HUMAN FACTORS AND ENVIRONMENTAL CONTROL/ LIFE SUPPORT SYSTEMS STUDY PROGRAM

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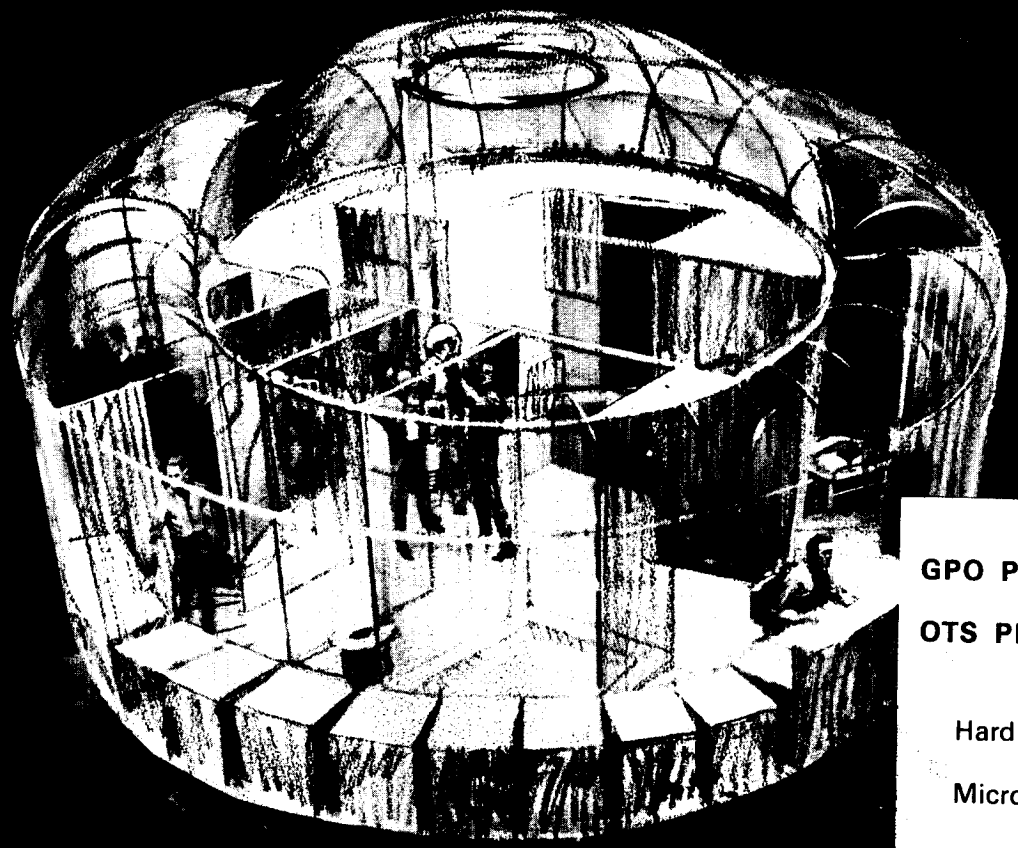

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LUNAR EXPLORATION SYSTEMS FOR APOLLO

NASA CONTRACT NAS 8-11447 MARSHALL SPACE FLIGHT CENTER

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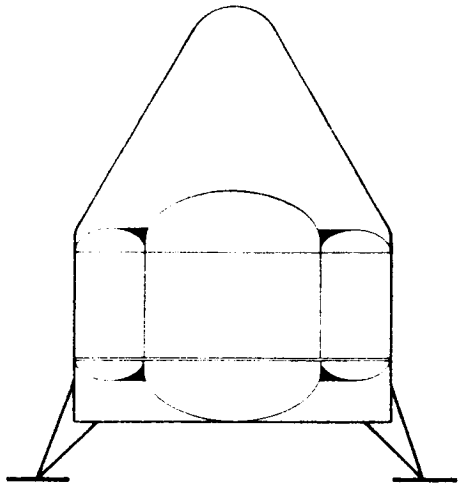

HUMAN FACTORS AND ENVIRONMENTAL CONTROL-LIFE SUPPORT SYSTEMS STUDY FOR LESA
MIDTERM STATUS REPORT

Prepared for the NASA Marshall Space Flight Center
under Contract NAS 8-11447

Report No. SS-3242

AiResearch Manufacturing Company
Los Angeles, California

December 16, 1964

HUMAN FACTORS AND EC/LSS STUDY FOR LESA

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SS-3242

I PROGRAM SCOPE AND PRESENT STATUS

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PROGRAM OBJECTIVES

Figure 1 summarizes the key objectives of the LESA Human Factors and EC/LSS study program. In previous studies of environmental control and life support systems for long-duration space missions, primary emphasis has been on minimizing lift-off weight. Modular system and vehicle concepts applied to advanced lunar exploration missions introduce a host of additional factors that must be considered in overall mission optimization. In particular, tradeoffs will be made involving initial weight, resupply weight, and manpower that may be more important than the simple weight tradeoffs ordinarily used for process selection. A significant part of the study program effort has involved more precisely definition of the system requirements. The LESA missions and bases are complex, from both the operational and the evolutionary standpoints; at present, many of the requirements can be given only approximately because the missions and equipment have been only partially defined. Therefore, it has been necessary to conduct much of the system studies on a parametric basis, within the framework of the LESA missions.

The study program has been divided into two primary work areas: Task A, concerned with the human factors requirements, and Task B, involved with the design and integration of the EC/LSS with the LESA missions.

PROGRAM OBJECTIVES

- ESTABLISH MOST FEASIBLE MODULAR EC/LSS CONCEPT
- EXPLORE INTERFACE AREAS
- IDENTIFY PROBLEM AND RESEARCH AREAS
- DETERMINE INSTALLATION AND SUPPORT REQUIREMENTS
- ESTABLISH DEVELOPMENT PROBLEM AREAS AND PRODUCTION COSTS

PROGRAM TASKS

TASK A	FORMULATION OF HUMAN FACTORS CRITERIA
TASK B	EC/LSS DESIGN AND INTEGRATION WITH THE LESA MISSIONS

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Figure 1

PROGRAM SCHEDULE

The two tasks forming the basis of the subject LESA study program are divided into the subtasks shown in Figure 2. The human factors work has involved operating procedure studies, task analyses, and studies to determine the most suitable shelter interior design. In the shelter interior design, considerable attention has been given to the problems of long-term habitability as well as to emergency conditions such as would occur with a solar flare or loss of pressurization in one compartment. A full-scale mockup of the shelter has been constructed for use as a human engineering tool to investigate space requirements and equipment placement.

The work related to the environmental control and life support systems has been concerned primarily with subsystem evaluation and analysis; system synthesis for the various LESA bases is now in progress. Consequently, the material in this presentation will be primarily directed to the subsystem and process selection areas. To arrive at the most feasible modular EC/LSS concepts, it is necessary to consider the various LESA mission requirements. In studies to date, attention has been concentrated upon the manned shelter module used in the LESA bases, although the systems required by the roving vehicles will be analyzed in the study program.

PROGRAM SCHEDULE

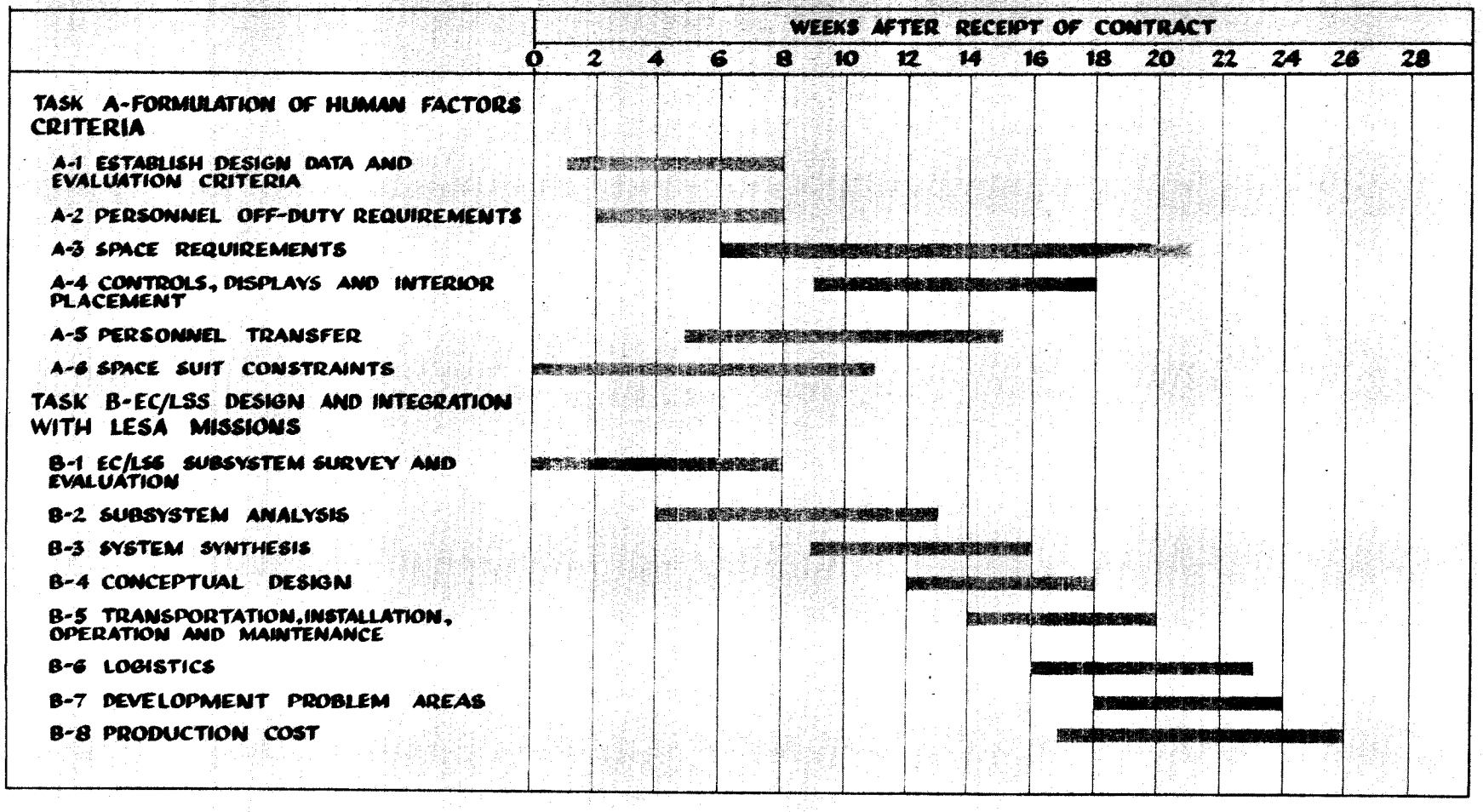

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Figure 2

BASIC SHELTER MODULE

The shelter configuration used in the present study program is essentially that developed in the Initial Concept study. The basic shelter module, intended to house a crew of six, is described in Figure 3. The two early LESA bases use one shelter for crews of three or six; the more advanced LESA bases use two or three shelters with correspondingly larger crews.

Although a number of different shelter configurations are under study in other LESA study programs underway, the Initial Concept design was chosen for the present study program for the human factors studies. A full-scale mockup of this basic shelter module has been constructed for use as a human factors research tool. A number of significant changes in interior design from that given in the Initial Concept study have been established. In particular, the rest area has been moved from the living compartment to the laboratory compartment.

As indicated above, the shelter configuration must be considered tentative. Regardless of the final arrangement, however, many of the conclusions regarding interior design, equipment placement, operating procedures, system design, etc., should be applicable to any shelter design conforming to the general limitations established by booster capability and mission requirements.

