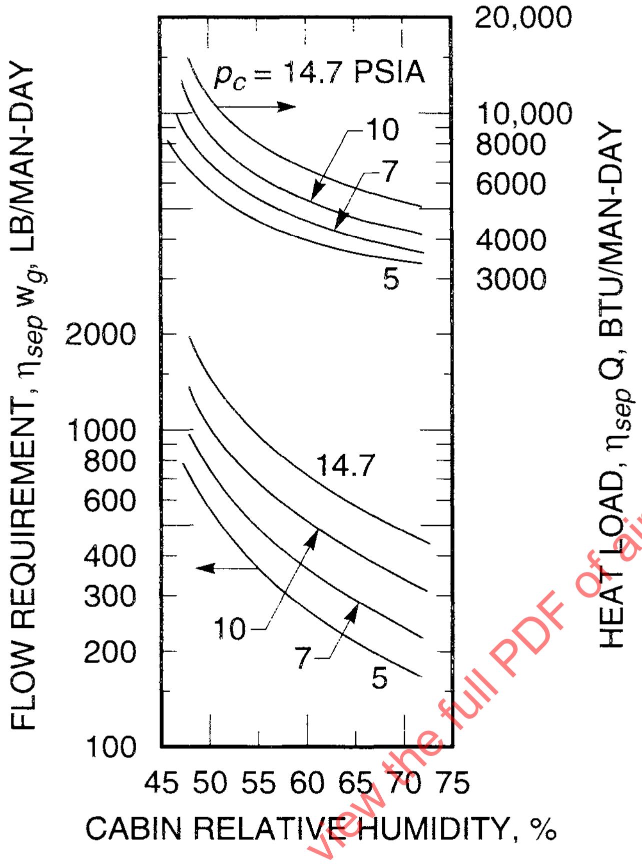

Figure 14-23 - Flow requirement and heat load for humidity control; condenser temperature 45°F

Where a refrigeration system is installed, it is advantageous to operate the heat exchanger at a temperature as low as possible. It should be noted that the surface temperature of the cooler-condenser must be kept above the freezing temperature of the water. The condensate blown out of the cooler-condenser by the process airstream is partly entrained in the form of small droplets and partly as drops of liquid water attached to the duct walls. Several means of removing the liquid water from the airstream have been proposed for zero gravity operation. Among these are filter separators (such as sponges) and centrifugal types such as bend, cyclone, rotating, and wick separators.

Sponge separators are inherently high-energy loss devices; their squeezing mechanism is relatively complex, and their weight is higher than the centrifugal type of separators. Of the centrifugal types of separators, the most attractive for simplicity and reliability is the cyclone separator.

A recent development in water separation for spacecraft is a wick type water separator. The wicking material is usually a synthetic fiber cloth or a porous metal material. The wicking

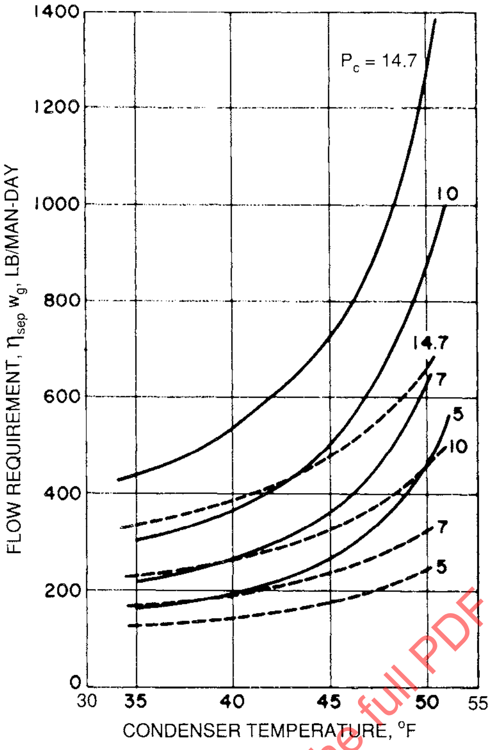

Figure 14-24 - Flow requirement variation with outlet temperature; dotted curve = 70% RH, solid curve = 60% RH

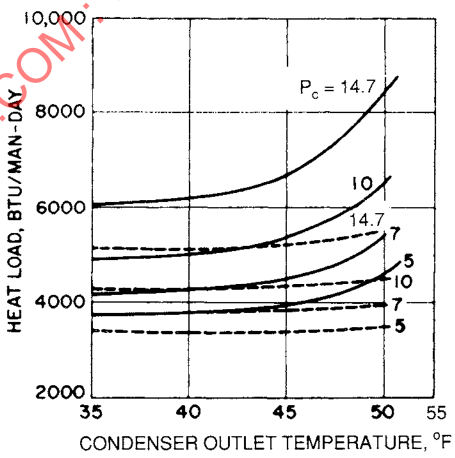

Figure 14-25 - Heat load variation with temperature; dotted curves at 70% RH, solid curves at 60% RH

material is located in the condenser in intimate contact with the heat transfer surface. An example of this type of construction is shown in Fig. 14-26. As air is cooled in the heat exchanger, water vapor is condensed on the heat transfer surface. The combination of the wetting of the surface and the capillary action of the wicking material causes the water to be removed from the heat exchanger core. A small pressure differential is required to cause the process to function. This can be provided with small pumps that are part of the water management system. In some systems where water evaporation is used as a heat sink, space vacuum can be utilized to provide the pressure differential.

3.3.3 Subsystem Comparison

The two competing humidity control subsystems considered are compared here on the basis of their equivalent weight and other characteristics pertaining to space vehicle installation. In calculating equivalent weight, the hardware weight, heat rejection load, heating requirement, power consumption, and water balance for the cooler-condenser and the silica gel subsystem were determined for typical vehicle and mission parameters as follows:

1. Cabin pressure = 7 psia.
2. Cabin relative humidity = 60%.
3. Number of crew members = 3.
4. Cooler-condenser subsystem air outlet temperature = 45°F.

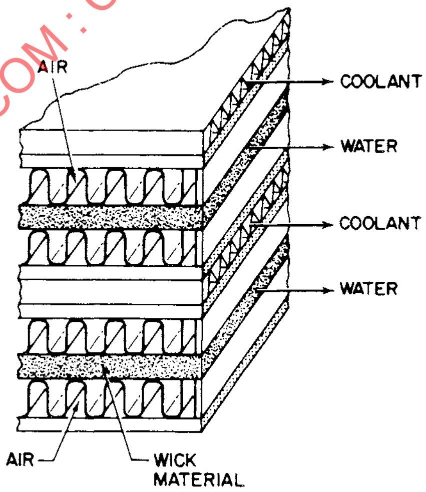

Figure 14-26 - A condenser/wick water separator fabrication method

For these conditions, the subsystem parameters are listed in Table 14-4.

An undesirable feature of the regenerable silica gel subsystem is the temperature cycling of the process air at the subsystem outlet. At the start of the adsorption period, the bed is hot (near 150°F), and the process air temperature will rise through the bed, approaching the temperature of the bed at the outlet. As the bed is cooled, the air temperature will decrease; the cyclic temperature of the outgoing air depends on the bed dynamic characteristics.

Removal of the moisture from the cabin air by a cooler-condenser offers the possibility of integration of the humidity control and cabin temperature control subsystems. This greatly reduces the installation number of components as well as control complexity. In actual practice, these two functions, humidity control and temperature control, are unified and effected in the same atmospheric control loop.

3.4 Carbon Dioxide Removal

The following paragraphs describe a carbon dioxide removal subsystem suitable for use in spacecraft life support systems. Carbon dioxide removal systems fall into two categories: expendable systems and regenerable systems. Only the most promising process of each category is considered here.

3.4.1 Expendable CO_2 Removal System

For short mission durations, lithium hydroxide (LiOH) absorption appears the most attractive means of space vehicle atmosphere CO_2 control. Successfully used on the Mercury capsule, this method represents the recent state of the art. Oxygen-producing superoxide systems are heavier than competing LiOH systems. In addition, the tendency of superoxide beds to plug up creates a control problem that does not exist in LiOH beds.

LiOH absorbs CO_2 according to the reaction:

$$2LiOH + CO_2 \rightarrow Li_2CO_3 + H_2O \qquad (14\text{-}12)$$

Table 14-4 - Comparison of Subsystem Characteristics

Parameter	Silica Gel Subsystem	Cooler-Condenser Subsystem
Hardware Weight, lb	28.1	10.3
Pumping Losses, W	1.55	4.81
Heat Rejection Load, Btu/hr	439	569
Temperature °F	70	45
Heating Requirement, Btu/hr	439	—
Temperature °F	150	—
Water Balance, lb/day	−6.6	+6.6

Some water vapor is necessary for the reaction to take place. The amount of water vapor present in space vehicle cabin atmospheres (from 50% to 70% RH) is suitable to catalyze the reaction.

Absorption of CO_2 by LiOH is exothermic, with 875 Btu / lb-CO_2 absorbed being released. Under normal operating conditions, some of this heat is expended in vaporizing the water of reaction. The amount of water vapor produced by the reaction is 0.41 lb-H_2O / lb-CO_2 and the LiOH consumption is ideally 1.059 lb / lb-CO_2. LiOH is commercially available at a purity of about 97% and a bulk density of 25-30 lb / ft^3.

The heat and mass transfer performance of a granular LiOH bed may be visualized by referring to Fig. 14-27, which shows temperature and CO_2 concentration profiles at two different times in a typical canister. Most of the reaction takes place in an absorption zone that slowly moves from the inlet end to the outlet end of the canister. When the leading edge of the absorption zone reaches the outlet end of the granular bed, the so-called breakthrough point has been reached; after this point, the CO_2 content of the gas leaving the canister rises fairly rapidly with time.

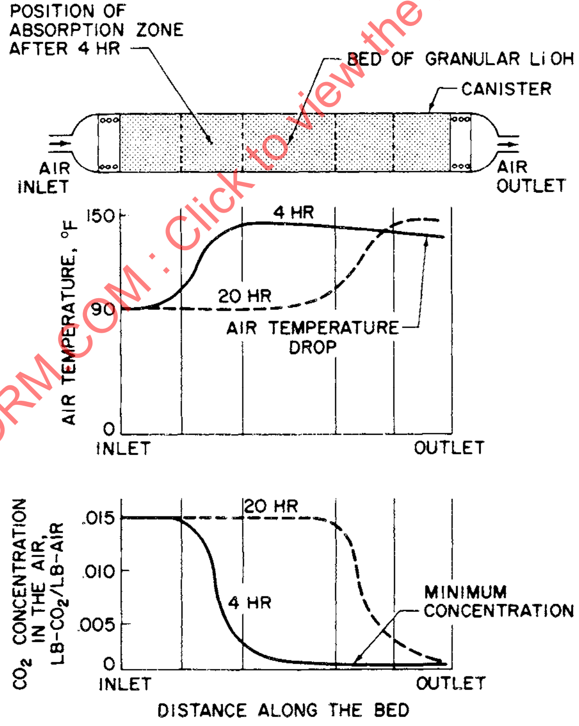

Figure 14-27 - Temperature and carbon dioxide concentration profiles in a typical LiOH canister; air temperature drops because of heat transfer to the bed and surroundings; minimum concentration at the outlet is limited to a CO_2 pressure of about 0.5mm Hg

The full theoretical capacity of LiOH for CO_2 absorption cannot be achieved in an actual system. Typical closed circuit test data are shown in Fig. 14-28. A closed circuit process involves recirculation of the process gas and addition of CO_2 at a constant rate. The inlet and outlet CO_2 concentrations in the process air are plotted in the figure versus test duration for a typical bed design.

It is interesting to note that the relatively constant difference between the inlet and outlet concentrations, even after breakthrough, indicates that all the CO_2 added to the airstream is removed. The CO_2 concentration at the bed outlet is approximately constant for a long period of time, but increases rapidly after breakthrough. The exact shape of the curves presented in Fig. 14-27 and the position of the breakthrough depend on the air superficial velocity, the canister dimensions, and the process air inlet temperature. The LiOH particle size is generally kept between 4 to 8 mesh size for high utilization efficiencies and low bed pressure drops. It appears that no channeling occurs with this particle size at gas velocities up to 1.0 fps.

The process air flow requirement for CO_2 absorption by LiOH has been calculated for the following conditions and assumptions:

1. The CO_2 partial pressure in the process airstream leaving the absorber bed is 0.5 mm Hg.

2. The CO_2 production rate in the cabin is 2.25 lb/man-day.

3. The cabin air molecular weight is calculated assuming a cabin RH of 60%.

The results of these calculations are plotted in Fig. 14-29 for various cabin atmospheric pressures.