BASIC SHELTER MODULE

	GROSS VOL, FT^3	FLOOR AREA, FT^2
LIVING COMPARTMENT	1421	113
LABORATORY COMPARTMENT	1875	161
AIR LOCK	148	14

ATMOSPHERIC LEAKAGE = 4.0 LB/DAY

LUNAR BASE CONCEPT	CREW	MISSION DURATION	NO. OF SHELTERS
NO. 1	3	3 MONTHS	1
NO. 2	6	6 MONTHS	1
NO. 3	12	1 YEAR	2
NO. 4	18	2 YEARS	3

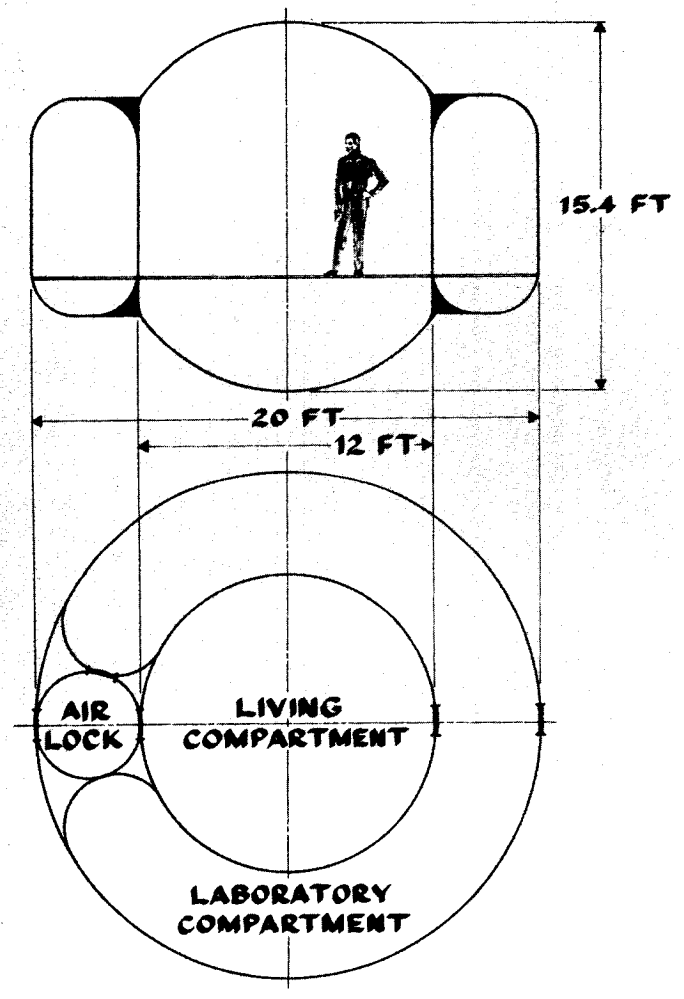

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Figure 3

EC/LSS PENALTY FACTORS

The penalty factors applied to subsystem characteristics such as power consumption, thermal energy consumption, heat rejection, etc., represent weight increases in other subsystems and as a consequence, result in increases in vehicle weight. Proper assessment of these weight penalty factors is therefore an important consideration in subsystem comparison and evaluation. Particularly important are the weight penalties chargeable to electrical power consumption. The power penalties shown in Figure 4 were derived from the LESA Fuel Depot Study and are applicable to a fuel cell-solar cell system designed for a 6-month mission; these penalties are representative of the power system presently comtemplated for Base Concept 2. For the more advanced base concepts, use of a nuclear power system providing an overall weight penalty of 0.5 lb per w was assumed for the studies covered by this report. On this basis, use of a radioisotope heat source providing a thermal energy output of 0.15 lb per w appeared attractive for life-support processes requiring a high-temperature thermal energy source. For the early base concepts, it is evident that the high power penalties for night operation will require careful design (possibly with periodic operation of some of the equipment during the day when solar energy is available) to minimize the weight penalties for power consumption.

The weight penalties, fixed weight, resupply weight, and manpower requirements for maintenance or operation are given in terms of costs. In this way, the tradeoffs between these characteristics can be evaluated to determine optimum arrangements.

EC/LSS PENALTY FACTORS

SYSTEM CHARACTERISTIC	APPLICABLE PENALTY FACTORS	TYPICAL VALUES FOR LESA
FIXED WT + Σ WT PENALTIES	WT COST	$5,000/LB
ELECTRICAL POWER CONSUMPTION	POWER WT PENALTY	4.38 LB/WATT (LUNAR NIGHT) 0.37 LB/WATT (LUNAR DAY)
THERMAL ENERGY CONSUMPTION (WASTE HEAT)	HEAT TRANSPORT WT PENALTY	0.005 LB/WATT
THERMAL ENERGY CONSUMPTION (HIGH TEMPERATURE)	HEAT SOURCE WT PENALTY	0.15 LB/WATT (Pu^{238} RI)
HEAT LOAD	HEAT REJECTION WT PENALTY	0.71 LB/WATT (50° F) 0.142 LB/WATT (70° F) 0.066 LB/WATT (100° F)
MATERIAL CONSUMPTION	STORAGE WEIGHT PENALTY	1.5 LB/LB O_2 4.0 LB/LB H_2 1.1 LB/LB H_2O
MAINTENANCE REQUIREMENTS	MANPOWER COST	$80,000/MAN-HOUR
RESUPPLY	LOGISTIC COST	$5,000/LB

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Figure 4

EC/LSS FUNCTIONS

The principal EC/LSS functions can be classified in three categories, "Thermal Control," "Atmospheric Control," or "Life Support," as shown in Figure 5. Many of these functions lead to problems similar to those for long-duration-mission spacecraft, such as reliability, efficient use of power, high material process recovery efficiency, etc. The presence of a gravitational field permits consideration of gravity-dependent processes, such as gravity-phase separators, although the reduced lunar gravity may result in low rates making preferable a gravity-insensitive device. Many of the EC/LSS design problems unique to LESA result from the lunar thermal environment. Obtaining suitable radiative sink temperatures for rejection of the low-temperature heat loads without use of heat pumping is a difficult problem compounded in complexity by possible degradation of surface spectral characteristics by dust, ultra-violet radiation, or particle bombardment. Storing of cryogens for one year on the lunar surface without active refrigeration or excessive vent losses is another problem associated with the lunar thermal environment. The first step in EC/LSS design involves establishing the system requirements for providing a suitable environment for man on the lunar surface.

EC/LSS FUNCTIONS

THERMAL CONTROL

- TEMPERATURE CONTROL
  - EQUIPMENT COOLING
  - MAN ENVIRONMENT
- HEAT TRANSPORT
  - VENTILATING GAS LOOP
  - LIQUID TRANSPORT LOOP
- HEAT REJECTION
  - RADIATOR
  - EXPENDABLE EVAPORANT

ATMOSPHERIC CONTROL

- COMPOSITION CONTROL
  - HUMIDITY CONTROL
  - O_2 PARTIAL PRESSURE CONTROL
- PRESSURE REGULATION
  - ATMOSPHERIC MAKEUP
- CONTAMINANT REMOVAL
  - CO_2 REMOVAL
  - ODOR & TRACE CONTAMINANT REMOVAL
  - AEROSOL & DUST FILTRATION

[redacted]

- FOOD SUPPLY
- WATER SUPPLY
- WASTE MANAGEMENT
- PERSONAL HYGIENE
- CLOTHING

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Figure 5

METABOLIC PARAMETERS

The design of the carbon dioxide and water removal systems, as well as comfort considerations, are strongly affected by metabolic rate. Durations of the various crew activities of the lunar base, as determined by preliminary task analysis, are summarized in the chart. The chart accounts for crew activity schedules for operations inside the shelter; extravehicular operations are not included, since the portable life-support system, or the lunar roving vehicle life-support system, will meet these requirements.

The metabolic rates listed for each of the activities are those for the corresponding activity on earth. Tests performed on earth simulating a reduced gravity environment have yielded contradictory metabolic rates; some tests have shown a 40 percent increase in metabolic rate at reduced gravity, while others have shown a 30 percent decrease. Although there is reason to expect that metabolic rates for various work functions (for example, lifting a weight) will be less in reduced gravity, until this issue is resolved, the metabolic rates corresponding to earth gravity will be assumed. The total energy expenditure given in the chart corresponds to an average metabolic rate of 500 Btu per man-hr. This corresponds to an average carbon dioxide production rate of 0.135 lb per man-hr, and an average oxygen consumption rate of 0.115 lb per man-hr. Figure 6 illustrates factors affecting design to meet metabolic requirements.

II DEFINITION OF REQUIREMENTS AND CONSTRAINTS

by Dr. P. J. Berenson

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METABOLIC PARAMETERS

ACTIVITY	DURATION (HR/MAN)	METABOLIC RATE (BTU/HR)	ENERGY EXPENDITURE (BTU/MAN-DAY)
SLEEPING	8.0	300	2400
EATING	1.5	500	750
EXERCISE	0.3	2000	600
RECREATION, HOUSEKEEPING AND PERSONAL MAINTENANCE	2.2	700	1550
SYSTEM MONITORING	8.0	500	4000
LABORATORY WORK	4.0	700	2800
			TOTAL 12,100 BTU/MAN-DAY

AVERAGE METABOLIC RATE = 500 BTU/MAN-DAY

Figure 6

ENVIRONMENTAL PARAMETERS

The selection of the atmospheric composition and pressure depends upon physiological and comfort limitations; thus, it is a very controversial subject. Particularly, advantages and disadvantages of a pure oxygen atmosphere vs a two-gas atmosphere have been sharply debated. The two-gas atmosphere could be O_2 and N_2 or a combination of O_2 and a suitable inert gas, probably helium. Due to the uncertainties and fire hazards associated with the use of a pure-oxygen atmosphere or the use of a diluent other than N_2, an O_2-N_2 atmosphere is assumed for LESA. This assumption will continue, pending establishment of facts justifying a change to either pure oxygen or oxygen-helium.

The considerations involved in selecting the pressure of the major constituents are summarized in Figure 7. Hypoxia or reduced oxygen supply sets the lower limit on oxygen partial pressure at a value of 110 mm Hg. The upper limit of 425 mm Hg is governed by oxygen toxicity. While a broad range of acceptable oxygen partial pressures exists within these limits, the sea-level equivalent partial pressure of 158 mm Hg appears desirable value for atmospheres intended for long-duration missions.

Aeroembolism, caused by the formation of bubbles in the blood stream as a result of decompression, establishes the upper limit on nitrogen partial pressure. As shown in the right-hand illustration in Figure 7, (an extrapolation of data), aeroembolism may be eliminated if the nitrogen partial pressure is less than 75 percent of the final total pressure. The pressure in the extravehicular life-support system has been tentatively established at a value of 3.5 psia. Therefore, an upper limit on nitrogen partial pressure of 2.6 psia or 136 mm Hg is assumed. Because fire hazard makes it desirable to maintain a high nitrogen pressure, the nitrogen partial pressure is assumed at the maximum value of 136 mm Hg.

No lower limit for CO_2 partial pressure exists; man normally functions with very low CO_2 concentrations in the inspired air. It is desirable to maintain a high CO_2 partial pressure to minimize the power and weight of the CO_2 processing system; an upper limit of approximately 30 mm Hg is set by the occurrence of hyperventilation, as shown in the left-hand illustration. The limit of 7.6 mm Hg usually specified for spacecraft cabins is based upon subjective submarine tests. A CO_2 partial pressure of 5 mm Hg is a conservative assumption for LESA.

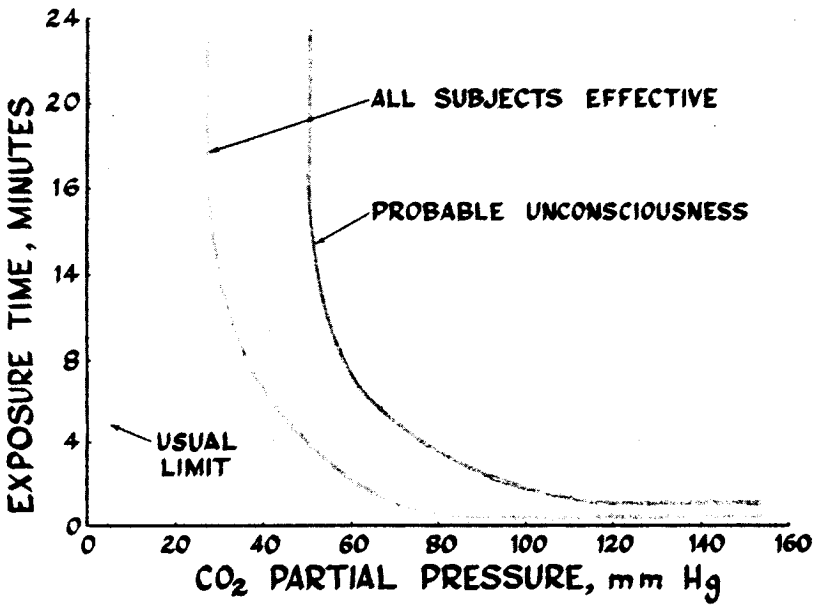
It is desirable to maintain the highest possible dew point, so that the dehumidifying function may be accomplished at a relatively high temperature. However, the water vapor partial pressure must be less than that corresponding to wall and equipment temperatures to eliminate the possibility of water condensing on these surfaces. The minimum limit is set by a physiological criterion requiring a water vapor partial pressure above a 32-deg dew point. Assuming that the minimum temperature of equipment exposed to the atmosphere is 50°F yields a water vapor partial pressure of 11 mm Hg.

For the lunar base, considerations such as the tradeoff between leakage rate and gas loop weight as a function of total pressure and composition, will have an insignificant effect on atmospheric selection, since physiological and safety factors must predominate. Based on the previous discussions, the atmospheric composition assumed corresponds to a total pressure of 310 mm Hg or 6 psia, as shown.