The process air temperature rise across the canister is shown in Fig. 14-30 against the cabin air CO_2 concentration. The flows calculated above were used in the computations. None of the heat of reaction is assumed transferred to the bed.

The consumption of LiOH is a function of the number of crew members in the cabin and of the duration of the mission. Under normal average conditions, 2.728 lb / man-day are consumed; the corresponding volume consumption is 188 in.^{3} / man-day. This leads to packaging problems as mission duration increases. In view of this, the use of rechargeable canisters is advisable for missions of long duration.

It is reasonable to assume that an interval of one day between charges will not hamper crew operation unduly. Consideration of potential composition transients, particularly during emergency situations when suit circuit operation is required, leads to the recommendation of a system using two LiOH canisters in parallel for CO_2 removal. The two canisters are

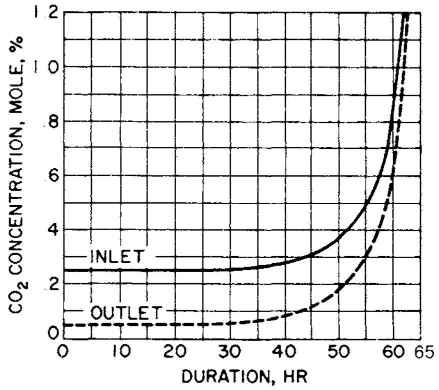

Figure 14-28 - Typical closed circuit LiOH performance; pellet size, 4-8 mesh; bed length, 8.0 in.; bed diameter, 6.0 in.; absorbent weight, 3.5 lb; air weight flow, 43 lb / hr; CO_2 weight flow, 0.043 lb / hr; air superficial velocity, 50 fpm; air total pressure, 14.7 psia; air inlet temperature, 182°F

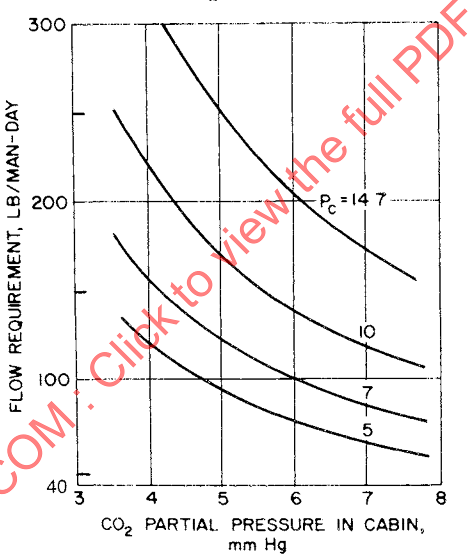

Figure 14-29 - Lithium hydroxide subsystem flow requirement

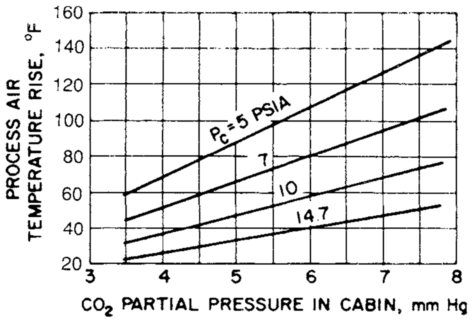

Figure 14-30 - Lithium hydroxide subsystem process air temperature rise

normally on stream, since operation on one canister involves a loss of system performance. Such a subsystem is illustrated in Fig. 14-31.

3.4.2 Regenerable CO_2 Removal

Many regenerable removal processes are possible, including electrodialysis, freeze-out, diffusion, and liquid and solid absorbents and adsorbents. Of the many processes that have been considered, at the present time it appears that use of regenerable adsorbents is the most practical and attractive from the standpoint of both performance and state of the art.

Application of adsorption methods to gas purification and chemical separation processes is well known and has been widely used in the chemical process industries. Some of the materials and technology have been applied to the problem of atmospheric purification for spacecraft systems. Specifically, this has involved application of molecular sieve adsorbents to regenerable CO_2 removal systems.

Adsorption systems are classified into the following categories according to the operating conditions obtained in the cycle during adsorption and desorption:

1. Thermal swing cycles
2. Pressure swing cycles
3. Purge gas stripping cycles
4. Displacement cycles
5. Combination cycles

Thermal swing cycles involve bed heating for the desorption process or bed cooling during the adsorption process. Pressure swing cycles are those that have desorption at reduced pressure. Purge gas stripping consists of using a nonadsorbable gas flow to reduce the partial pressure of adsorbate in contact with the adsorbent, thereby causing desorption.

Displacement cycles use an adsorbent substance that is either more or less strongly adsorbed than the adsorbate to displace the adsorbate: the substance effecting the displacement is then removed by another process. Combination cycles utilize two or more of the four previous processes.

In molecular sieve systems used for atmospheric purification, a variety of thermal swing, pressure swing, and purge gas stripping processes will be used in combination. This is brought about by the necessity of separate removal of water vapor from the process gas prior to CO_2 removal. Where it is desired to return water vapor to the cabin, the predrying function is usually accomplished by a desiccant adsorbent that is regenerated by purge gas stripping.

Where the water vapor is vented overboard to space vacuum with the CO_2, the desiccant can operate on the pressure swing cycle with the CO_2 adsorbent. In long duration space missions using oxygen recovery systems, it will be desirable to recover the CO_2 at a relatively high pressure for processing. The CO_2 adsorbent can then best operate on a thermal swing cycle.

Fig. 14-32 is a schematic diagram of a regenerable CO_2 removal system in which the CO_2 adsorbent (molecular sieve) is regenerated in a pressure swing cycle by exposure of the adsorbent to a vacuum; the desiccant (silica gel) is regenerated in a purge gas stripping cycle using hot, dry, process gas. This system was essentially the original molecular sieve system concept proposed for spacecraft atmospheric control.

It was found in breadboard system tests that the silica gel was partially desorbed by the dry process gas and that it was not necessary to heat the desiccant bed at every desorption cycle; at every fifth cycle, the process gas could be heated to approximately 250°F to provide complete desorption of the desiccant. The system is characterized by high peak thermal energy requirements that can be alleviated somewhat through use of waste heat.

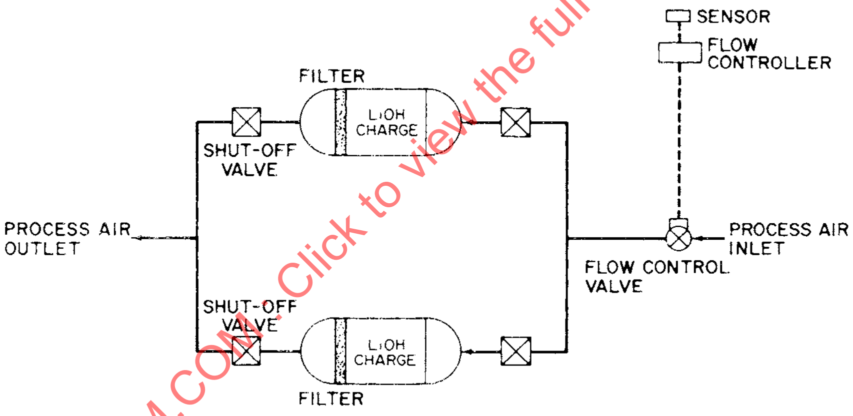

Figure 14-31 - Lithium hydroxide subsystem schematic diagram

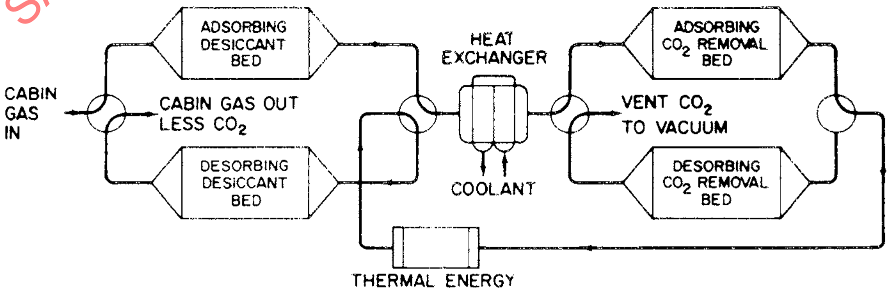

Figure 14-32 - Purge gas desorbed desiccant

It was also found that in most applications where a system of this type would be used, waste heat would not be available at temperature levels sufficiently high to permit providing more than a small part of the total energy requirements in this way. The high power penalties obtained in present spacecraft concepts place this type of molecular sieve at a disadvantage relative to other types for use as an open cycle system.

A regenerable CO_2 removal system with low power consumption penalties is shown schematically in Fig. 14-33. In this particular arrangement, the desiccant and molecular sieve beds are in thermal contact, so that the waste heat from the adsorbing bed is transferred to the desorbing bed to facilitate desorption. This heat transfer is particularly beneficial to the desiccant bed where the heat effects are comparatively large and the desorption rates tend to be low.

The adsorbent beds can be operated adiabatically if an independent bed arrangement is preferred for reliability. With two two-bed systems, each provided with its own valving, failure of one system would not necessarily involve loss of the CO_2 removal function, since one two-bed system would provide the required CO_2 removal at a somewhat higher partial pressure level. The valving arrangement is simple for the system relative to other types of molecular sieve systems. Valving can be integrated into a single multipleport design, if desired.

The low power consumption is obtained at the expense of loss of water vapor overboard with the CO_2. In vehicles using hydrogen-oxygen fuel cells, water in excess of metabolic requirements may be produced as a by-product of power generation. Therefore it will not be necessary to penalize the system in such applications for loss of water vapor, and use of a system of this type may be preferred. In applications where power penalties are high but water recovery is important, the system described next may be used to advantage.

The thermal swing system shown in Fig. 14-34 depends upon achieving a high desiccant bed loading by cooling during the adsorption cycle. During regeneration of the desiccant, the bed is heated by using waste heat at a moderate temperature level to achieve partial desorption. Because of the relatively high residual moisture loading at the start of the adsorption cycle, the dewpoints provided by the desiccant bed will not be as low as those where the desiccant is completely desorbed. The outlet dewpoint temperature level from the desiccant will depend upon the temperature swing available in the thermal control system.

Assuming the transport fluid to be available at a high temperature of 150°F and a low temperature of 40°F, more than 90% of the moisture contained the process gas will be removed by the desiccant bed and will ultimately be returned to the cabin. The remaining 10% of the moisture in the process gas will be adsorbed in the CO_2 adsorbent bed, from where it will be vented overboard with the CO_2. In this type of system, there will be some loading up of the CO_2 adsorbent with water vapor, necessitating a weight allowance or provisions for bed heating.

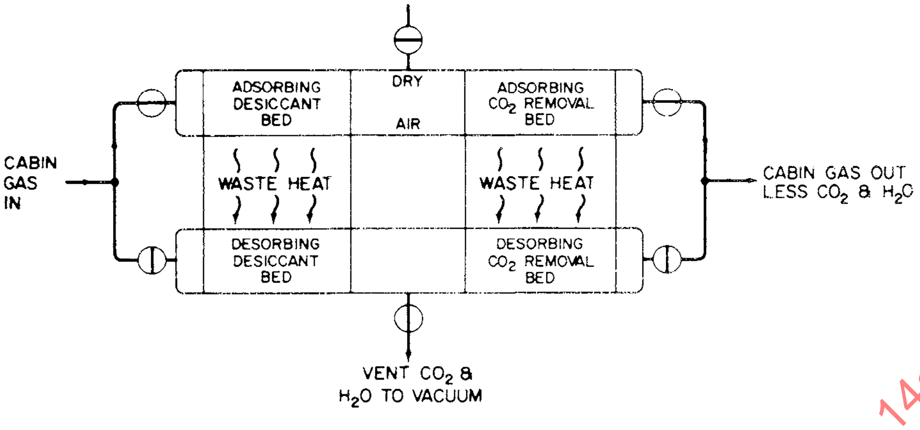

Figure 14-33 - Vacuum desorbed desiccant

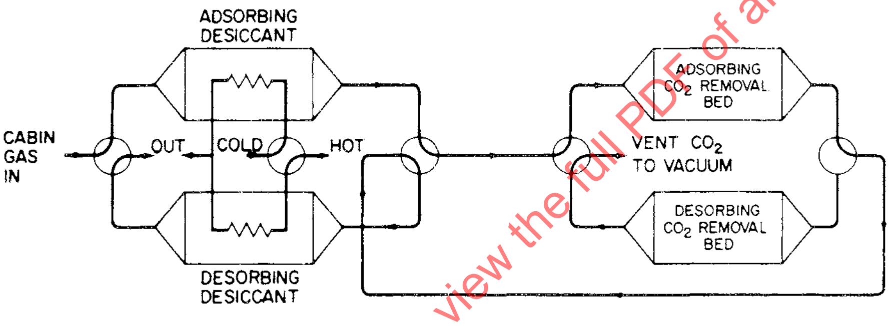

Figure 14-34 - Thermal swing desiccant desorption

The thermal swing system, like the vacuum-desorbed desiccant system, has low power requirements, but provides recovery of much of the moisture in the process gas, at the expense of valving complexity and thermal control system penalties represented by imposition of a low-temperature heat load for a high-temperature heat load. It is difficult to evaluate accurately the penalties associated with the thermal swing system without going into the details of the thermal control system with regard to heat loads, permissible temperature levels, and available heat sinks.

For missions where O_2 recovery is desired, it is necessary for the CO_2 removal system to provide the concentrated CO_2 at a pressure level suitable for subsequent processing. One means of accomplishing this involves heating the CO_2 adsorbent bed to a temperature level in excess of 400°F (for the usual CO_2 loadings).

Fig. 14-35 shows a system of this type in which bed heating is accomplished with a CO_2 recirculation loop. The desiccant bed is regenerated by dry process gas, which is heated in passing through the initially hot CO_2 adsorbent bed. Thus, desiccant regeneration is

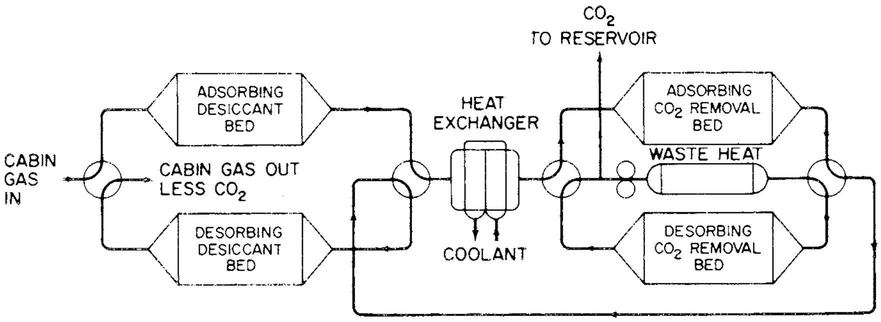

Figure 14-35 - Thermal desorbed CO$_2$ adsorbent

obtained from waste heat produced by regeneration of the CO$_2$ adsorbent. Since waste heat, in adequate quantity and temperature level, should be available from the O$_2$ recovery process equipment, it is possible to obtain the function of CO$_2$ removal entirely by use of waste heat.

3.5 Control of Trace Contaminants

The job of trace contaminant control is defined as the removal of tangible particles such as dust and microscopic particles of smoke or vapors, the removal of odors and trace gases, and the control of microorganisms.

The control of trace contaminants in space vehicles poses a difficult problem because these materials, being present in low concentration, are difficult to detect and identify. The very low partial pressures of trace contaminants render difficult their removal by the normal techniques such as reaction with chemical reagents, adsorption, and absorption. A large number of trace contaminants are toxic; many others possess undesirable odors. Over a period of time, in addition to their deleterious effects on health, these materials can corrode vital equipment and attack vehicle finishes.

3.5.1 Sources

Trace contaminants originate from a variety of sources. These may be classified roughly as follows:

1. Crew:
   a. Perspiration
   b. Respiration
   c. Flatus
   d. Desquamated skin, hair, nails, etc.
   e. Defecation
   f. Urination

2. Equipment
   a. Effects of heat
   b. Wear
   c. Attrition
   d. Radiation

At the present time, the control of waste contaminants is complicated by lack of definite knowledge of generation rates. The toxic effects of most contaminants on the basis of continuous exposure is not known. Present data on the toxicity of trace contaminants, as illustrated by values for the maximum allowable concentration shown in Table 14-5, are based on a a 8-hr day, 40-hr week exposure. On a continuous exposure basis, the allowable concentration could conceivably be much smaller, since the relation between exposure and toxicity often follows an exponential form.

Another consideration is the possible synergistic effect of a number of contaminants. In a few cases the toxic effect of one contaminant may be neutralized by the presence of another compound; more often, a number of contaminants will exhibit a greater effect than the sum of their single values.

Contaminants produced by humans include various high molecular weight compounds. These include: valeric acid, $CH_3(CH_2)_3COOH$, and caproic acid, $CH_3(CH_2)_4COOH$, which are present in perspiration; skatole, C_9H_9N, present in trace quantities in flatus and feces; and many others, arising from oxidation and deterioration of finishes, insulation, hydraulic fluids, coolants, lubricants, transistors, Freons, and food preparation. Low molecular weight compounds are present in larger quantities. Man produces, on the average, 2 liters of flatus per day, the approximate composition of which is given in Table 14-6.

3.5.2 Contaminant Control

Control of trace contaminants in a space vehicle cabin may be accomplished by a combination of filtration, catalytic oxidation, and adsorption.

3.5.2.1 Filtration

Filters may be classified by the principle on which they operate. So-called dry filters remove dust particles by forcing air to flow through a screening material such as tightly woven Dacron felt or Fiberglas. Most of these units can be vacuum cleaned, air blown, or dry cleaned for re-use.

Dry filters operate most efficiently with air flows up to approximately 2000 cfm and light dust loadings, and are suitable for use in spacecraft. They are highly efficient and, when clean, offer low resistance to air flow. Resistance builds up rapidly, however, and dust holding capacity is relatively small. Change in resistance usually indicates that the filter should be replaced or cleaned.

3.5.2.2 Adsorption

Of the several methods for removing odors and objectionable vapors, adsorption is very efficient and is usually the method chosen. When the carbon has adsorbed approximately 20% of its own weight, it must be replaced or reactivated.

Table 14-5 - Atmospheric Contaminants

Group and Compound	Max. Acceptable Conc., ppm[1]	Mol Wt.	Removal Method	Removal By-products	By-products Treatment	Comments
CREW GENERATED						
Gaseous						
Hydrogen, H_2	2,800(air)	2	Cat. burner			
Methane, CH_4	27,600(air)	16	Cat. burner			
Hydrogen sulfide, H_2S	20	34	Carbon-cat. burner	Sulfur oxides	Carbon-mol. sieve	Possible contam. in mol. sieve CO_2 removal system
Ammonia, NH_3	100	17	Specific sorbent			
Amines, RNH_3	10	30-150	Carbon-cat. burner	Nitrogen oxides	Carbon-mol sieve	
Mercaptans, RSH	20	48-100	Carbon			
Indole, C_8H_7N	...	131	Carbon			
Particulate						
Bacteria	...	...	UV	...		Bacteria burned in cat. burner
Desquamated skin	...	...	Filter			
Hair (depilation)	...	...	Filter			
SPACECRAFT GENERATED						
Gaseous						
Acetic acid, $C_2H_4O_2$	10	151	Carbon		...	Carbon has high cap.
Acetone, C_3H_6O	1000	58	Carbon		...	Carbon has high cap.
Acrolein, C_3H_4O	0.5	56	Carbon		...	Carbon has high cap.
Amyl acetate, $CH_3COOC_5H_{11}$	200	130	Carbon	...	...	Carbon has high cap.
Amyl alcohol, $C_5H_{11}OH$	100	68	Carbon	...	...	Carbon has high cap.
Aromatic solvents, C_6HR	25-400	78-100	Carbon			Carbon has high cap.
Cello-solvents, $RO(CH_2)_2OH$	25-50	76-120	Carbon		...	Carbon has high cap.
Carbon disulfide, CS_2	20	76	Carbon-cat. burner	Sulfur oxides	Carbon-mol. sieve	Carbon has low cap.
Carbon monoxide, CO	100	28	Cat. burner			
Chlorinated solvents, RCl_x	25-50	50-154	Carbon			Carbon has high cap.
Dioxane, $O:(CH_2CH_2)_2:O$	100	88	Carbon			
Ethyl acetate, $CH_3COOC_2H_5$	400	86	Carbon			
Fluorine, F_2	0.1	38	Absorbent		...	Adsorbed by mol sieve; absorbed by LiOH
Formaldehyde, HCHO	5	30	Carbon-cat. burner			
Hydrogen chloride, HCl	3	36.5	Carbon-absorb			HCl and HF retained by mol. sieve
Hydrogen fluoride, HF	3	20	Carbon-absorb	...	...	HCl and HF retained by mol. sieve
Methyl alcohol, CH_3OH	200	32	Carbon			
Methyl ethyl ketone, $CH_3COCH_2CH_3$	200	72	Carbon			
Nitrogen dioxide, NO_2	5	46	Carbon	...	...	Carbon has low cap. for nitrogen oxides
Ozone, O_3	0.1	48	...	...	...	Ozone decomposed in cat. burner

(continued)

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[1] American Conference of Government Industrial Hygienists, *Threshold Limit Values for 1961*.

Table 14-5 - Atmospheric Contaminants (continued)

Group and Compound	Max. Acceptable Conc., ppm[1]	Mol Wt	Removal Method	Removal By products	By-products Treatment	Comments
SPACECRAFT GENERATED						
Phenol, C_6H_5OH	5	94	Carbon			
Phosgene, $COCl_2$	1	98	Carbon			
Sulfur dioxide, SO_2	64	5	Carbon-absorb	. . .	.	Efficiently adsorbed by mol. sieves
Sulfuric acid, H_2SO_4	90	5	Carbon-absorb			Efficiently adsorbed by mol. sieves
Particulate						
Organic dust	.	. . .	Filters-sorption beds	. .	.	Sorption beds in atm control system
Inorganic dust (metals, paints); Fe, Cu, TiO_2, etc.	.	. . .	Filters-sorption beds	. . .		Sorption beds in atm control system
Aerosols	.	. . .	Sorption beds	. .	.	Sorption beds in atm control system

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[1] American Conference of Government Industrial Hygienists, *Threshold Limit Values for 1961*.

Table 14-6 - Human Flatus Composition

Composition	Concentration Range, mol %
Carbon Dioxide, CO_2	5.9–38.0
Hydrogen, H_2	0–54.0
Hydrogen Sulfide, H_2S	$0–6.4 \times 10^{-4}$
Nitrogen, N_2	10–87.7
Oxygen, O_2	0–10.3
Methane, CH_4	0–55.0
Ammonia, NH_3	Trace
Mercaptan, RSH	Trace
Indole, C_8H_7N	Trace
Alkyl Amines, RNH_2	Trace
Carbon Monoxide, CO	Trace

Although activated carbon effectively adsorbs hydrocarbons of medium and high boiling points, it is ineffective in removing gases with very low boiling points, such as CO, CO_2, H_2, and CH_4 (methane). A catalytic burner, described in Par. 3.5.2.3, must be provided to remove the low boiling point gases and vapors.

3.5.2.3 Catalysts

Catalytic burners are effective in removing low molecular weight contaminants such as CO, CH_4, and H_2, which are not effectively adsorbed by activated carbon. The burners utilize catalysts to oxidize toxic contaminants into nontoxic products.

The exact size and weights of the burners depend upon the flow rate and pressure drop. The unit shown in Fig. 14-36 is presented as an example of catalytic burner construction. The burner has a cylindrical shape and consists of a catalytic reactor core and a counterflow heat exchanger. The reactor core consists of a cylindrical platinum heating element surrounded by a shell packed with 1/8 in. cylindrical catalyst pellets. The catalyst is composed of 0.3% palladium coated on an activated alumina carrier and the bed size is 150 cc.

At an operating temperature of 450°F, this unit is capable of oxidizing 100% of the methane passed through it. The unit is designed to operate at an inlet temperature of 105°F, outlet temperature of 140°F, heater power of 8 W, heater warmup time of 5 hr, a gas flow rate of 0.6 lb / hr, and 7 psia pressure. Under these conditions, the burner removes 0.0066 lb / hr of methane when the inlet methane concentration is 1.1% by volume (atmosphere = 44.2% O_2, 54.7% N_2, and 1.1% CH_4). Fig. 14-37 represents the performance of the catalyst as a function of temperature.