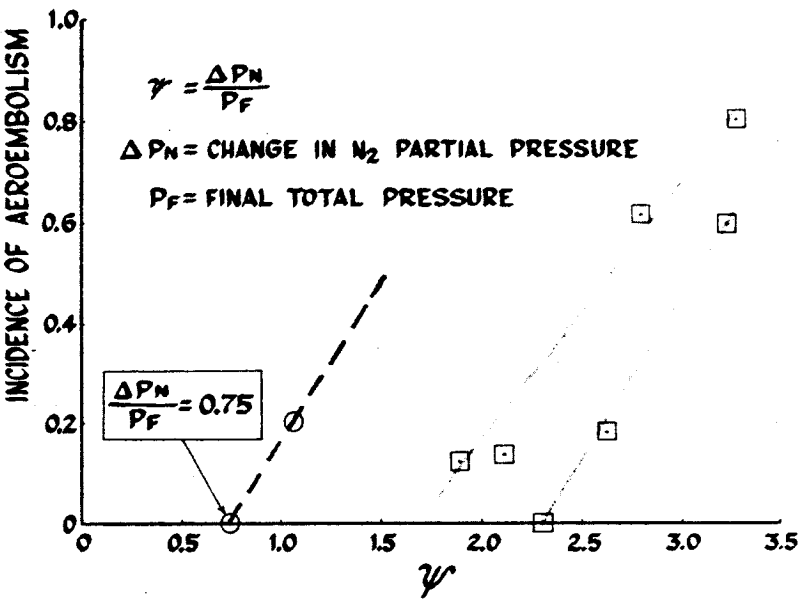
ENVIRONMENTAL PARAMETERS

ATMOSPHERIC SELECTION

CO_2 PARTIAL PRESSURE LIMIT



AEROEMBOLISM CRITERION



RECOMMENDED ATMOSPHERIC COMPOSITION

CONSTITUENT	MAX LIMIT	MIN LIMIT	PARTIAL PRESSURE
O_2	TOXICITY (425 mm Hg)	HYPOXIA (110 mm Hg)	158 mm Hg
N_2	AEROEMBOLISM (136 mm Hg)	FIRE HAZARD (NOT ESTABLISHED) PHYSIOLOGICAL (UNKNOWN)	136
CO_2	HYPERVENTILATION (30 mm Hg)	NONE	5
H_2O	DEW POINT (13 mm Hg)	COMFORT ZONE (3 mm Hg)	11
			310 mm Hg (6.0 psia)

Figure 7

SHIRTSLEEVE ENVIRONMENT

Man dissipates the energy generated by the metabolic process through convection, radiation, and evaporation. The analysis of these energy transfer processes depends upon many variables, as shown in Figure 8.

While storage of heat may be accommodated for a short time by a change in the average body temperature, long-term conditions require a balance between the heat generated in the body and that removed by heat and mass transfer commensurate with comfortable skin temperatures and clothing conditions. The split of the metabolic heat load between the sensible heat (including radiation and convection) and latent heat is important in the design of environmental control systems. This is because the latent cooling load must be rejected to the environment at low temperature, requiring relatively large radiator areas. It is, therefore, desirable to minimize the sweat rate, while maintaining comfortable conditions.

A large number of empirical comfort criteria have been developed on earth, but most are too limited to be applicable to the low-pressure, low-gravity environment existing on the moon. The one generally applicable comfort criterion relates comfort to the ratio of the evaporation rate required by the heat balance to the maximum evaporation rate possible if the body were completely wet. A minimum value of approximately 10 percent is set by the diffusion of water vapor through the skin. Up to a required evaporation rate equal to 25 percent of the maximum evaporative capacity, a person is comfortable. Between 25 and 70 percent, the conditions are tolerable. If the evaporation rate required by the heat balance is greater than 70 percent of the maximum evaporation rate, the conditions are uncomfortable. The application of this comfort criterion to the lunar shelter is outlined in Figures 8 through 12.

SHIRTSLEEVE ENVIRONMENT

THERMAL FACTORS

VARIABLES

- METABOLIC RATE, M
- ATMOSPHERE TEMPERATURE, T_a
- ATMOSPHERE COMPOSITION
- GAS VELOCITY, V
- RADIANT SINK TEMPERATURE, T_w
- CLOTHING
- SKIN TEMPERATURE, T_s
- DEW POINT TEMPERATURE
- INDIVIDUAL PHYSIOLOGICAL CHARACTERISTICS

MODES OF ENERGY TRANSFER

- CONVECTION, Q_c
- RADIATION, Q_R
- LATENT (PERSPIRATION AND RESPIRATION), Q_L

HEAT BALANCE

$$M = Q_R + Q_c + Q_L$$

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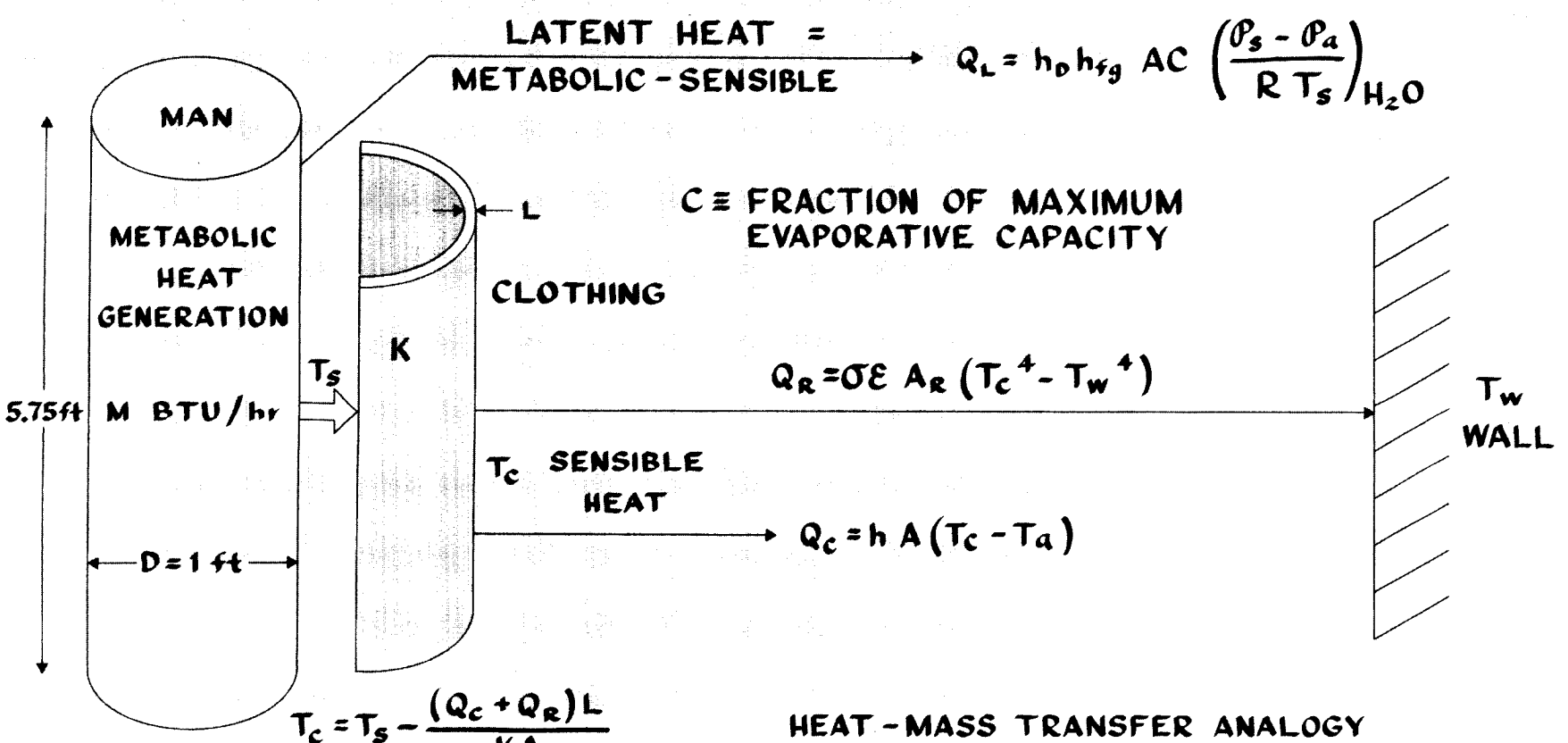
Figure 8

THERMAL ANALYSIS

The heat transfer model used in the analysis of the shirtsleeve environment is represented in Figure 9. It consists of a cylinder with an average diameter of 1 ft and a total surface area of 19.5 sq ft. Sensible heat removal is represented by radiation and convection at the outer surface of the clothing. It is assumed that latent heat transfer occurs with the exaporation of moisture on the skin, with the water vapor diffusing through the clothing to be swept away by the atmosphere. The heat transfer analysis for the shirtsleeve environment will be based upon an average metabolic rate of 500 Btu per hr and skin temperatures in the comfortable range of 90°F to 93°F. The purpose of the analysis is to establish the combination of atmospheric temperatures, velocities, and pressure under which man will comfortably function.

A well verified analogy between heat and mass transfer also is presented, which is extremely important in the analysis. The heat and mass transfer coefficients, which must be predicted, can correspond to either free or forced convection, depending upon which is required to provide comfort; if possible, free convection will be used, since it eliminated the need for additional equipment, power, and heat rejection.

THERMAL ANALYSIS



$A = 19.5\ ft^2$

$A_R = 15.5\ ft^2$

HEAT - MASS TRANSFER ANALOGY

$$\frac{h}{\rho V c_p} Pr^{\frac{2}{3}} = \frac{h_D}{V} Sc^{\frac{2}{3}}$$

$$Pr \equiv \frac{c_p \mu}{k} \; ; \; Sc \equiv \frac{\mu}{\rho D_v}$$

Figure 9

FORCED CONVECTION ENERGY TRANSFER

The general correlations for heat and mass transfer, which can be found in most standard heat transfer texts, are summarized in Figure 10. The equations given apply to flow normal to cylinders. Because the forced-convection airflow will be both parallel and perpendicular to a man in a sitting position, the corresponding equations for forced convection parallel to a surface were considered. It was found that the use of parallel flow equations departed from the equations presented by less than 30 percent.

Simplified equations for air were developed by inserting the properties of air in the general correlations and combining the results with the relations summarized on the previous chart. This yielded the equations shown for the convection and latent cooling capacities. The parameter C in the expression for the latent cooling capacity is the ratio of the required evaporative cooling rate to the maximum evaporative capacity. The maximum evaporative capacity, obtained by setting C equal to one, is shown parametrically in the figure as a function of pressure and velocity, since this parameter is directly related to comfort. The results shown were developed for a skin temperature of 91°F, and a dew point of 50°F. It can be seen that the maximum evaporative capacity increases with increasing velocity and decreases with increasing pressure due to the decrease in the diffusion coefficient.

FORCED CONVECTION ENERGY TRANSFER

GENERAL CORRELATIONS

HEAT TRANSFER:

$$\frac{hD}{K} = 0.6\left(\frac{\rho V D}{\mu}\right)^{\frac{1}{2}} Pr^{\frac{1}{3}}$$

MASS TRANSFER:

$$\frac{h_D D}{D_V} = 0.6\left(\frac{\rho V D}{\mu}\right)^{\frac{1}{2}} Sc^{\frac{1}{3}}$$

SIMPLIFIED FOR AIR

$$Q_c = 0.407(\rho V)^{\frac{1}{2}}(T_c - T_a)$$

$$Q_L = 1355\, C \frac{T_a}{T_s}\left(\frac{V}{P}\right)^{\frac{1}{2}}(\rho_s - \rho_a)_{H_2O}$$

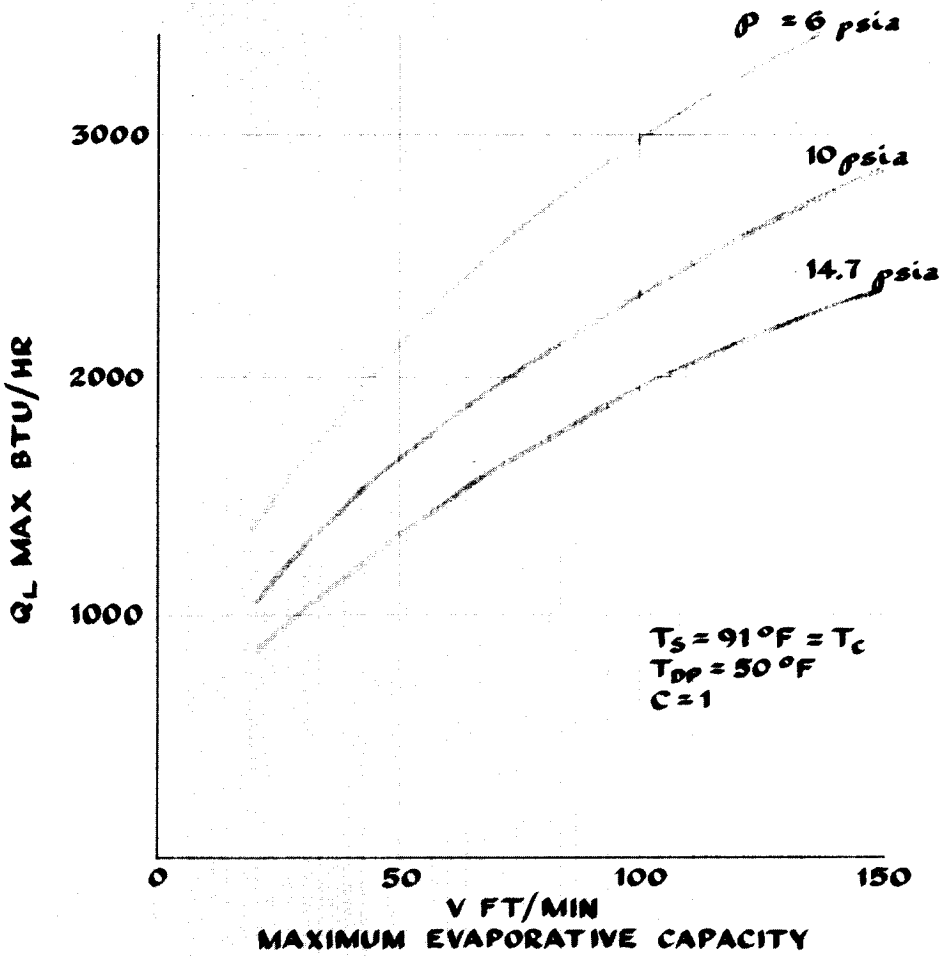


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Figure 10

NATURAL CONVECTION ENERGY TRANSFER

The general correlations for natural convection heat and mass transfer are summarized in Figure 11. The equations are identical for a 1-ft-diameter cylinder with a plate 2.5 ft long. Since these two conditions approximate those of a man in a sitting position, the natural convection results are considered independent of the flow direction. Simplified equations for air obtained from the general correlations are summarized on this chart. It can be seen that both the latent and convective cooling capacity are proportional to the 1/4th power of gravity. The convective heat transfer increases with pressure while the latent cooling capacity decreases with increasing pressure.

Results corresponding to conditions in the LESA lunar shelter are summarized in the figure on the chart as a function of atmospheric temperature. These results were obtained for the following conditions: 6-psia pressure, 1/6 g, a 91°F skin temperature, and a 50°F dew point. The latent cooling is that corresponding to the minimum sweat rate. It can be seen that, while the convective heat loss goes to zero when the atmospheric temperature equals the skin temperature, the latent cooling is almost independent of atmospheric temperature. This is because the driving force for latent cooling is the water vapor partial pressure difference, which is independent of atmospheric temperature.

NATURAL CONVECTION ENERGY TRANSFER

GENERAL CORRELATIONS

HEAT TRANSFER:

$$\frac{hL}{k} = 0.67\left(\frac{P_r}{0.952 + P_r}\right)^{\frac{1}{4}}\left(\frac{gL^3 \rho \Delta \rho P_r}{\mu^2}\right)^{\frac{1}{4}}$$

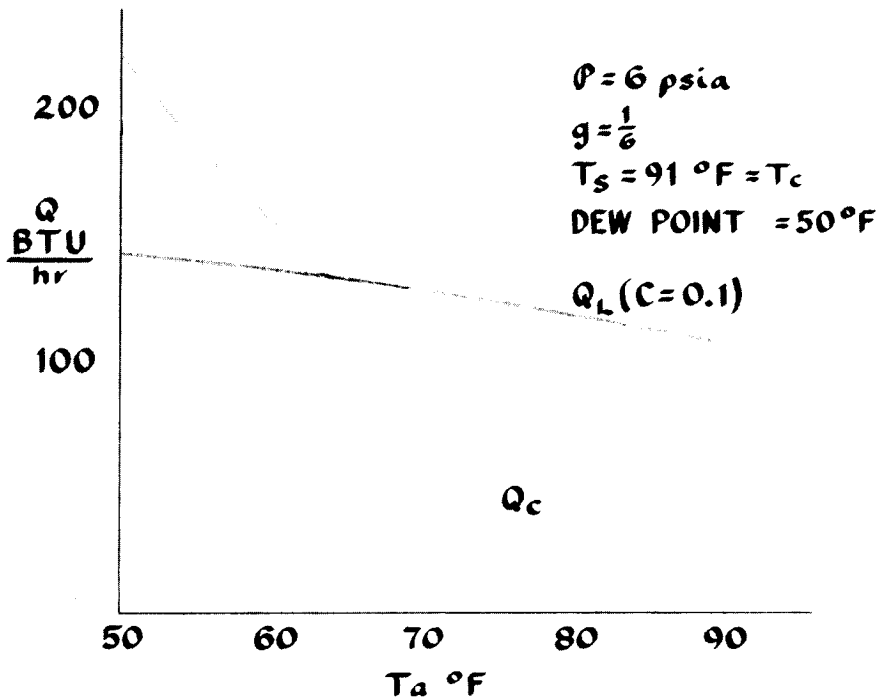
MASS TRANSFER:

$$\frac{h_D L}{D_v} = 0.67\left(\frac{S_c}{0.952 + S_c}\right)^{\frac{1}{4}}\left(\frac{gL^3 \rho \Delta \rho S_c}{\mu^2}\right)^{\frac{1}{4}}$$

SIMPLIFIED FOR AIR

$$Q_c = 4.4(T_c - T_a)\left\{P\, g\left[\frac{2.7P\,(T_c - T_a)}{T_a} + (P_c - P_a)_{H_2O}\right]\right\}^{\frac{1}{4}}$$

$$Q_L = \frac{7.5 \times 10^6 C}{P\, T_s}(P_s - P_a)_{H_2O}\left\{P\, g\left[\frac{2.7P\,(T_c - T_a)}{T_a} + (P_s - P_a)_{H_2O}\right]\right\}^{\frac{1}{4}}$$



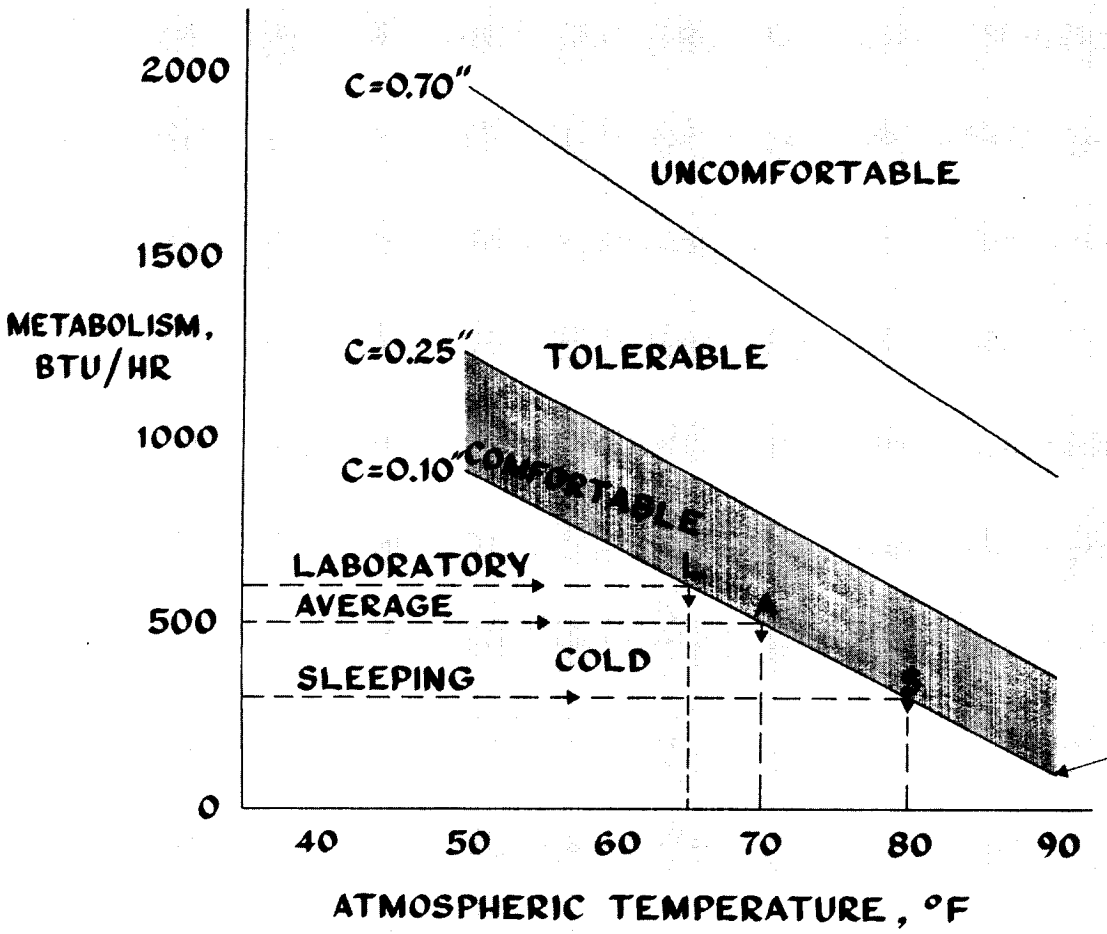
NATURAL CONVECTION COOLING

Figure 11

NATURAL CONVECTION COMFORT ZONES

The comfort criteria discussed previously, based upon the ratio of required latent cooling to the maximum evaporative cooling rate, has been combined with the natural convection equations presented in the previous figure to yield the results shown in Figure 12. These results were obtained for very light clothing, approximating a nude condition for heat transfer, an air atmosphere, a pressure of 6 psia, 1/6 g, and a dew point of 50° F. Metabolism is plotted vs atmospheric temperature, and the lines representing 10, 25 and 70 percent of the maximum evaporative capacity are shown in Figure 12. The cross hatch area is the comfortable zone spanning a sweat-rate between 10 and 25 percent of maximum evaporative rate. Metabolisms corresponding to sleeping, laboratory, and cabin average were used to define the required temperatures in these areas. These were determined by the point where they intercept the line of minimum sweat rate, since it is desirable to minimize the sweat rate in order to minimize the low-temperature cooling requirements. The recommended temperatures for each of these areas are summarized in Table 1. Even though the intersection with the curve is at 80° F, 75° F is recommended for the sleeping area, to allow for use of a very light blanket; the latter is desirable for psychological reasons. The important conclusion from Figure 12 is that natural convection provides adequate cooling for the atmospheres and metabolisms assumed for the LESA shelter.

NATURAL CONVECTION COMFORT ZONES



- AIR
- VERY LIGHT CLOTHING ($T_c = T_s$)
- $P = 6$ psia
- $g = \frac{1}{6}$
- DEW POINT = 50 °F
- $T_w = T_a$

RECOMMENDED TEMPERATURES

AREA	TEMP °F
SLEEPING (WITH BLANKET)	75
LABORATORY	65
CABIN	70

LINE OF MINIMUM SWEAT RATE (~100 BTU/HR)

NATURAL CONVECTION PROVIDES ADEQUATE COOLING

Figure 12

FORCED CONVECTION COMFORT ZONES

Figure 13 was prepared to show the characteristics resulting from the combination of the comfort criteria with the forced convection equations. Because velocity is an additional variable in forced convection, it is necessary to select one metabolism and then plot the velocity vs atmospheric temperature, as shown. A high metabolism of 1000 Btu per hr was selected as indicative of metabolism in maximum work areas. Assuming one is working at this rate in a 65^{0}F laboratory area, we find that a velocity of approximately 60 ft per min is required. A velocity lower than that required by the intersection of the 65^{0}F abscissa with the line of minimum sweat rate was chosen because fan power is proportional to velocity. This rate of work will probably be maintained for only relatively short periods and will have little effect on the average moisture content of the atmosphere. It should be noted that an alternate solution is (1) to decrease the laboratory area temperature to between 50^{0}F and 60^{0}F, at which point a metabolism of 1000 Btu per hr is comfortably rejected by natural convection, and (2) to require persons working at a lower rate to wear heavier clothing when in the laboratory. Detailed subsystem analysis will determine the optimal solution for the LESA shelter.