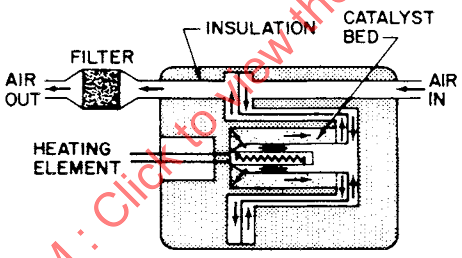


Figure 14-36 - Typical catalytic burner

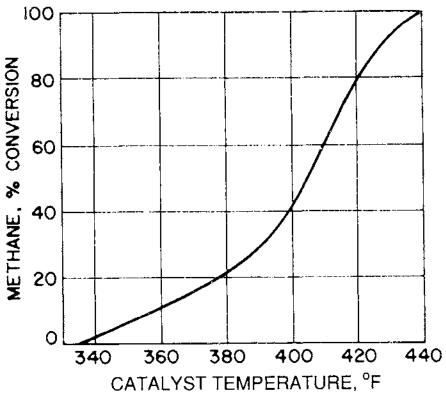


Figure 14-37 - Catalytic burner performance

Ammonia is not oxidized to the desired water and nitrogen over most catalysts under these conditions and instead may tend to form nitric oxide and nitrous oxide, which are toxic. Also, ammonia is not adsorbed by activated charcoal. It is, however, removed by specially treated charcoal known as reconstituted charcoal. Reconstituted charcoal is a proprietary product, able to adsorb about 5% – 10% of its weight in ammonia. It is probable that solid acidic materials may also be employed for removal of ammonia and low molecular weight amines. These compounds would remove ammonia by chemical reaction, forming solid ammonium compounds as products (for example, potassium acid sulfate).

Fluorinated hydrocarbons will be removed in the catalytic burner and molecular sieve beds. Glycol and methanol will be oxidized in the catalytic burner.

3.5.2.4 Microorganisms

In dynamic microorganism ecology, a natural balance of organic life is maintained. When this balance is upset, microorganisms may change their diet and habits, as well as their characteristics, in order to survive. By the same token, any given dynamic system can be balanced with no evidence of growth; however, the introduction of any novel compound compatible with that system may trigger growth and, in a matter of hours, severe contamination may occur. Sublethal doses of nonspecific anti-microbial compounds will not be effective in an environmental control system because they may inhibit beneficial as well as harmful organisms, resulting in an overgrowth of nonsensitive or resident strains of organisms.

Many similar effects must be investigated to determine the overall effects of contaminants in systems. The effects on microbiological growth of the many factors encountered by a relatively stable system, from fabrication to finished end use, must be understood, including their effects on amino acid structure and on the cytochrome, flavochrome, and energy transference cycles. Other effects to be investigated include selective screening of isolated and combined factors in systems against individual organisms and combinations of organisms recovered in their selective environments.

The most reasonable approach to take in determining these effects is to expose selected microorganisms and their transmuted forms to the same environmental conditions of temperature and electrochemical action, metals, coatings, and corrosion found in components of the spacecraft. A number of organic substances have microbiostatic properties. Some of the substances that appear promising include halogens, acids, alkalies, heavy metal salts, phenols, alcohols, and quaternary compounds.

The catalytic burner may provide some bacterial control through thermal action. However, if mockup testing demonstrates that the catalytic burner is insufficient to handle the microorganism production rate, ultraviolet (UV) lamps can be incorporated in the air processing loop ductwork for additional control of bacterial infection. Present estimates indicate that 1 hr operation of the lamps every 8 hr should be sufficient.

4. GAS STORAGE

Storage of low boiling point fluids such as nitrogen and oxygen in space vehicles can be accomplished by several techniques. The most common methods considered are:

1. Ambient temperature gas storage at high pressure.
2. Single phase cryogenic fluid storage at supercritical (higher than fluid critical) pressure.
3. Two phase cryogenic fluid storage at subcritical (lower than fluid critical) pressure.

A brief discussion of each of these methods is presented in the following paragraphs.

4.1 High-Pressure Storage

High-pressure storage is attractive mainly from the standpoint of reliability due to system simplicity. While this storage method is only optimum (weight and volume) for relatively small payload missions, it has an inherent, almost unlimited, standby capability and is advantageous for low consumption, long duration missions. Procedures for the design and optimization of high-pressure vessels are fairly well known. Basically, these relate to the desirability of minimizing container volume penalties by the use of elevated storage pressures without incurring excessive shell weight.

It can be shown that if the stored fluid acts as an ideal gas, the weight of the container designed to hold a given charge is virtually independent of pressure. Thus, with the development of high-strength structural materials, there is an incentive to investigate high-pressure storage. Gas compressibility effects, however, are also of importance in optimizing storage vessel designs. At pressures over several thousand psi, gases become decreasingly compressible, so that volume savings at high pressures are diminished. Thus, as pressure is increased, overall vessel volume may pass through a minimum and actually increase as a result of wall thickness effects. Therefore it is important to investigate thoroughly the effect of charge pressure level on both container weight and volume in optimizing storage vessel designs.

Figs. 14-38 and 14-39 show some representative weights and sizes for high-pressure spherical vessels. Figs. 14-40 and 14-41 show the density of oxygen and nitrogen at high storage pressures.

The vessel geometry and its effect on overall vehicle design is an additional consideration in optimizing high-pressure storage tanks. That is, full utilization of the allowable volume must be investigated with respect to geometry. Though vessel weight optimization seemingly indicates use of spherical containers, this depends realistically on the available volume. The cylindrical vessel affords greater volume utilization and thus permits the storage of a given amount of gas at a lower pressure. Fig. 14-42 shows the cylindrical-to-spherical weight ratio as a function of the L/D of a cylinder for various ratios of end cap to cylindrical thickness, R.

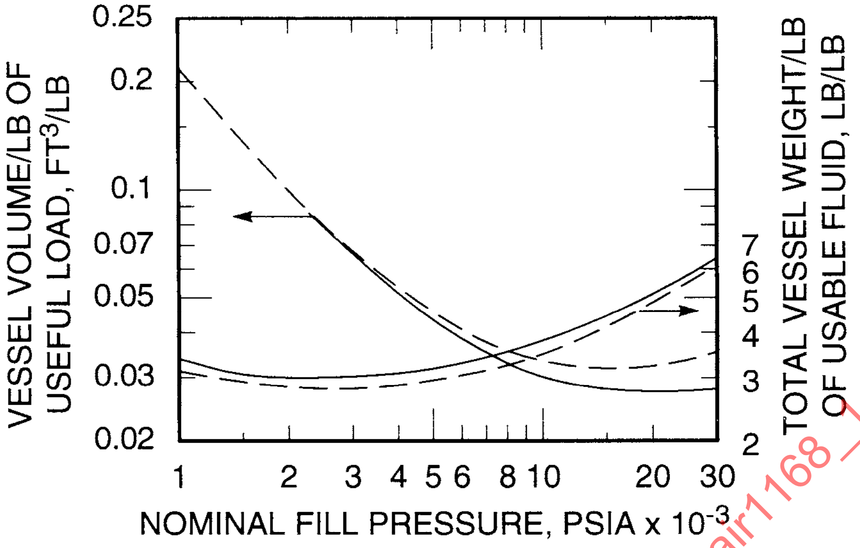


Figure 14-38 - Weight and volume of spherical oxygen storage vessels, safety factor 1.88; solid curves for SAE 4340 steel and dotted curves for Ti C-120 AV

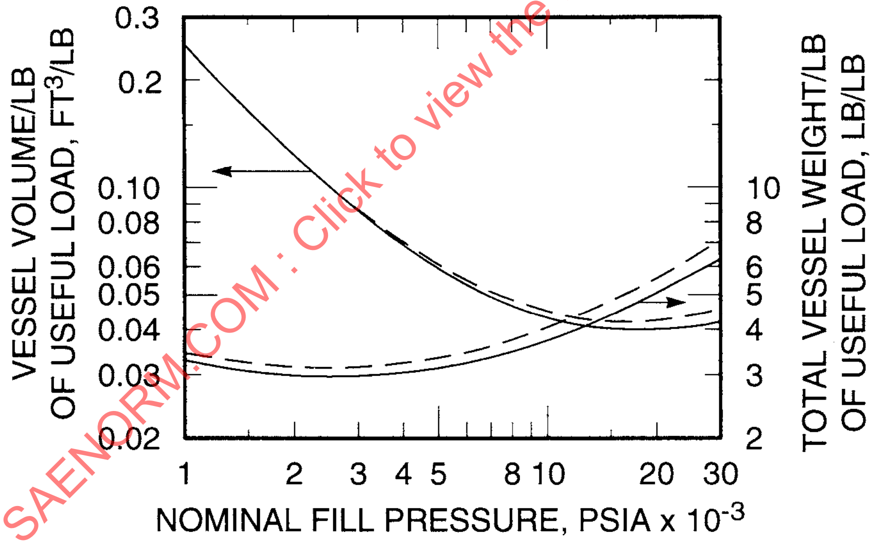


Figure 14-39 - Weight and volume of spherical nitrogen storage vessels, material Ti C-120 AV; solid curve safety factor 1.67, dotted curve safety factor 1.88

Although high-pressure storage of oxygen has been used, primarily because of its simplicity, it must be realized that there is a problem with respect to high gas flow delivery rates. Since the process within the tank tends to be a purely isentropic blowdown process, adiabatic cooling can lead to partial liquefaction of the contents. According to classical theory, when

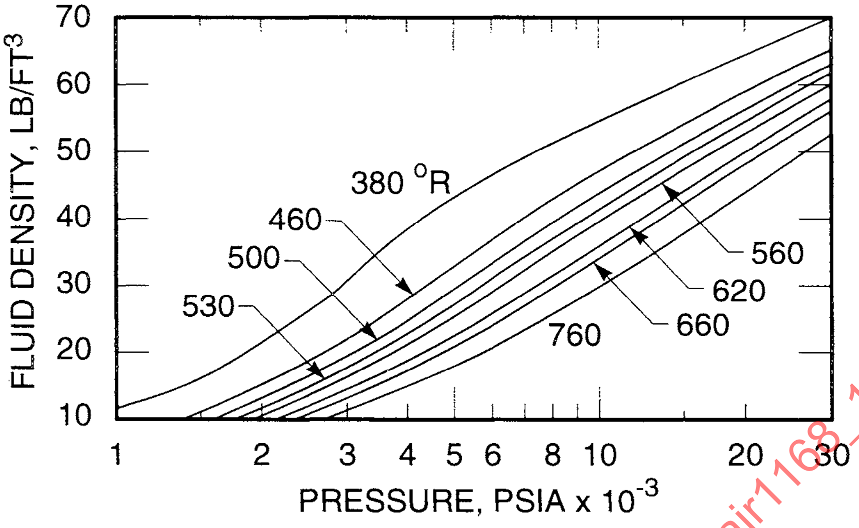


Figure 14-40 - Oxygen densities at high pressure

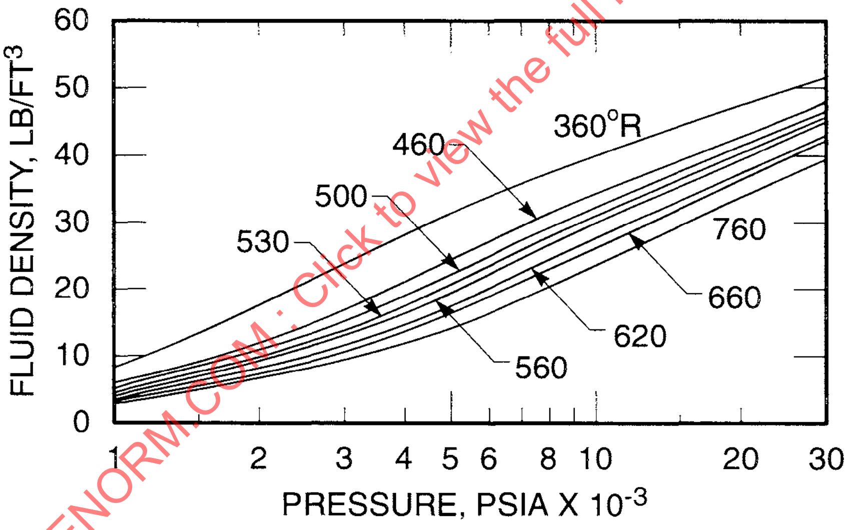


Figure 14-41 - Nitrogen densities at high pressure

gravity does not exist, heat transfer coefficients do not exist. Without the possibility of convective heat transfer, radiation and conduction are the only modes of heat transfer to the contents which would allow substantial deviation from the purely isentropic process.

Detail studies have shown that these modes of heat transfer are sufficient only for the special case of relatively low flow rates. By dimensionless analysis, it can be shown that the significant parameter is the ratio of the surface area of the tank to the time required to reach the liquid vapor dome. This can be explained with reference to Fig. 14-43. Point A indicates

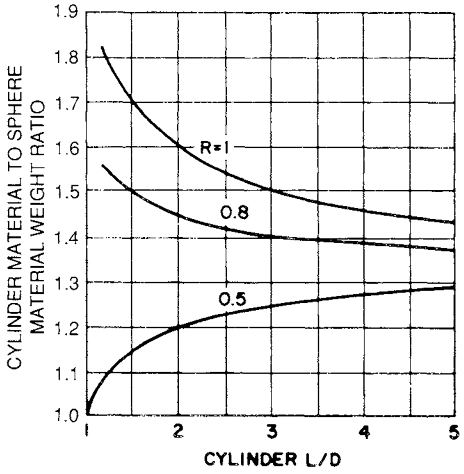


Figure 14-42 - Comparison of spherical and cylindrical vessel weights (L/D = overall length-to-diameter ratio)

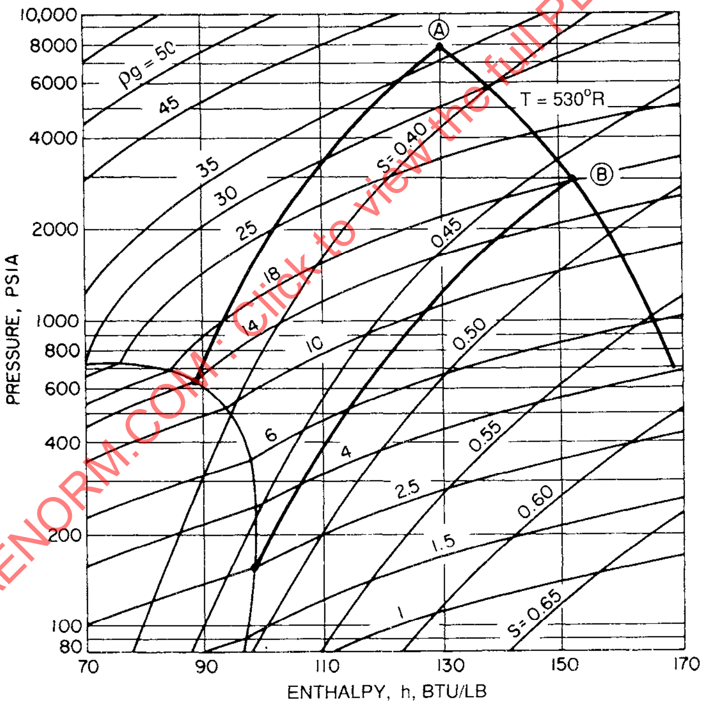


Figure 14-43 - Isentropic blowdown process; temperature, 530°R

the storage conditions beginning at 7500 psia and 530°R. Following along an isentrope until it intersects the liquid vapor dome, the density is approximately 14 lb / ft.^{3} This represents 64% utilization.

In order to deviate from the isentrope significantly, heat must be added to the gas. Because the radiation and conductive modes limit the amount of heat transfer, it may be difficult to achieve the heat transfer required. Actually, because of the thermal diffusivity of the gas, strong temperature and density gradients are established when the heat is added externally, as from the tank walls.

If high-pressure gas is to be used for rapid repressurization of the cabin, a lower pressure should be utilized. Point B on Fig. 14- 43 shows the corresponding state point for 3000 psia storage. The initial density at 530°R is 18 lb / ft^3, while the density at which the liquid vapor dome is reached is 2.5 lb / ft^3 for a utilization of 86%. Note, however, that if the storage quantity is sized for multiple repressurization, with sufficient time between repressurizations, this utilization penalty may be ignored. Tank heaters, similar to those used for cryogenic tanks, can be installed to avoid this problem.

4.2 Supercritical Storage

Supercritical cryogenic storage of fluids ensures single phase vapor delivery under all gravity conditions just as high-pressure gas storage does; however, supercritical cryogenic storage permits large payload quantity storage in a minimum system volume and weight. Therefore, supercritical cryogenic storage is used for large payload capacity and high consumption applications that require minimum storage volume and weight.

Supercritical storage of cryogenic fluids is illustrated in Fig. 14-44. The initial tank fill condition is indicated by point 1. The fill state represented here as point 1 is a mixture of saturated liquid and vapor at atmospheric pressure. After fill, heating results in pressurization at constant density. During this process (1-2), the liquid expands until it fills the entire container.

Once the desired supercritical pressure is reached at point 3, fluid delivery can be initiated. Constant pressure operation, as indicated by path 3-4, is achieved by the simultaneous addition of heat to the storage volume. Here, as long as supercritical pressures are maintained, the stored mass remains as a homogeneous, single phase fluid.

As shown in the figure, the fluid temperature rises during operation. When the temperature of the fluid in the vessel becomes significantly higher than the critical temperature, controlled heat input is not necessary for maintenance of a single phase. The ambient heat leak into the vessel in most cases is adequate to maintain a somewhat isothermal path to point 4' while vessel pressure is free to decay. Nearly full utilization of the stored fluid is still realized, since the difference in residual densities at points 4 and 4' is of secondary importance compared to the total charge.

Fig. 14-45 illustrates a supercritical storage and supply system.

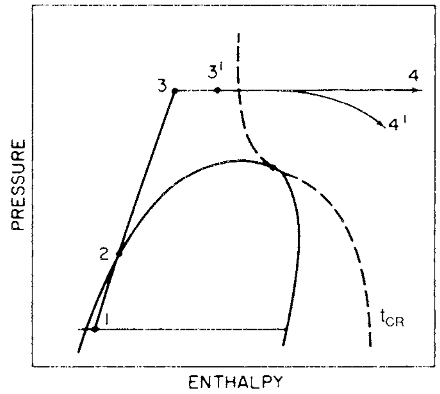


Figure 14-44 - Pressure-enthalpy diagram, thermally pressurized supercritical storage; points 1 = fill, 1-3 = initial pressurization, 3-3' = standby venting, 3-4 = constant pressure withdrawal

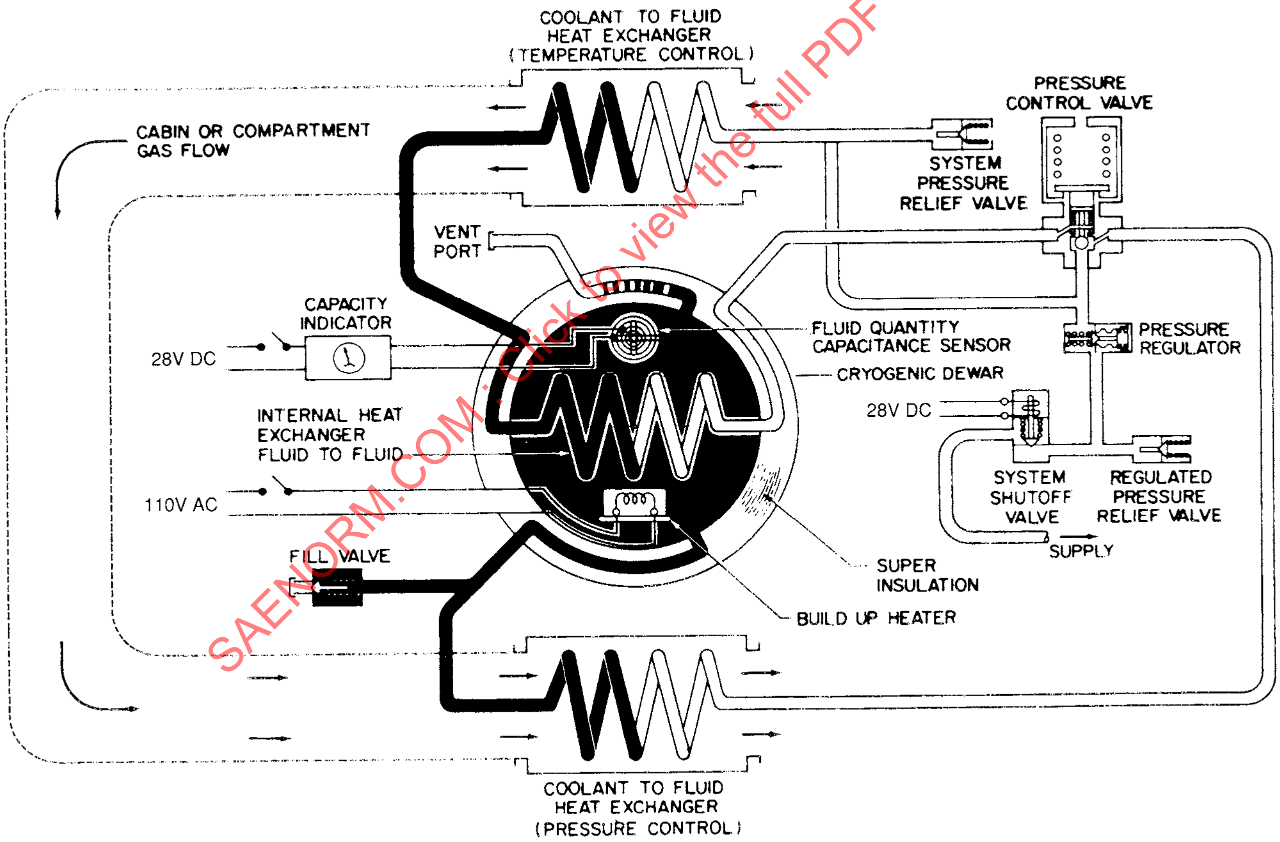


Figure 14-45 - Supercritical storage and supply system, cryogenic fluid coolant loop heat exchange pressure and temperature control

4.3 Subcritical Storage

The supply system of the two-phase subcritical tank makes use of the difference in temperature of equilibrium mixtures of liquid and vapor at different pressures, to ensure withdrawal of fluid as a vapor. Fig. 14-46 schematically describes the thermodynamic states involved. The fluid being withdrawn from the container is passed through an internal pressure regulator in which the fluid pressure is throttled from vessel storage pressure to system delivery pressure. This pressure regulator senses delivery pressure and closes when there is no flow demand on the system.

The expanded fluid is passed through a heat exchanger within the vessel prior to entering the transfer line to the vessel exterior. By designing this internal heat exchanger for complete vaporization when 100% liquid enters the withdrawal port, vapor delivery under all other liquid-vapor mixture states is ensured. Since stored liquid is evaporated within the vessel or internal heat exchanger prior to withdrawal, heat must be added to the fluid in the vessel during fluid withdrawal, to compensate for the heat of vaporization of the liquid phase.

A number of schemes have been considered for introducing and controlling the heat input to the vessel. The method under consideration is shown in Fig. 14-47. The storage pressure is used as the criterion for determining the amount of external heat required. A heating coil located within the storage vessel and a bypass valve are used, together with external heat exchangers. This method of controlled addition of heat has been used to accomplish the same function in supercritical storage and supply systems. In actual laboratory tests, these systems performed well, and similar performance is anticipated under zero gravity conditions, perhaps demonstrated by now.

The normal supply internal pressure regulator monitors downstream pressure. If downstream pressure is below the specified setting, the valve permits flow. If downstream pressure rises above this setting, the rapid vaporization of liquid in the internal heat exchanger raises the pressure in the delivery line and closes the internal pressure regulator. The delivery line volume is sized to keep system pressure fluctuation small.

Zero gravity venting of fluid to prevent excessive pressure buildup during standby presents the same problem as zero gravity delivery. For this reason, an additional internal pressure regulator is required. When vent pressure is reached, the regulator vents fluid into the internal heat exchanger, located in the delivery line. Delivery line pressure is prevented from rising excessively by an external relief valve. As the delivery line is used for venting, a second pressure regulator is required in the supply system. This regulator is normally open, but closes during standby venting condition to prevent a rise in system delivery pressure.

During low demand operation, the quantity of fluid withdrawn from the storage vessel is of the same order of magnitude as the amount of fluid vaporized by heat leak from ambient. If the fluid withdrawn from the vessel is the vapor thus formed, then no pressure change occurs.