FORCED CONVECTION COMFORT ZONES

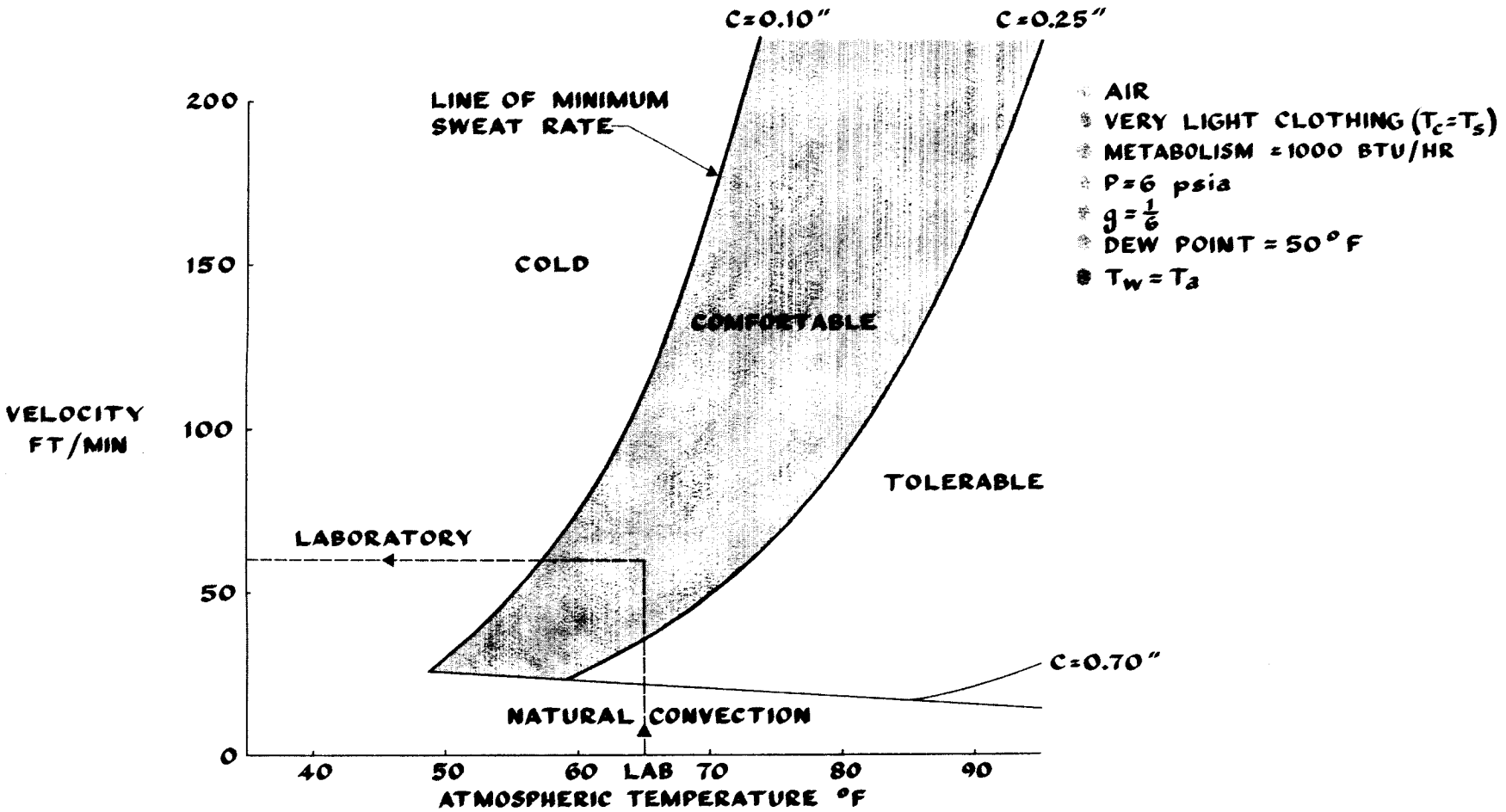


Figure 13

THERMAL CONTROL

Solution of the thermal control problem for LESA requires first determining the heat loads that are to be rejected, then comparing the heat loads and temperature levels with the heat sinks available on the lunar surface. The analysis is then repeated; heat loads and temperature levels are varied, and the effect of this on heat rejection requirements are determined.

A model heat load for the LESA study is shown in Figure 14. The heat load is conveniently divided into three portions, as discussed below.

The first portion is the low-temperature heat load, consisting of 3000 Btu per hr of metabolic heat (500 Btu per hr per man, 6 men), 400 Btu per hr for fans and other small electrical equipment, and an assumed heat leak of 200 Btu per hr. This heat is removed during cooling and dehumidification of the shelter atmosphere. Since the shelter atmosphere will be around 70°F with a 50°F dew point, it must be cooled below 50°F to remove moisture. Thus, the model low temperature heat load is to be rejected between 70°F and 45°F.

The second heat load is 7750 Btu per hr for cooling of fuel cells, in those LESA shelters which use fuel cell power. Since the fuel cells will supply power only at night, and since daytime conditions determine heat rejection capacity, this fuel cell heat load will not be considered further at this time.

The third (high-temperature) heat load is the heat removed from the electrical power-consuming equipment aboard LESA. A model of 10,200 Btu per hr, or 3 kw, was taken from the Initial Concept study. Some of this heat would undoubtedly be removed by natural or forced convection to the cabin atmosphere at 70°F. Direct cooling of the equipment by cold plates and liquid transport loops is desirable, however, wherever this is possible. In this study is was assumed that the entire 10,200 Btu per hr is removed at a temperature level of 100°F to 125°F.

III THERMAL CONTROL

by R. A. Stone

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Potential Heat Sinks (continued)	36
Heat Load and Heat Sink Matching	38
Counterflow Radiator	40

THERMAL CONTROL

HEAT LOADS

SOURCE		REMOVAL	TEMP
METABOLIC HEAT	3000 BTU/HR	SHELTER ATMOSPHERE	
FANS	400	COOLING & DEHUMIDIFYING	70°-45°F
HEAT LEAK	200		
FUEL CELLS	7750 BTU/HR	FUEL CELL COOLING LOOP (NIGHT ONLY)	120°-150°F
POWER CONSUMING EQUIPMENT	10,200 BTU/HR	ATMOSPHERE COOLING (NAT'L OR FORCED CONVECTION TO AIR)	70°F
		OR	
		LIQUID COOLING BY COLD PLATES WHEREVER POSSIBLE	100°-125°F

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Figure 14

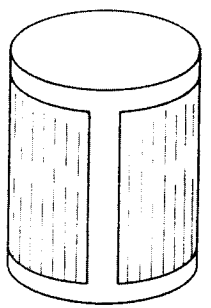
POTENTIAL HEAT SINKS

Figures 15 and 16 summarize six potential heat sinks available in LESA. The first, in Figure 15, is a vertical cylinder, which forms the exterior surface of the LESA shelter. A vertical cylinder on the moon will have a sink temperature of 115°F at lunar noon with α_s/ε_T (solar absorptivity over thermal emissivity) of 0.20. The temperature will be somewhat higher in the morning and afternoon, since the radiator will then receive approximately the same thermal influx and, in addition, direct solar radiation. The principal advantage of using a vertical cylinder as a radiator is that a fixed, nondeployable radiator can be used; also, the area is already available on the exterior surface of the LESA shelter. However, the high sink temperature precludes the use of this configuration without considerable heat pump penalties. That is, for the temperature levels required, the external surface is not a usable radiator. This configuration also requires a low value of α_s/ε_T.

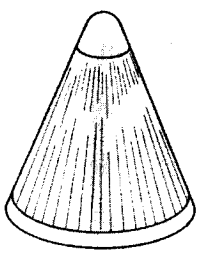
The second potential heat sink is a vertical cone, which has a sink temperature of 72°F. It will receive somewhat more direct sunlight than the vertical cylinder. Since the conical surface is slanted away from the lunar surface, however, it has a lower view factor for lunar radiation. The area is potentially available, and again this could be used without deployment. However, the sink temperature, as in the case of the vertical cylinder, is too high.

The third configuration shown in Figure 15 is the horizontal flat plate. With $\alpha_s/\varepsilon_T = 0.2$, the horizontal flat plate has a sink temperature at lunar noon of 16°F, and lower at other times. This is a usable sink temperature. The horizontal flat plate radiator will require deployment of the panels, and its major disadvantage is its extreme sensitivity to α_s/ε_T. For example, the value assumed here of 0.2 yields a sink temperature of 476°R. If degradation of the coating were to raise α_s/ε_T from 0.2 to 0.25, the sink temperature would rise to about 45°F, which is too high to permit radiation of the low-temperature heat load. A degradation in coating characteristics to a value of 0.5 would increase the sink temperature to 140°F. This is the major disadvantage of a horizontal flat plate radiator.

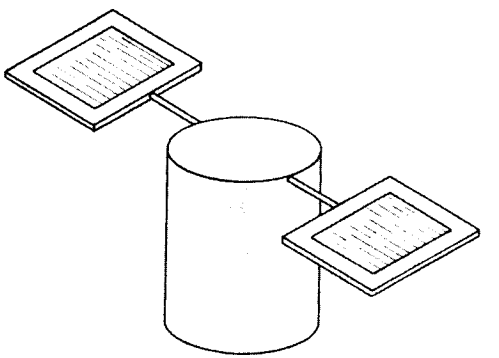
POTENTIAL HEAT SINKS



VERTICAL CYLINDER



VERTICAL CONE



HORIZONTAL FLAT PLATE

	VERTICAL CYLINDER	VERTICAL CONE	HORIZONTAL FLAT PLATE
SINK TEMPERATURE	115 °F	72 °F	16 °F
ADVANTAGES	AVAILABLE AREA NO DEPLOYMENT	POTENTIALLY AVAILABLE AREA NO DEPLOYMENT	USABLE SINK TEMPERATURE
DISADVANTAGES	SINK TEMPERATURE PRECLUDES USE WITHOUT HIGH HEAT PUMP PENALTIES NEED LOW α_s/ε_T	HIGH SINK TEMPERATURE NEED LOW α_s/ε_T	REQUIRES DEPLOYMENT VERY SENSITIVE TO α_s/ε_T

Figure 15

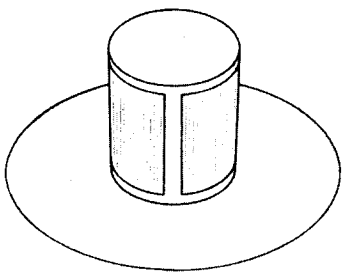
POTENTIAL HEAT SINKS

Figure 16 shows three more heat sink configurations. The vertical cylinder with a reflector deployed on the lunar surface is the concept described in the Initial Concept study. If a large reflector is deployed, the radiator will have a high view factor toward the reflector and a low view factor toward the lunar surface, thereby reducing the incident thermal radiation, or the radiator sink temperature. Another advantage of this configuration is that the radiator itself does not require deployment, although the large reflector mat does. The disadvantages of this configuration include the considerable solar influx to the radiator, both direct and reflected from the deployed reflector. Secondly, the reflector described in the Initial Concept study was 100 to 200 ft in diameter and might impede operations around the lunar shelter. Use of this configuration is strongly dependent on the α_s/ϵ_T of the radiator surface.

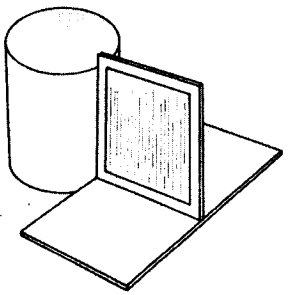
The final radiator configuration, and the one that appears most attractive for LESA, is a vertical flat plate radiator with a horizontal reflector. This configuration provides a low view of the lunar surface, as does the previous one. However, a vertical flat surface can be erected in the lunar east-west direction, or the ecliptic plane, and will receive little or no direct sunlight and no sunlight reflected from the reflector, if a specular surface is available. The upper portion of the radiator has a much higher view factor to the moon than the lower portion, thus leading to a variation of sink temperature with height along the radiator. These predictable sink temperature variations permit "counterflow" operation, described later. Since the radiator does not receive any direct sunlight and only a small amount reflected from the lunar surface, it is almost completely insensitive to α_s/ϵ_T. The reflector does not need a low value of α_s/ϵ_T, but only low absolute values of α_s and ϵ_T. In this study, $\alpha_s/\epsilon_T = 1.0$ was assumed for the reflector. This configuration has the disadvantage of requiring deployment of both the radiator and reflector.

The final heat sink shown on Figure 16 is a water boiler. This provides a heat sink substantially independent of temperature. When used in a shelter with fuel cell power, the fuel cells will produce enough water during the night to provide the entire low-temperature heat sink during the day. When fuel cells are used, waste water recovery and purification is not required. Since the fuel cell water can be drunk, it is possible that waste water, either wash water or urine, can be evaporated in the water boiler to provide the low-temperature heat sink. The major disadvantage of this method of heat rejection is that it is practical only for bases with fuel cell power.