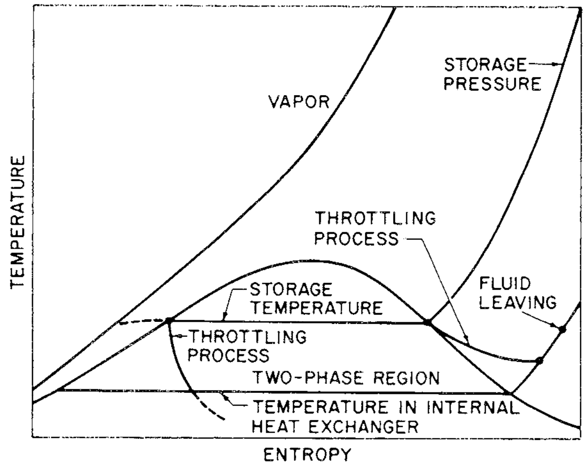


Figure 14-46 - Temperature-entropy diagram describing subcritical storage with vapor removal

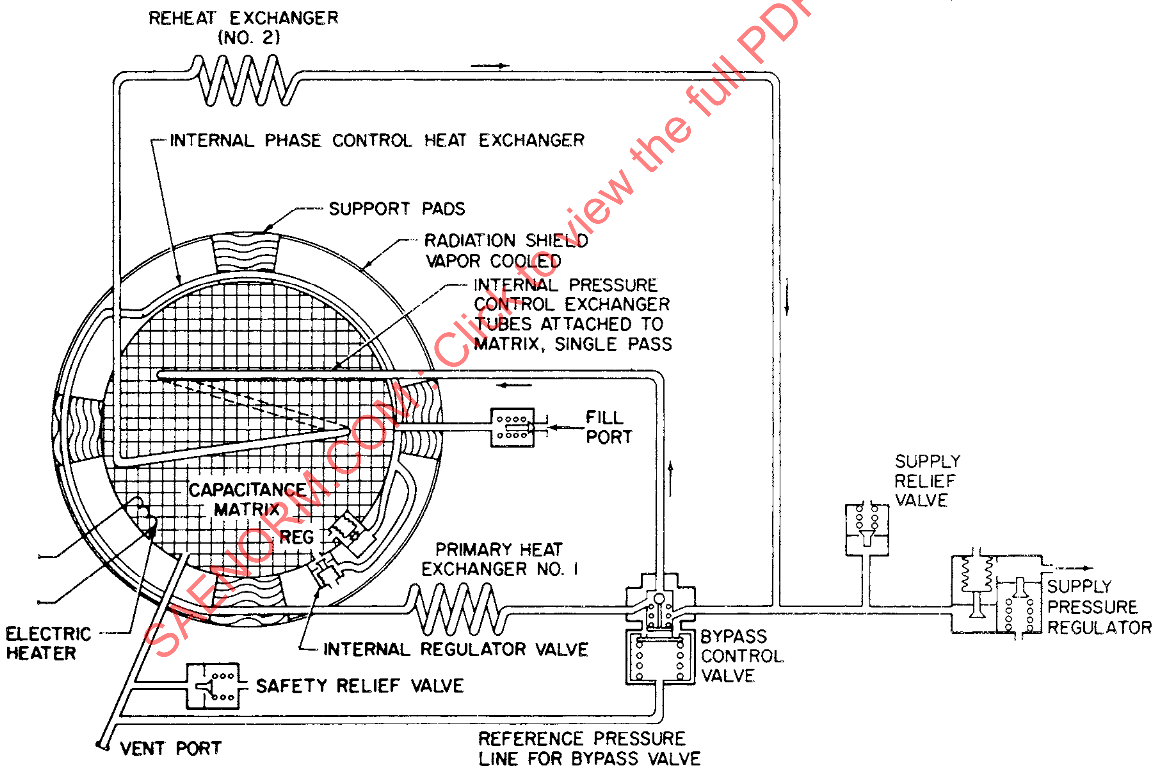


Figure 14-47 - Subcritical cryogenic storage and supply system

The internal heat exchanger assures that only vapor is supplied to the delivery line. Heat removed from the stored fluid causes condensation of vapor within the vessel, with consequent lowering of tank pressure. This pressure drop is simultaneously being counteracted by heat input from ambient. Thus, a stable operation is established. In other words, the enthalpy of the fluid leaving the storage vessel / internal heat exchanger system is kept at a maximum and the enthalpy of the stored fluid at a minimum. This minimizes venting or loss of stored fluid.

The vent system also uses the internal heat exchanger to maximize the enthalpy of vented fluid. Although, at vent pressure, liquid may leave the storage vessel, it is vaporized at a lower pressure in the internal heat exchanger. This vaporization results in the condensation of vapor within the vessel and a reduction in internal pressure. An additional feature of this vent system is that leakage through the internal vent valve can be directed to the supply line. Further, during non-use periods, this leakage is treated in the same manner as normal vent fluid, so that the internal leakage results in no more fluid loss than if there were no leakage.

A comparison of the weights of cryogenic storage systems for oxygen and nitrogen is shown in Figs. 14-48 and 14-49. The effect of nonvented standby time on cryogenic storage is shown in Figs. 14-50 and 14-51.

4.4 Comparison of Storage Concepts

Some of the comparative advantages and disadvantages of the three storage concepts are shown below.

4.4.1 High Pressure, Gaseous Storage

Some advantages of this system are: simplicity and reliability, indefinite standby, rapid repressurization flow (see discussion in Par. 4.1), and high-pressure source for backpack charging. Its great disadvantage is its excessive weight.

4.4.2 Supercritical Storage

The advantages of this system are: production status is operational, simplicity, conventional capacitance probe quantity sensor, and compatibility with 1000 psia accumulator and backpack tanks. Its disadvantages are: it cannot transfer fluid in a supercritical state effectively, it has heavier tank weights than subcritical, and ground top-off is complex due to pressure buildup.

4.4.3 Subcritical Storage

Advantages are: it has the lightest weight, filling and top-off is much simpler than supercritical, and zero gravity fluid transfer appears possible, although not completely developed. Its disadvantages are: complex quantity measuring by three-dimensional capacitance matrix, not readily compatible with a high pressure accumulator, more difficult operational procedures for refilling backpack tanks, and delivery system is more complex and requires more plumbing connections.

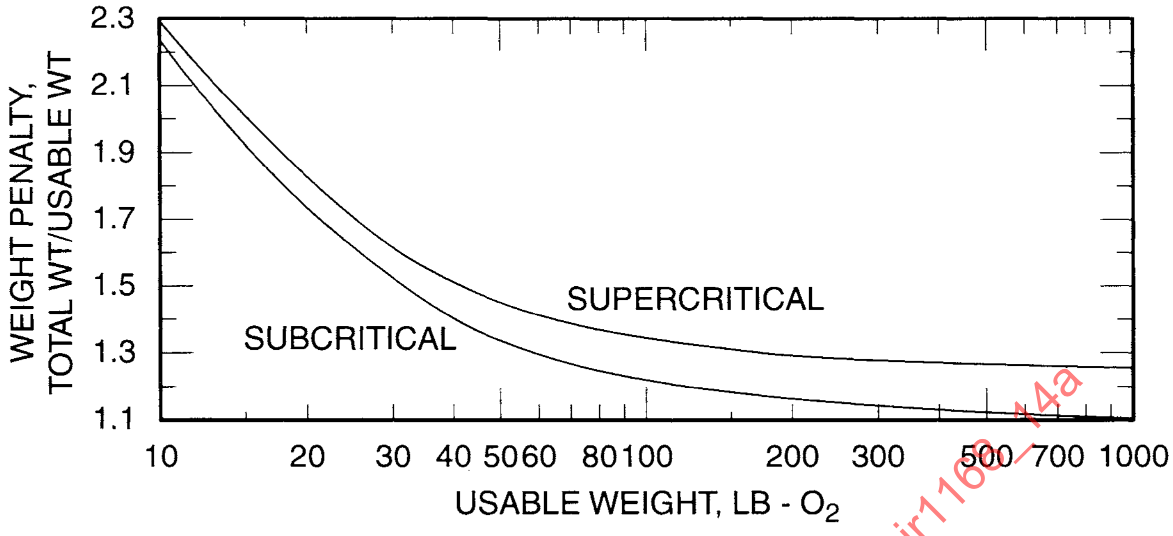


Figure 14-48 - Cryogenic oxygen tank weights as a function of usable weight. Conditions: P_c = 738 psia, 72 hr standby time, 1.0 lb / hr average flow rate, relief pressure = 1000 psia

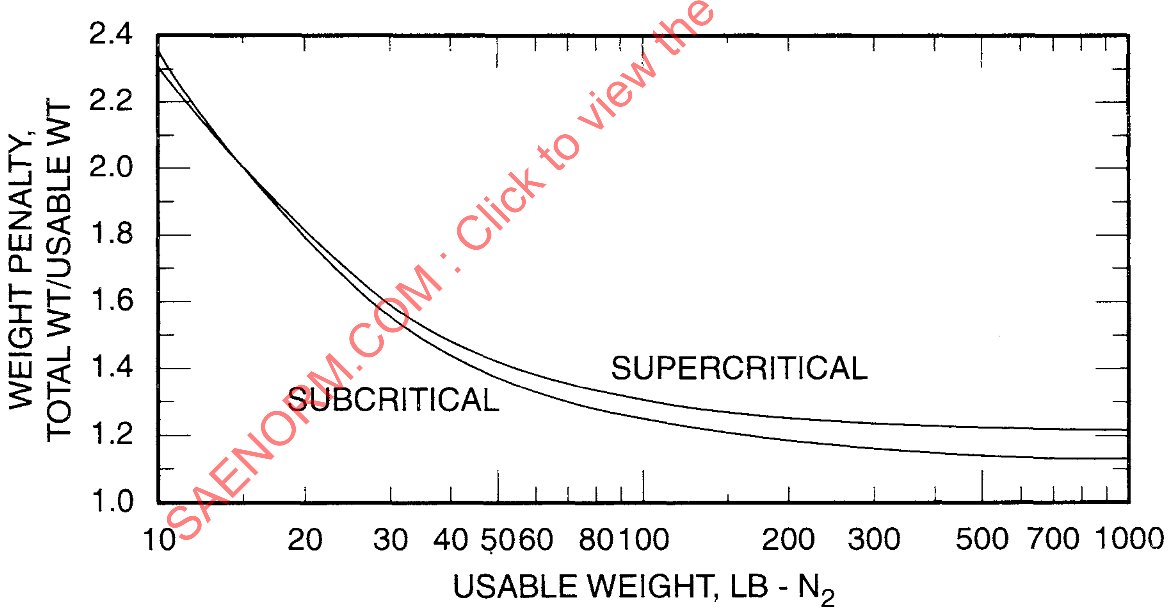


Figure 14-49 - Cryogenic nitrogen tank weight as a function of usable weight. Conditions: P_c = 493 psia, 72 hr standby time, 1.0 lb / hr average flow rate, relief pressure = 600 psia

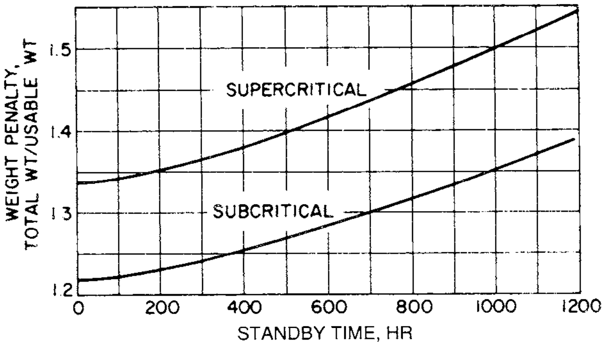


Figure 14-50 - Effect of nonvented standby time on cryogenic oxygen tank weights

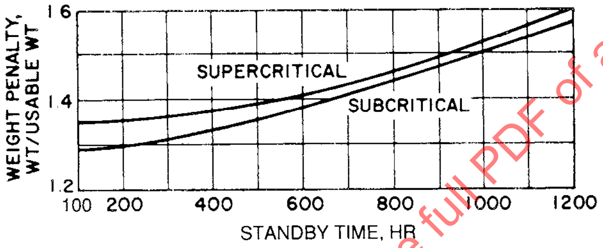


Figure 14-51 - Effect of nonvented standby time on cryogenic nitrogen tank weights

5. WATER RECLAMATION

5.1 Introduction

To enable man to expand space travel beyond short duration exploration of space (30 – 60 days), the replacement of or modification to several presently used spacecraft life support techniques must be made. This must be done to reduce the overall spacecraft weight which, based upon anticipated thrust capabilities, limits the spacecraft mission duration and possible accomplishments. In the field of life support equipment, the areas being closely considered for significant total equivalent weight reduction (total equivalent weight is defined as the sum of equipment weight, expendable weight , and the weight charged to the life support system for system power requirements) include atmosphere supply storage techniques, carbon dioxide reduction, and water reclamation.

The last of these areas mentioned above, the purification of body waste water, wash water, and condensed water from the cabin environment, has been extensively studied, leading to the design and fabrication of several prototype water reclamation systems by NASA, the Air Force, and the leading life support system suppliers. Several water reclamation techniques based upon different principles have been evaluated. These techniques include: liquid-to-vapor phase change, electrodialysis, electrolysis with subsequent recombination, and chemical treatment.

An analytical examination and prototype design of these systems has been performed in an attempt to determine which is more suitable for spacecraft application in terms of total equivalent weight required to meet overall spacecraft life support requirements. At this time no single candidate system concept has proved itself to be a singularly outstanding choice for all extended duration missions. The single largest reason for this uncertainty is the varying development status of the competing systems. No one system is truly optimized nor has performance been qualified for a spacecraft application; thus, ultimate system weight cannot be accurately determined.

Other factors that lead to the uncertainty in concept choice are power penalty and mission duration for which a comparison can be made. The reason for this is that some concepts require a higher system weight with comparatively low power and expendable weight requirements, while other systems by comparison are light but require significant power or expendables. Expendable weight is a direct function of mission duration, whereas power equivalent weight is dependent primarily upon the type of power supply used and the system power requirements. For the purpose of discussion of the relative merits of the candidate system concepts, a set of mission requirements and restraints must be established. For the following comparisons the conditions will be:

1. Mission duration of 420 days (typical on a Mars type mission).
2. Power penalty of 500 lb / kW (depending on the particular spacecraft selected, a range of values between 200 to 500 lb / kW would be more correct).
3. Crew size of six men.
4. Water from fecal waste will not be recovered.

Each of the candidate systems will be presented, discussing the system concept, the predicted flight configuration performance, total equivalent weight, the status of system development, and the problem areas that must be resolved. The discussion will consider urine, wash water, and humidity condensate water reclamation separately because of the differences in contaminants present and the purification techniques required for each type of waste water.

The discussion of the reclamation concepts will point out both the problems that must be solved and the merits of each system. The assessments are not sufficient at this time to finalize the selected system concept. However, it will be seen from the comparative discussions that a few of the system concepts should be eliminated unless significant technological breakthroughs occur, and that concentrated effort must be expended in certain areas to define an optimum water reclamation system concept for extended duration missions.

5.2 Water Reclamation From Urine

5.2.1 Water Reclamation by Electrodialysis

Water reclamation by electrodialysis has received considerable interest throughout the industry because of its apparent simplicity, low weight, and power requirements. Industry experience in commercial brackish water purification has been extended into the water reclamation field, thus offering a system with considerable previous experience in general terms although somewhat limited in specific application.

Fig. 14-52 presents the basic schematic for the electrodialysis process. The primary component of the electrodialysis system is the stack itself. This stack consists of alternate pairs of anion and cation permeable membranes, with a potential difference maintained across the membranes with electrodes to remove electrolytes from the circulating solution, thus purifying the water. Nonelectrolytes cannot be removed prior to or subsequent to processing by the membranes. Thus, the only major contaminant that will be removed from urine by the electrodialysis stack is sodium chloride.

Since urea, which is a nonelectrolyte, is the main contaminant present in urine, the process must include some alternate means of removing urea. In the proposed system, the urea is removed prior to the membrane stack by charcoal filtration after having been treated with a complexing agent. A suitable complexing agent, which precipitates the urea and allows it to be filtered out by the charcoal, has been developed.

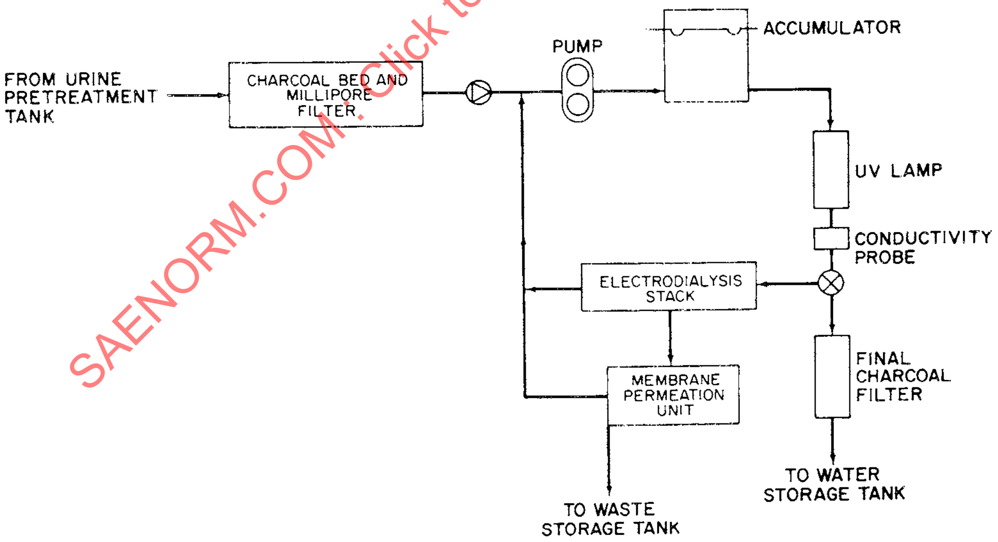


Figure 14-52 - Water reclamation by electrodialysis

After filtration the treated urine is passed to the electrodialysis stack where the ions are evenly distributed at the inlet. However, upon coming in contact with the potential difference across the membranes, ion separation occurs. The positively charged ions pass through the cation permeable membranes under the influence of the applied potential, but are unable to pass the anion permeable membranes. A similar action is imposed on the negatively charged ions by the anion permeable membranes, thus removing both types of ions from the main process stream.

By alternating cells throughout the electrodialysis stack and passing the process water through every other cell, purification can be achieved. The alternate cells which pass the water become depleted of ions , with the other cells becoming more concentrated by the removed ions. The process is continually repeated and the process water recycled until the required degree of desalination is achieved. The concentrate stream contains a certain quantity of endosmotic water that has dissolved in it all the salts and represents a fraction of the original water that cannot be recovered by this process. After completion of desalination in the electrodialysis cell, the processed water is final treated by charcoal filtration and irradiation with ultraviolet light prior to storage for final usage.

Some problems may exist in the basic electrodialysis stack in separating trace quantities of oxygen and hydrogen that appear at the electrodes. Basically, the process is quite adaptable to zero gravity operation if these trace gases can be minimized or suitably removed. This remains as a design and development problem, which must be solved prior to utilization of this approach; however, it is not considered a major problem because it is primarily a gas-liquid separation process that has received considerable attention for other applications.

In the electrodialysis process, some water (called endosmotic water) is transferred into the concentrate stream along with the ions. This limits to approximately 95% the amount of water that can be recovered from urine by the electrodialysis stack. In an effort to increase the yield still more, the addition of a membrane permeation unit has been proposed. This will extract water from the concentrate stream and raise the overall recovery to approximately 97%. The membrane permeation unit extracts water from the concentrate stream by distilling water through a perm-selective membrane that will pass water vapor but not salt ions. While this additional unit increases the yield, it also increases the system complexity.

Many problem areas of the electrodialysis process must be resolved before it is suitable for manned space vehicle applications. The problem of heavy expendable weights due to charcoal is perhaps the greatest of these problems. However, other problems that have become apparent are those of functional operation of the membrane permeation unit and demonstration of membrane reliability in use with urine over an extended period of time.

Membrane life has been quite good in brackish water plants; however, the problems may be significantly different and can best be proved by extended duration testing.

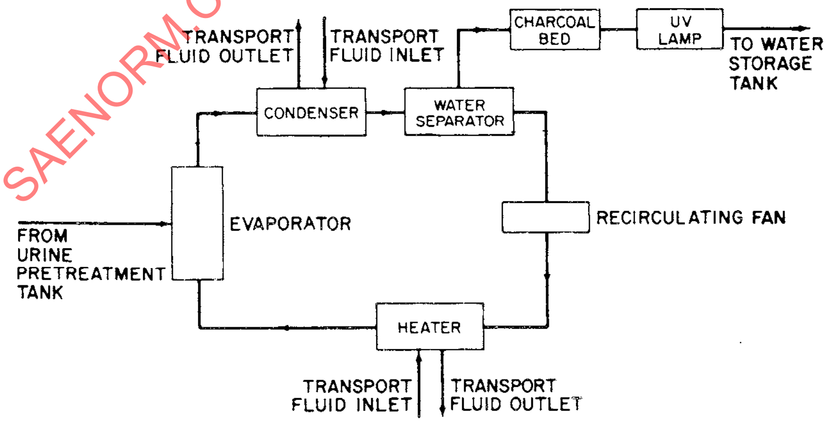
One study has indicated that the membrane pore size is so small as to inhibit the passage of large ions. This means that any large ions present in the urine would remain in the effluent stream and could lead to progressive buildup of contaminants within the system. This area must also be more fully evaluated experimentally prior to a system selection. There exists the possibility that in a urine solution, organic membranes may serve as sites for bacterial growth.

If extended testing proves that high-purity water is repeatedly attainable, and if the membrane problems can be overcome, then electrodialysis can be considered a very promising approach. Among its advantages are that it requires a minimum of moving parts, has low weight, volume, and power requirements, and has predictions of long life.

5.2.2 Water Reclamation by Air Evaporation

Water reclamation by direct evaporation into a circulating air stream is the simplest of all water reclamation approaches. Fig. 14-53 presents a schematic of the air evaporation system considered in this analysis. This is a closed system; that is, air is constantly recirculated throughout a closed loop. Air evaporation may also be used in an "open loop" system approach where the circulating cabin air is the process media; however, development testing on the problem of odor carryover into the cabin is required before full evaluation of this method can be completed.

In the closed system operation the circulating air is the normal cabin atmosphere at normal cabin pressure, so that there is no pressure loading on the system ducting. The system consists



Insert Figure 14-53 - Water reclamation by air evaporation of an evaporator, condenser, fan, water separator, and heater. The process urine is brought into the wick evaporator after a series of pretreatment and filtration processes and is distributed through wicks in the evaporator where the hot air evaporates the water, leaving the solids in the wicks. From this point, the vapor is condensed to water droplets similar to the condensation process taking place in the main environmental control system, and is then removed by a water separator similar to or identical to (depending upon size requirements) the one in the main system.

The cool air then passes through a heater where the heat required for evaporation is returned to the air by a circulating heat transport fluid (in a closed system) or by the cabin heat load (in an open system). The hot air then reenters the air evaporator to close the cycle and complete the process. The condensed moisture separated by the water separator is pumped out to storage or post-treatment, depending on its eventual use. One of the virtues of this system is the ability to recover 100% of the water. This is achieved simply by operating the system till the wicks are dry.

In the pretreatment process, a chemical additive serves two purposes. First, it disinfects the urine to retard bacterial growth, and secondly, it complexes the ammonia ions so that they will not be distilled as free ammonia along with the water vapor. This treatment is important because the urine-soaked wicks can retain only contaminants that are nonvolatile.

One other element that may be necessary in the overall system is an odor control device within the circulating air stream. This is desirable as a means of minimizing the potential odor generation by the evaporating urine and to preclude any immediate problems that could be caused by a leak in the system. The amount of charcoal required for this odor protection is small in comparison with other expendables.

The primary expendable requirements for an air evaporation system are the wicks in the evaporator, pretreatment chemicals, and charcoal filters. Since the solids in the urine remain in the wicks, the wicks must be changed periodically to maintain their capacity and efficiency. This replacement problem must be the subject of development to assure an optimum method of replacement from a weight and ease of maintainability point of view, but is considered minor in its effect on overall development status of the system. The evaporators may provide some problem in wick distribution, but this is also considered a development problem and is not a severe design drawback.

Water reclamation by the air evaporation approach is a promising contender because of its extremely low fixed weight and power penalty and overall simplicity. The achievement of complete water recovery is very significant, and means that useful water beyond the basic metabolic needs may be provided for other purposes, such as electrolysis. Reliability is enhanced because heat transfer to the urine occurs at a gas-liquid interface rather than across a metallic surface where scaling and corrosion could be troublesome.

In this system the urine residue is deposited on the wicks in the evaporator and, when saturated, the wicks are dried out by simply operating the system without the addition of urine. When the reside is in this dry solid form, handling and storage presents no problem. Another interesting factor is the potential ease of application within the main thermal control system. If development testing illustrates that an "open loop" approach can be taken to air evaporation, a further reduction in system fixed weight is possible, since the air evaporation unit condenser, water separator, fan, and heater can be eliminated and their functions can be performed by the corresponding components in the basic environmental control system.