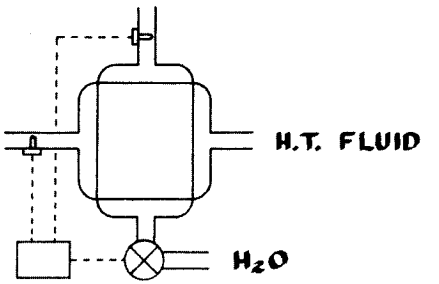
POTENTIAL HEAT SINKS



VERTICAL CYLINDER WITH REFLECTOR



VERTICAL FLAT PLATE WITH REFLECTOR



WATER BOILER

ADVANTAGES

RADIATOR SEES REFLECTOR INSTEAD OF MOON, THEREBY REDUCING SINK TEMPERATURE

NO DEPLOYMENT OF RADIATOR

LOW VIEW OF MOON

LITTLE OR NO DIRECT OR REFLECTED SUNLIGHT IN ECLIPTIC PLANE

PREDICTABLE TEMPERATURE GRADIENTS PERMIT "COUNTERFLOW" OPERATION

INSENSITIVE TO a_s/ε_T

HEAT SINK INDEPENDENT OF TEMPERATURE

FUEL CELLS PRODUCE ENOUGH WATER TO PROVIDE DAYTIME ATMOSPHERIC COOLING & DEHUMIDIFYING

DISADVANTAGES

RADIATOR RECEIVES CONSIDERABLE SOLAR INFLUX, DIRECT & REFLECTED

MAY IMPEDE OPERATIONS AROUND SHELTER

NEED LOW a_s/ε_T

DEPLOYMENT OF BOTH RADIATOR AND REFLECTOR IS REQUIRED

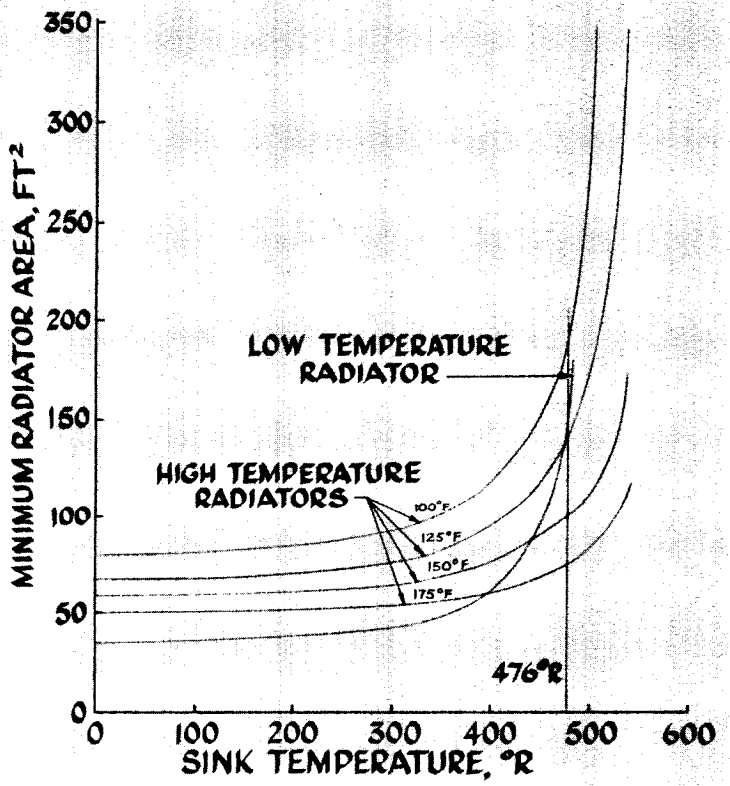
PRACTICAL ONLY IN CONJUNCTION WITH FUEL CELLS

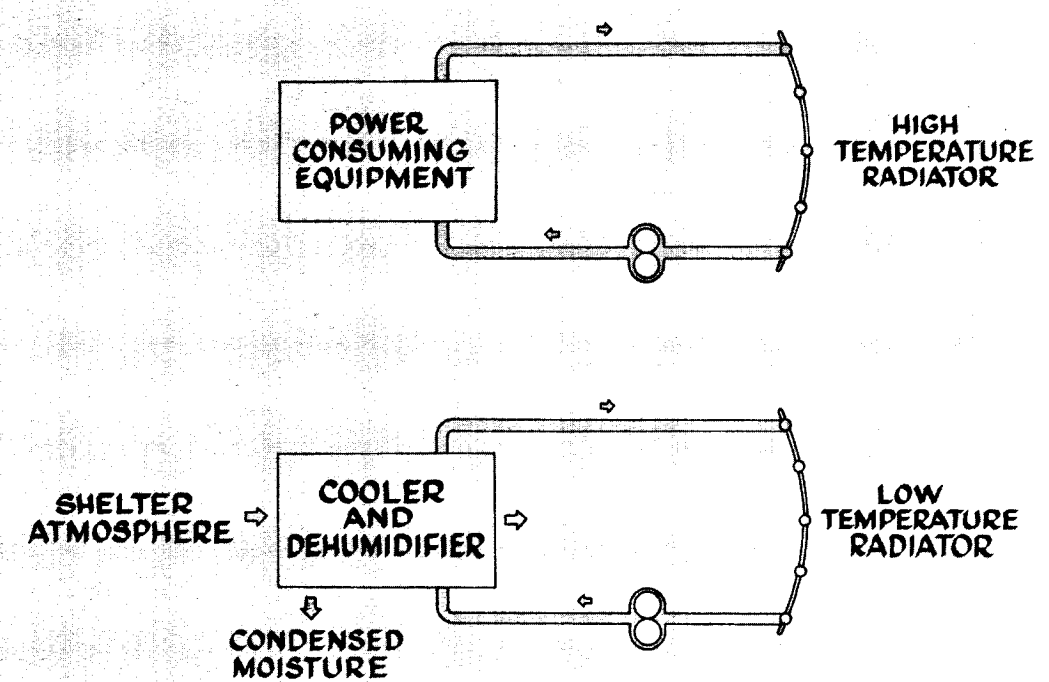
Figure 16

HEAT LOAD AND HEAT SINK MATCHING

Figure 17 shows schematically the high-temperature and low-temperature heat load. It also contains a plot of minimum radiator area required as a function of sink temperature, both for the low-temperature radiator and the high-temperature radiators. For the latter, these data are shown for radiator inlet temperatures of 100°F to 175°F. It is seen that the area requirements are very strongly affected by temperature level of the heat load and by sink temperature. The vertical line drawn at 476°R shows the condition for horizontal flat plate with $\alpha_s/\epsilon_T = 0.2$. This shows that this condition is marginal for the low-temperature radiator, and that the high-temperature radiators also have a very steep slope of area vs sink temperature in this region. Small degrations in α_s/ϵ_T leading to small increases in sink temperature make use of the horizontal radiator without heat pumps impracticable.

HEAT LOAD AND HEAT SINK MATCHING





- AREA REQUIREMENTS ARE STRONGLY AFFECTED BY TEMPERATURE LEVEL AND BY SINK TEMPERATURE
- HORIZONTAL FLAT PLATE WITH $\alpha_s/\epsilon_t = 0.18$, SINK TEMPERATURE OF 476°R IS MARGINAL

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Figure 17

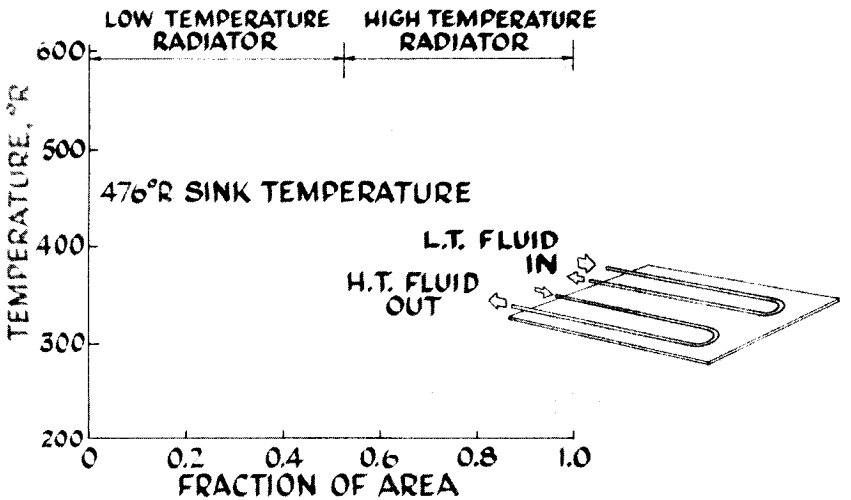
COUNTERFLOW RADIATOR

Figure 18 shows the two types of radiator design which are considered prime candidates for the LESA application. On the left is the conventional design, a horizontal flat plate, with $\alpha_s/\epsilon_T = 0.2$. Plotted on the figure is temperature versus area. The sink temperature of 476°R is constant for the entire radiator. Somewhat more than half the radiator is taken up by the low-temperature radiator, and the balance by the high-temperature radiator. At the cold end is a temperature pinch where the fluid approached within less than 30°R of the sink temperature. This radiator requires 280 sq ft. Since a horizontal flat plate on the lunar surface can radiate only from one side, this will require two 11.8-ft-sq panels.

The right side of Figure 18 shows the "counterflow" design, a vertical flat plate radiator with a horizontal reflector. The sink temperature varies from 280°R at cold end of the radiator to 540°R at the hot end. The low temperature radiator takes up only about 20 percent of the radiator area because of the high available ΔT at the cold end of the radiator. There is only a mild pinch at the hot end, where the radiating power, $(T^4 - T_s^4)$, is higher. This design requires 210 sq ft, or a single panel 4.9 sq ft by 21.5 sq ft, radiating from both sides compared to the two panels, each larger than this size, required for the horizontal flat plate. The reflector area was assumed to be equal to the radiator area, i.e., there will be two flat reflectors, each 4.9 sq ft by 21.5 sq ft. A value of $\alpha_s/\epsilon_T = 0.2$ was used for the radiator surface characteristics; if α_s/ϵ_T were as high as 1.0, the required radiator area would increase by only 30 percent. While further studies will consider the use of vapor-cycle refrigeration, or heat pumps, to raise the radiator temperature and reduce the radiator area, the vertical flat plate with reflector has been chosen as the most promising radiator configuration for the LESA study.

COUNTERFLOW RADIATOR

CONVENTIONAL DESIGN



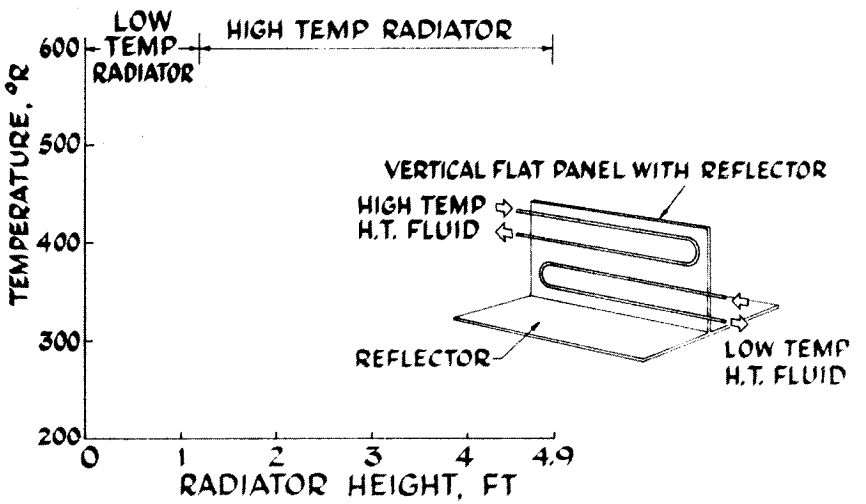
HORIZONTAL FLAT PLATE

CONSTANT SINK TEMPERATURE OF 476°R

TEMPERATURE PINCH AT COLD END

REQUIRES 280 FT^2, RADIATING FROM ONE SIDE, OR TWO 11.8 x 11.8 FT PANELS

COUNTERFLOW DESIGN



VERTICAL FLAT PLATE WITH REFLECTOR

SINK TEMPERATURE, VARIES FROM 280°R TO 540°R

GREATEST AVAILABLE ΔT AT COLD END

ONLY MILD PINCH AT HOT END

REQUIRES 210 FT^2, RADIATING FROM BOTH SIDES, OR ONE 4.9 x 21.5 FT PANEL

Figure 18

IV ATMOSPHERIC CONTROL

by J. Rousseau

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CO_2 Removal	50
O_2 Recovery	52
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O_2 Recovery	56
O_2 Recovery System Characteristics	58
(Substitute for O_2 Recovery)	60

CABIN ATMOSPHERE CONTROL

The atmosphere control system provides a suitable gaseous environment for man. Consequently, the atmosphere control functions include pressure regulation, humidity control, CO_2 removal, contaminant removal, ventilation, and composition control. Several gas loops will be required for the atmosphere control functions in the LESA shelters. Two basic types of environment will be provided, one represented by man in a shirtsleeve cabin, another by man in a pressure suit. Although most of the operations in the LESA shelters will be in a shirtsleeve environment, provision for operation in pressure suits will be required, both for emergency operations inside the shelter and for extravehicular operations during preparatory periods and egress through air locks. Therefore, the suit loop system will be a pure oxygen gas loop provided with pressure controls for operation independent of cabin pressure. By use of umbilicals, the suit loop system can also be used for extravehicular operation adjacent to the shelter. Because of the desirability of maintaining crew members in suits inside the shelter on a standby basis for emergencies during extravehicular operations, it may be necessary to provide each shelter with two independent suit loop systems.

The cabin atmosphere control provisions for the shirtsleeve environment will employ circulation of the atmospheric gas at flow rates determined by different requirements. Cabin thermal control, for example, is provided by a relatively high gas flow circulated through heat exchangers for local area temperature control. A second gas circuit is provided for atmospheric composition control. The flow through this circuit is determined by the humidity control requirements. This flow is also sufficient to provide odor removal. CO_2 removal is accomplished by processing part of the dehumidified process gas through a regenerable CO_2 removal system. Two alternatives are shown in Figure 19 for CO_2 removal, one used when CO_2 is vented overboard, and the other used when the CO_2 is processed for oxygen recovery.