The system requires limited expendables for pre-treatment and post-treatment as well as periodic changing of the wicks in the evaporator. The weight of the expendables is approximately 3% of the total weight of urine processed.

5.2.3 Water Reclamation by the ELF Technique

Water reclamation by the ELF technique (electrolysis cell / fuel cell system) combines ion exchange membrane electrolysis cells with ion exchange membrane fuel cells so that oxygen and hydrogen, which are electrolyzed from urine, recombine in the fuel cell to produce potable water.

Fig. 14-54 presents a simplified schematic of the ELF system. Operation is quite simple, with no major moving parts, and success is mainly dependent upon the reliability of the electrolysis cell and the fuel cell. Raw urine is fed into the electrolysis cell where it is disassociated into hydrogen and oxygen. The two gases are then utilized as the input fuel for the fuel cell, where recombination occurs as part of the process and potable water is an end product. The power

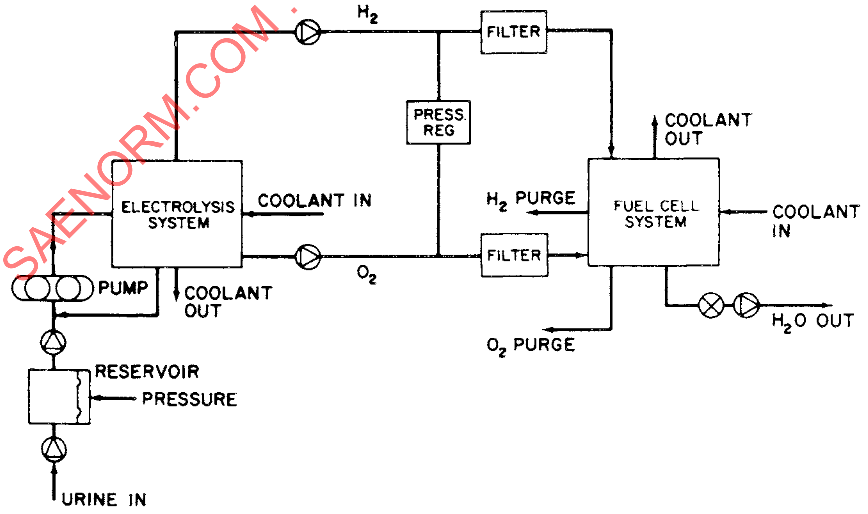


Figure 14-54 - Water reclamation by the ELF technique

generated by the fuel cell contributes to reducing the high power requirements of the electrolysis cell. Development work on this system has been limited, and certain long term mission hesitancies arise from detailed analysis. Membrane life problems have occurred during some extended life testing.

Another area of concern with this approach is the apparent lack of membrane protection in the electrolysis cell itself. The introduction of raw urine directly to the electrolysis cell may create problems for long life operation, caused by the urea and other contaminants that remain within the cell as the hydrogen and oxygen are given off. These questions make application of the system somewhat more complex than illustrated in the schematic of Fig. 14-54. If an ELF system were to be operated for extended periods, the cell electrolyte would have to be replaced. In this study an expendable weight penalty was determined, assuming the replacement of electrolyte at 60 day intervals.

The ELF water reclamation system has as its main potential advantage a simplified stop-start procedure in comparison with many other water reclamation systems. However, the extremely high power requirements coupled with the membrane life problem may make the system noncompetitive for the initial long duration missions. Later system applications, where the cost of power and the launch capacity of the booster are more favorable, could evolve the ELF system as a definite candidate, depending upon the final expendable utilization rates.

Qualitatively, the system reliability should be considerably less than that of some of its counterparts because of the comparatively exotic processes utilized and the considerable amount of valving required for actual system operation (not shown in the simplified schematic). This feature would have to be evaluated further prior to utilization of this approach.

Water has been tested and appears potable from the results of system operation to date. A reclamation efficiency of approximately 90% has been exhibited, which is low by comparative standards and would require some improvement for both the case where urine is used solely to provide the metabolic water balance and especially for the case where the excess water generated by the crew is utilized as a partial oxygen make-up.

5.2.4 Water Reclamation by Vapor Compression

Fig. 14-55 presents a simplified schematic diagram for a vapor compression system. The system consists essentially of a urine evaporator, compressor, and condenser. For adequate operation, the urine must be treated prior to introduction to the evaporator and subjected to a certain amount of post-treatment after condensation, to assure potability. The schematic indicates that the problem of gas-liquid separation in zero gravity is solved for this approach by rotation of the evaporator and condenser.

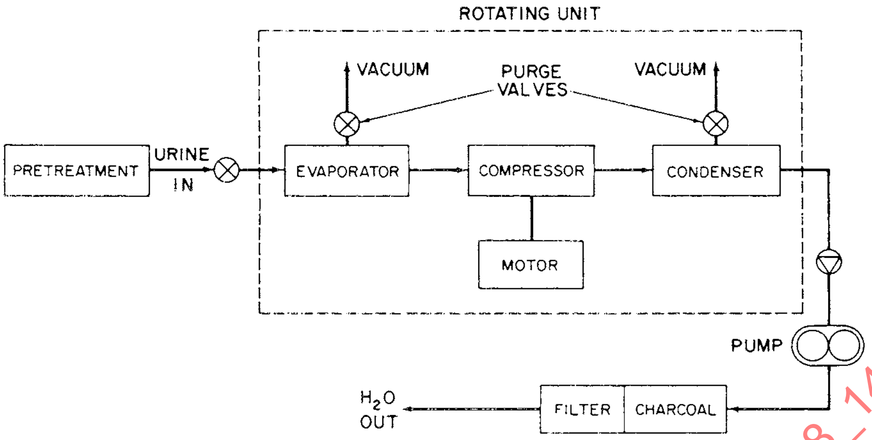


Figure 14-55 - Water reclamation by vapor compression

In actuality, the evaporator and condenser are regenerative in nature, with evaporation occurring in the center cylinder of a rotating set of concentric cylinders and condensation occurring between the walls of the two cylinders, providing regenerative heat exchange through the condenser wall to the evaporator. The compressor is included in this rotating configuration and provides the energy input to the system. The process operates at low pressures which are maintained by periodic purging of the system to space vacuum.

System operation may be traced as follows: The pretreated urine is evaporated after introduction to the system. The compressor raises the vapor pressure of the steam and the condenser condenses the vapor to water. The compression allows the latent heat of condensation to be used to evaporate the water from the urine. Condensate is drawn off the condenser, post-treated, and then passed to storage tanks for eventual use.

This system has the primary problem of scale formation on the evaporator heat transfer surfaces. This formation, if allowed to continue for an appreciable period of time, degrades the heat transfer process to a point where system efficiency is below acceptable limits. However, the system minimizes this problem by operating as a semi-batch type process with periodic cleaning of the evaporator by removing a plastic liner. This method of scale removal presents a slight initial degradation to the heat transfer surface, owing to the presence of the plastic liner, but allows the complete cleaning of the surface. A disadvantage of this approach is the somewhat complex operating procedure required for plastic liner removal. Development work will be required in this area prior to acceptance of this system for long duration missions with minimum maintenance.

The weight evaluation of the vapor compression system makes it a very attractive approach for further study as a potential candidate for application in an overall life support system. The system has received considerable early development attention both in industry and in the work of NASA. The basic principles have been proved and estimated future recovery efficiency is quite good. It is expected that approximately 95% of the water can be recovered from urine.

Three problems exist and these must be solved prior to utilization of this system in the final space configuration. The first of these problems, the scaling of the evaporator heat transfer surfaces, has been previously mentioned. The second problem, that of separation of the liquid-vapor phase in the evaporator and condenser for zero-*g* operation, has not been fully evaluated for zero-*g* conditions and may require more development work prior to satisfactory operation. The present method of rotating the evaporator and condenser and creating an artificial gravity field seems the most direct solution to this problem. However, rotational speeds and equipment sizes may require considerable optimization prior to final system qualification.

The third area of concern, which must be investigated further during development aspects, is that of the potential presence of noncondensables in the condenser. The present design utilizes a purge to vacuum to rid the condenser of these noncondensables, which inhibit condensation. This approach is satisfactory for adequate condensation, but startup and periodic purging of the condenser creates a penalty for the air lost over a long period of time. The primary disadvantages of the system are the unadaptability to intermittent operation, the reliability problems associated with rotation of the evaporator and condenser, and the reduced pressure operation of the entire system. All these require further analysis and evaluation testing.

5.2.5 Water Reclamation by Oil Jet Evaporation

Fig. 14-56 illustrates the oil jet evaporation system. This is essentially a vapor compression system in that reclamation occurs by evaporating the urine and condensing and recovering the distillate. The primary difference between this and the standard vapor compression system is the inclusion of a circulating oil transport loop to eliminate the scaling and heat exchange fouling problems in the evaporation portion of the cycle.

The urine from the pretreatment tank is fed into the system through an ejector type nozzle and evaporation occurs at this nozzle, thus presenting a vapor formation within the circulating oil. A separator installed downstream of the evaporator is utilized to remove the water vapor from the circulating oil, leaving the solids to be carried off by the circulating oil stream. The separated vapor is then compressed and condensed. The heat of condensation is rejected to the oil which then returns to the evaporator inlet to complete the cycle.

The circulating oil carries off the urine solids from the evaporator and the heat transfer area and gives them up to a filtration system within the oil loop. Thus, removal of solids from the system can be accomplished simply and directly by changing the filter media periodically rather than by cleaning the evaporator, as is required for other vapor compression approaches.

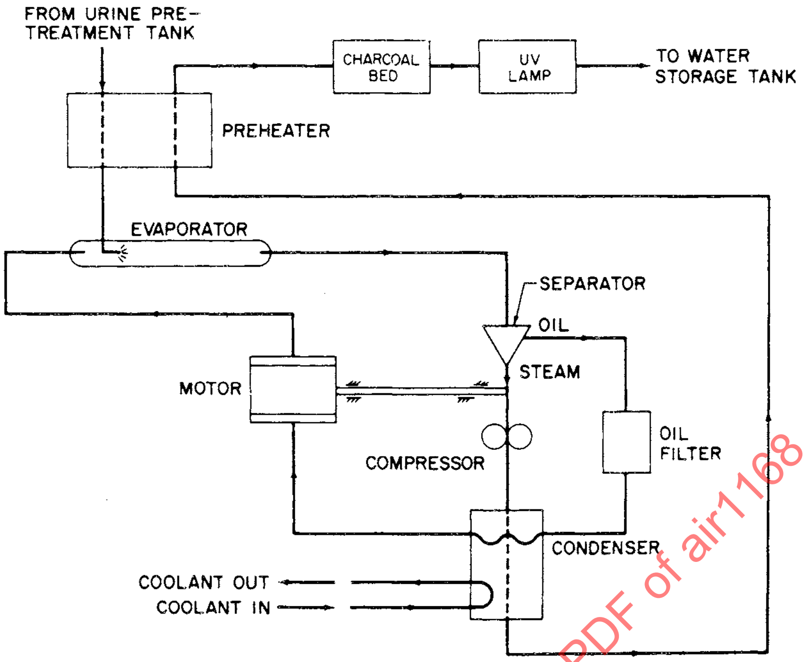


Figure 14-56 - Water reclamation by oil jet evaporation

Tests indicate that the oil will act as a washing solution and remove the scale from the evaporator. The urine inlet nozzle feasibility has been demonstrated using research equipment, but no prototype test work has been accomplished.

A potential replacement for the circulating oil loop is raw urine itself. This exchange should reduce system weight substantially by eliminating the complexities of dual fluids. In this case, a portion of the raw urine would be circulated through the system to provide the transport media for the evaporated urine and the urine contaminants. This concept has been established sufficiently to allow its consideration at this point in time.

The oil jet water reclamation system is attractive because of this simplification of the evaporator scale removal problem and its high water reclamation efficiency, which approaches 100%. These two factors are desirable in any water reclamation system and make this approach worthy of consideration upon initial evaluation.

Many problems exist in development of a system of this type. The most significant is the design of the condenser for zero-*g* operation. If a condenser were available with an operating effectiveness of the order of those utilized in aircraft systems, power requirements for this approach could be reduced in the order of 15%. Other areas of concern in design of a system of this type are potential clogging of the pitot pump, which could foul system operation and