CABIN ATMOSPHERE CONTROL

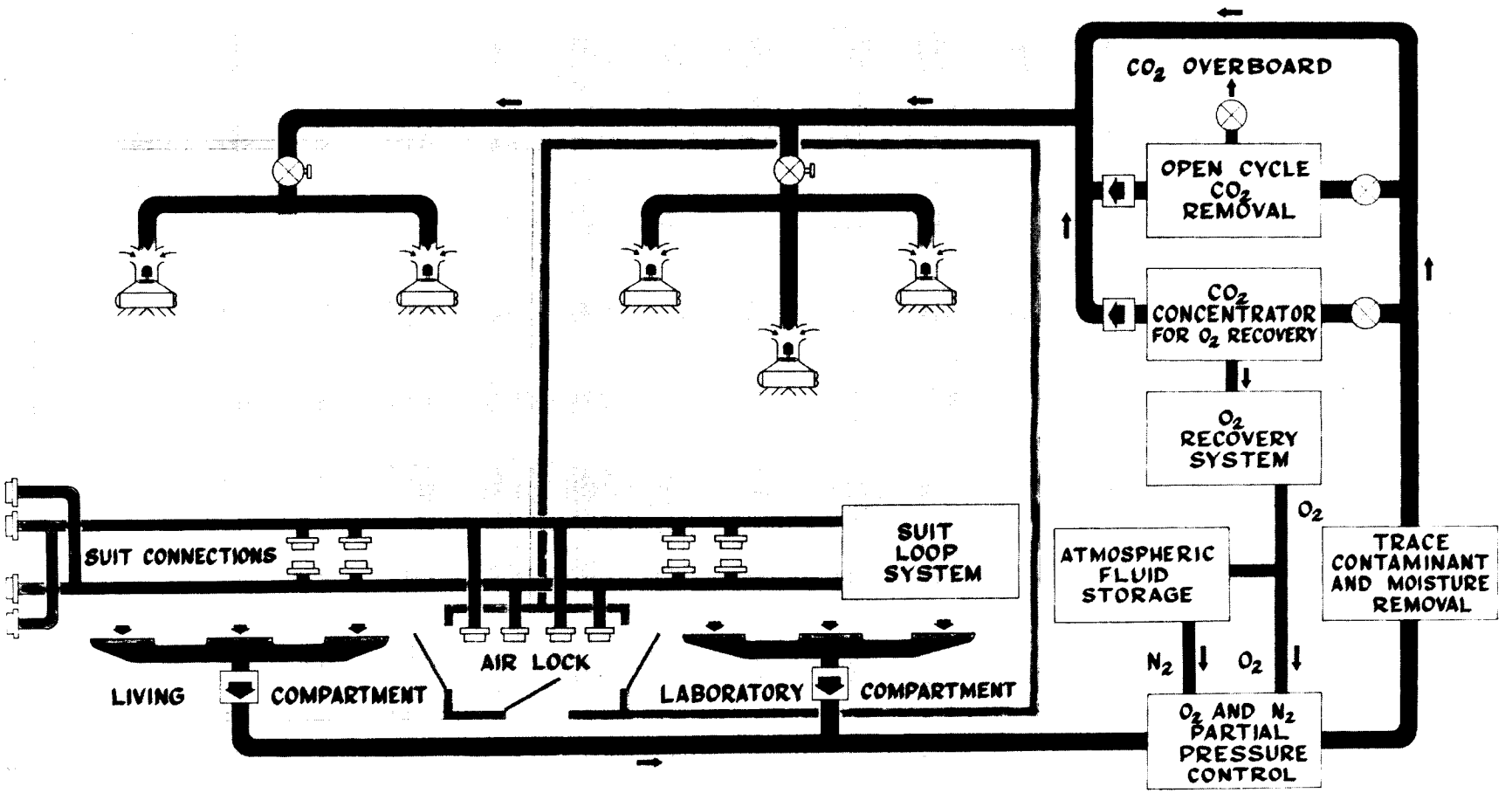
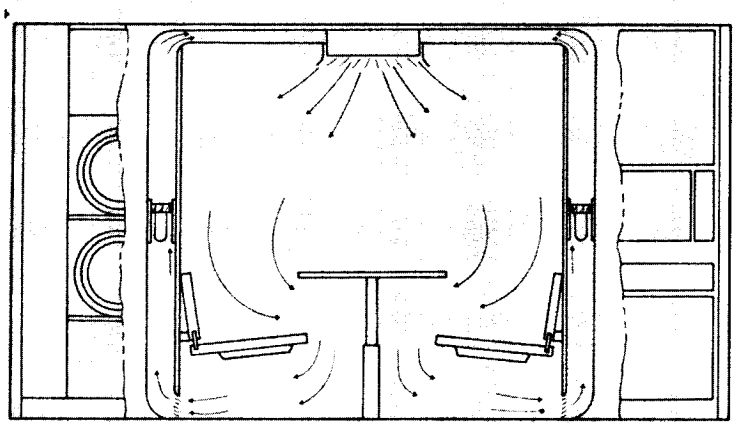


Figure 19

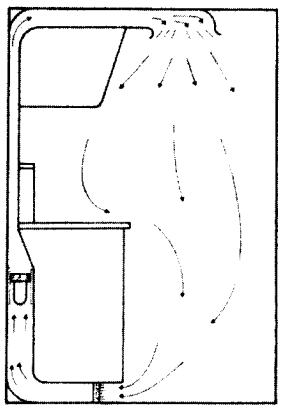
VENTILATION

The first requirement of the atmosphere control system is to provide ventilation for the purpose of temperature control in the various shelter stations. It has been demonstrated that natural convection will provide adequate cooling of the body under comfort conditions for lunar cabins at metabolic rates characteristic of sedentary activity levels. Therefore, in low activity areas, the ventilating flow required can be assumed to be equal to that needed for moisture and odor removal. The ventilation flow requirements for major shelter are listed in Figure 20. Also shown are typical ventilation circuits for the living and work areas. It should be noted that the ventilation ducts are located behind the equipment and do not interfere with flow traffic in the various compartments. Because of the high rate of odor generation in the personal hygiene and toilet area, it is advisable to provide charcoal beds in the ventilation ducts in these areas. Separate humidity control of these areas might also be advisable.

VENTILATION



LIVING AND RECREATION AREA



TYPICAL WORK STATION

AREA	NO. STATIONS	MIN. VENT FLOW/STATION
LIVING AND RECREATION	1	240 CFM
PERSONAL HYGIENE AND TOILET	1	240 CFM
WORK STATION	3	400 CFM
CO'S QUARTERS	1	80 CFM
SLEEPING	4	40 CFM

Figure 20

CONTAMINANT CONTROL

Trace contaminant control will be an important factor in maintaining suitable atmospheric environments for the LESA shelters. The most important means of contaminant control will be the preventative measures adopted to eliminate materials and equipment designs that serve to generate atmospheric contaminants. In this way, it should be possible to maintain contaminant production rates at sufficiently low levels to minimize the possibility of toxic atmospheres and to reduce the provisions required for contaminant removal.

State-of-the-art methods of trace contaminant removal include odor removal by charcoal adsorption; oxidation of low molecular weight contaminants in a catalyst bed; microbiological growth control by ultraviolet radiation and the use of germicides; and aerosol removal by filtration. All of these methods are recommended for the LESA systems.

Impregnation of the activated charcoal with catalyst metals improves its sorption properties for substances such as ammonia and halogen acids. For this reason, Whetlerite is preferred for odor removal in the LESA shelters.

As mentioned previously, the Whetlerite adsorption bed should be installed in the humidity control air duct so that only one fan is required for humidity control and odor removal. This arrangement should yield a condensate of high purity.

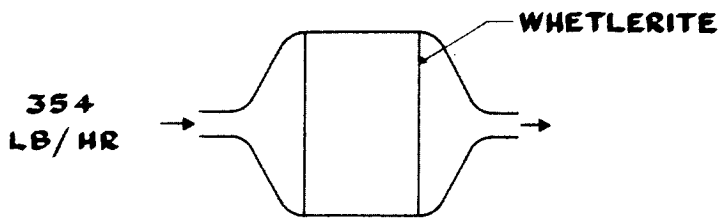
The problems involved in the design of the catalytic burner are twofold: first, catalyst poisoning by sulfur compounds and nitrogen compounds must be prevented; and second, toxic and/or noxious substances produced within the catalytic bed must be removed from the burner exhaust stream. In the LESA system, introduction of a composite bed of Whetlerite and calcium carbonate upstream and downstream of the catalytic burner is recommended for these purposes. It is estimated that 1 lb of Whetlerite will be sufficient for a 6-man, 6-month shelter with the catalytic burner.

The ultraviolet light is also installed in the ducts provided for humidity control. Any ozone formed within the ducts as a result of ultraviolet irradiation will be adsorbed on the Whetlerite bed, which has a high capacity for this substance.

Aerosols and particulate matter will be filtered from the process air stream by means of fibrous filters. In addition, portable vacuum cleaners are recommended, together with the use of germicide and portable ultraviolet lights, for use within the shelter itself.

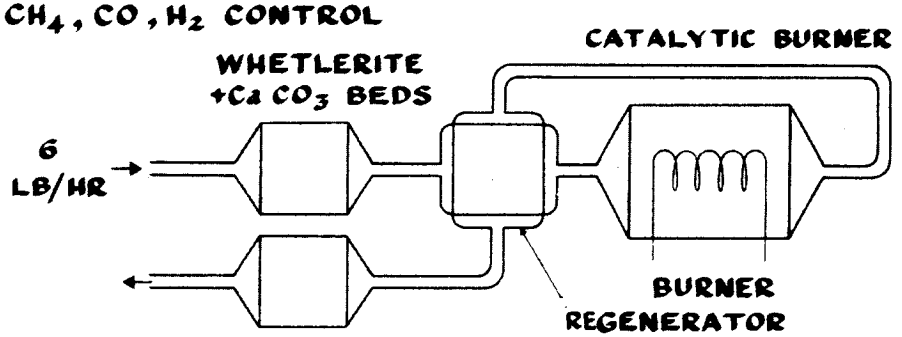
CONTAMINANT CONTROL

ODOR CONTROL



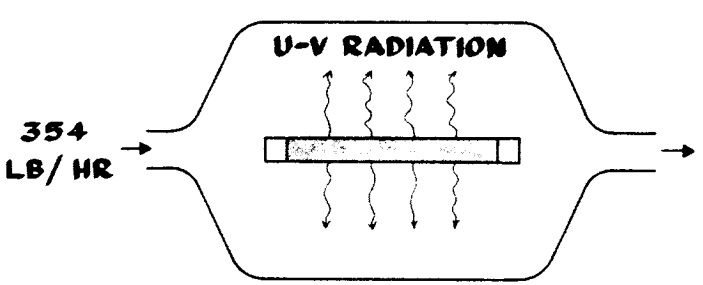
$\Delta P = 0.26$ IN. H_2O
FIXED WT = 5.5 LB
EXPENDABLE WT (6 MONTHS) = 32.5 LB
VOLUME = 1190 IN^3

CH_4, CO, H_2 CONTROL



$\Delta P = 6.0$ IN. H_2O
FIXED WT = 5.2 LB
EXPENDABLE WT (6 MONTHS) = 1.0 LB
POWER = 20 WATTS D-C

MICROBIOLOGICAL CONTROL



POWER = 5 WATTS
FIXED WT = 0.5 LB

Figure 21

CO_2 REMOVAL

As indicated in Figure 22, removal of CO_2 from the LESA shelter atmosphere by regenerable molecular sieve adsorption has been selected for all base concepts. For the Base 1 and Base 2 concepts (solar cell-fuel cell power), where no oxygen is recovered from the CO_2, the molecular sieve beds are desorbed by exposure to vacuum. Desorption of the silica gel bed is provided at no power penalty by use of the thermal swing cycle: during adsorption the bed is cooled with 50^0F heat transport fluid from the thermal control loop, and during desorption the bed is heated to 120^0F with hot fluid.

For the more advanced base concepts (3 and 4) involving nuclear power, it becomes desirable to recover the O_2 from the CO_2. Therefore, thermal desorption is used for providing CO_2 to the O_2 recovery system at a pressure level sufficient for subsequent processing. The heat used for molecular sieve desorption is used again to desorb the silica gel bed, and no additional source of heat is necessary for desiccant regeneration. The heat used to desorb the desiccant is stored in the form of a hot CO_2 adsorbent bed; the heat is transported by the dry process gas to the desorbing desiccant bed. The power required for CO_2 desorption imposes a pentlty of 270 lb on a 6-man system, if electrical power is used. Consequently, a radioisotope heat source would reduce the weight penalty for thermal desorption to 80 lb for a 6-man system.

One of the major problems associated with the use of molecular sieve systems for CO_2 control in space applications is the relatively low reliability of these systems resulting from the cyclic nature of the process and the complexity of the valving functions. Reliability analyses were performed to determine the degree of redundancy required for the LESA systems.

The basic reliability of the basic four-bed molecular sieve system (including a compressor) is comparatively low and is only marginal even for very short missions. The addition of a redundant compressor improves the reliability significantly. Two molecular sieve systems, each capable of handling the load and featuring redundant compressors as well as redundant controls, are required for a reliability of about 0.99 for a 6-month mission. For longer missions (Base 3 and 4 concepts), reliability can be increased by resupply of complete systems or by repair of the failed systems. Repair provisions include replacement of valves, compressor and controls and, possibly, recharging of adsorbent canisters.

System effectiveness studies will be performed at the system level to determine which is preferable for the LESA missions - system replacement or repair of components.

CO_2 REMOVAL

MOLECULAR SIEVE SYSTEM CHARACTERISTICS

BASE CONCEPT	1 AND 2	3 AND 4
TYPE OF DESORPTION	VACUUM	THERMAL
INLET AIR TEMPERATURE, °F	50	50
TOTAL PRESSURE, PSIA	6.0	6.0
CO_2 PARTIAL PRESSURE, MM Hg	5	5
FLOW, CFM	22.5	22.5
ELECTRICAL POWER, WATTS	35	42
FIXED WEIGHT, LB	71	80
COOLING REQUIREMENT BTU/HR		
AT 50°F	1460	950
AT 70°F	570	1030
HEATING REQUIREMENT, BTU/HR		
AT 120°F	1980	—
AT 400°F	—	1843
ATMOSPHERE LOSSES, LB/DAY	0.17	0.01

RELIABILITY

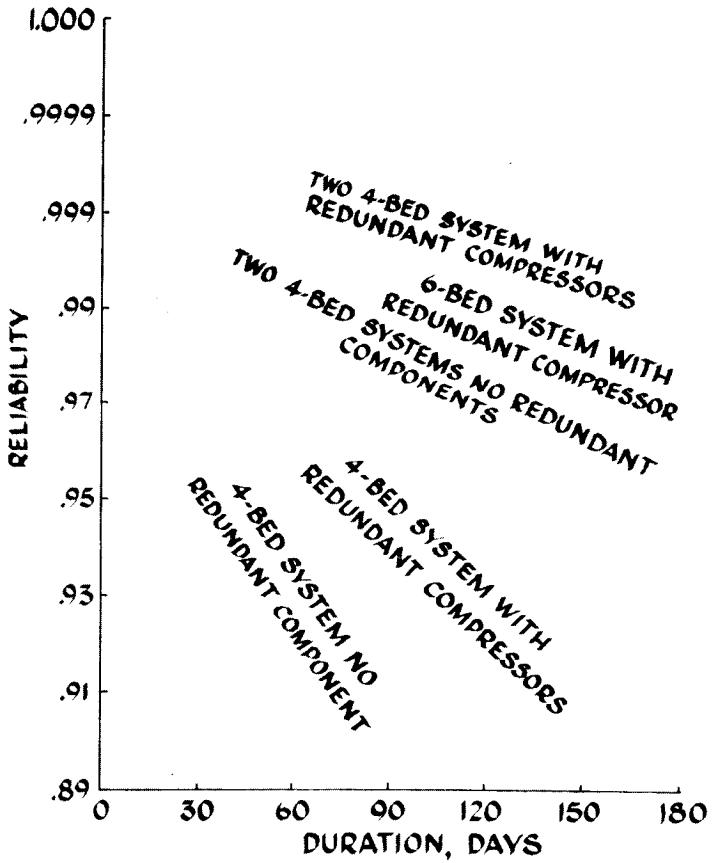


Figure 22

O_2 RECOVERY

The applicability of oxygen recovery to LESA depends essentially on the overall material balance for the shelter, particularly with respect to oxygen and water. The daily shelter oxygen requirements for Base Concepts 2, 3 and 4 are the same; it is double that of the 3-man Base I shelter. The potential oxygen sources, however, differ depending on the base concept considered. In general, three oxygen sources are available:

Cryogenic storage
Electrolysis of water
Oxygen recovery from carbon dioxide

As indicated in Figure 23, cryogenic-oxygen storage for a 6-man, 6-month shelter involves a penalty of 3920 lb, including tankage. Two methods considered for reducing this penalty and apparently offering advantage are: (1) electrolysis of excess water during daytime operation on Base Concept 2, and (2) CO_2 reduction and electrolysis of water on Base Concepts 3 and 4.

The metabolic water requirement of Base Concepts 1 and 2 can be fulfilled by production of fuel-cell water and by processing of a small amount of condensate. What remains can be purified and electrolyzed for the purpose of oxygen production. Evidently, it is thermodynamically unsound to use oxygen to power a fuel cell for the purpose of recovering oxygen by electrolysis of water. Considerable savings are possible, however, through water electrolysis during daytime operation with solar cell power.

For Base Concepts 3 and 4, water balance indicates that the only excess water is that produced metabolically through oxidation of the food. This amounts to about 0.9 lb per man-day, which is insufficient to provide for all the oxygen requirement. Oxygen recovery from CO_2 is then contemplated. Savings from processing CO_2 for oxygen recovery amount to an equivalent weight of 2560 lb in terms of oxygen storage.

It should be noted that oxygen recovered from CO_2 is in sufficient to provide all the oxygen required, and that supplemental oxygen provided by tankage or by electrolysis of excess water will be required.

Penalties are involved, however, in these oxygen recovery processes; these are discussed later, and actual savings derived from the approaches mentioned above are presented.

O_2 RECOVERY

POTENTIAL SAVINGS
(6 MAN, 6 MONTH BASIS)

O_2 PLUS TANKAGE WEIGHT FOR SHELTER	3920 LB
SAVINGS BY WATER ELECTROLYSIS DURING LUNAR DAY (SOLAR CELL/FUEL CELL POWER)	1960 LB
SAVINGS BY CO_2 REDUCTION	2650 LB

- POTENTIAL SAVINGS REDUCED BY PENALTIES FOR
  - ELECTROLYSIS OF WATER
  - CO_2 REDUCTION

Figure 23

CO_2 PROCESSING REACTIONS

Carbon dioxide reduction processes can be divided into two general categories: (1) the processes where the CO_2 molecule is broken into carbon and oxygen, and (2) the processes which involve CO_2 reduction with hydrogen. In the latter case, the end products are carbon and water; oxygen recovery is effected by electrolysis of the product water. The first category of processes is in the early stage of development; in general, these processes require very high temperatures (2000°F to 10,000°F). Relatively inefficient, they require large quantities of electrical or thermal energy. For these reasons, they were not considered applicable to the LESA missions.

The first water-forming reduction process considered involves hydrogenation of CO_2 to methane and water, according to the Sabatier reaction. Reactors have been fabricated and catalysts developed which are very efficient (100 percent) in promoting this reaction at relatively low temperature levels (500°F). Catalyst life is indefinite if suitable means are provided to prevent catalyst poisoning. The process is self-supporting and does not require any power, since the reaction is highly exothermal. Unfortunately, an external source of hydrogen is necessary for the reaction to proceed, since product water electrolysis yields only half the hydrogen necessary for the reaction to proceed. The other half is discarded with the carbon as methane. In view of the advantages of the Sabatier process, a number of processes were considered for recovery of hydrogen from methane. These include reduction of unreacted CO_2 with product methane, catalytic decomposition of methane, and thermal decomposition of methane. Basic characteristics for these processes are shown in Figure 24.

Another process considered is the direct reduction of CO_2 with hydrogen to carbon and water. This process, based on the Bosch reaction, takes place in a single step. Low yields are obtained in a single pass, so that recirculation is necessary. Presence of methane in the reactants is necessary for the reaction to proceed at reasonable rates, which suggests that the Bosch reaction is probably a combination of the Sabatier reaction, together with methane pyrolysis and CO_2-CH_4 reaction. The Fischer-Tropsch process also was considered; however, liquid hydrocarbons are formed in this process, and low yields necessitate recirculation The liquid hydrocarbons would foul lines, heat exchangers, and other equipment in the closed circuit around the Fischer-Tropsch reactor. For this reason, it is not attractive for space applications. The hydrogen losses incurred when dumping the hydrocarbons formed in the reaction also make the process unattractive, unless end products with relatively high carbon-to-hydrogen mole fractions are obtained. Of the processes discussed, the Bosch reaction appears preferable from a thermal standpoint to either methane decomposition or reaction of CO_2 and CH_4 because of the exothermic nature of the process. The heat of reaction can be used to make up for heat leaks from the high-temperature reactor.

CO_2 PROCESSING REACTIONS

PROCESS	REACTION	ΔH (KCAL/MOLE)	TYPE OF REACTION	HEAT PRODUCED	REMARKS
DIRECT REDUCTION	$CO_2 = C + O_2$	94.4	ENDOTHERMAL	3860 BTU/LB CO_2	VERY LOW YIELDS
DIRECT PYROLYSIS	$CO_2 = CO + 0.5O_2$	67.9	ENDOTHERMAL	2780 BTU/LB CO_2	LOW YIELDS AT VERY LOW PRESSURES AND VERY HIGH TEMPERATURES
	$2CO = CO_2 + C$	-41.5	EXOTHERMAL	1330 BTU/LB CO	
METHANATION (SABATIER)	$CO_2 + 4H_2 = CH_4 + 2H_2O$	-41.5	EXOTHERMAL	1695 BTU/LB CO_2	NO SIDE REACTIONS; VERY LONG CATALYST LIFE
CH_4 REDUCTION OF CO_2	$CO_2 + CH_4 = 2C + 2H_2O$	-0.9	EXOTHERMAL	37 BTU/LB CO_2	CO FORMED IN SIDE REACTION; HIGH CATALYST CONSUMPTION
METHANE PYROLYSIS	$CH_4 = C + 2H_2$	20.3	ENDOTHERMAL	2280 BTU/LB CH_4	NO SIDE REACTION; LOW OR NO CATALYST CONSUMPTION
REDUCTION TO C (BOSCH)	$CO_2 + 2H_2 = C + 2H_2O$	-21.2	EXOTHERMAL	868 BTU/LB CO_2	CO FORMED IN SIDE REACTION; CATALYST CLEANING REQUIRED
FISCHER-TROPSCH	$CO_2 + H_2 = CH_x + H_2O$	—	EXOTHERMAL	—	SIDE REACTIONS; LOW YIELDS

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Figure 24

O_2 RECOVERY

Systems based on the water-forming processes discussed previously were evaluated comparatively for the LESA oxygen recovery systems. Problems with CO_2 reduction are associated mainly with carbon deposition in the reactor bed and power consumption resulting from the high reactor temperature (1000°F to 1500°F).

In catalyzed carbon-forming reactions, the carbon deposits on the surface of metal catalyst result in catalyst fouling and reactor plugging. Two design approaches can be used here. First, used catalyst charges can be replaced periodically. This involves the use of two reactors in parallel for continuous operation and results in considerable inefficiencies, since the reactor must be cooled before charge replacement and heated to reaction temperature before usage. The second approach involves the use of cleanable catalyst, such as pellets in a fluidized bed; the pellets are continuously cleaned in the reactor itself by abrasion or are circulated through the reactor and cleaned outside the reactor. Other types of catalyst beds which can be cleaned in the reactor itself include plates, disks, and cylindrical catalyst surfaces from which carbon can be scraped periodically and collected downstream of the reactor.

It should be mentioned that most of the research and development in the area of oxygen recovery from CO_2 has been concentrated on process development rather than hardware design; little attention has been paid to engineering problems such as power requirements, catalyst usage, and disposition of carbon.

A comparative evaluation of the processes considered for LESA is shown in Figure 25. Each system was evaluated by comparison to the Sabatier process since CO_2 reduction systems based on this process are by far the simplest and most advanced in development. However, as mentioned previously, the Sabatier process alone is not applicable to the LESA missions because of the hydrogen deficiency given by the material balance.

In general, processes based on the Sabatier reaction as a first step in a two-stage process result in more complex systems than that based on the Bosch process because of the requirement for two reactors, two water condensers, and additional provisions for composition control.

For the case of the Sabatier reaction followed by catalyzed methane decomposition, recirculation of the process gases from the decomposition reactor through the Sabatier reactor leads to certain problems in the Sabatier reactor. In the methane decomposition reactor, unreacted CO_2 will be reduced to carbon monoxide which, in turn, will be reduced to carbon in the Sabatier reactor. The consequent high catalyst usage in the Sabatier reactor for this condition makes this process unattractive.

On the basis of the present studies and evaluations, the continuous reduction of CO_2 by the Bosch process is recommended for LESA. The Bosch process appears to offer several significant advantages over the other processes considered with regard to operational and maintenance characteristics. For example, system maintenance is minimal involving only periodic carbon removal from the collection device. Also, catalyst usage is minimal, since only one reactor is necessary. On the other hand, complexities arise from carbon collection devices and moving parts within the hot reactor (1400°F). However, the use of lunar gravity should simplify the problem of carbon separation and collection. Catalyst usage is low and maintenance requirements can be reduced to a minimum, since it involves only the periodic removal of collected carbon from the reactor. The system power requirement should be slightly lower than that for systems using pyrolysis, since the Bosch reaction is exothermic.

O_2 RECOVERY

PROCESS EVALUATION

	SABATIER ALONE	SABATIER AND CATALYZED PYROLYSIS	SABATIER AND UNCATALYZED PYROLYSIS	SABATIER AND CO_2 - CH_4 REACTION	BOSCH-RELOAD	BOSCH CONTINUOUS
STATE-OF-THE-ART DEVELOPMENT	5	3	2	3	4	4
TEMPERATURE LEVEL	5	3	2	3	3	3
CATALYST USAGE	5	1	5	3	3	3
POWER CONSUMPTION	5	3	1	2	3	3
NORMAL MAINTENANCE	5	1	4	2	2	4
RELIABILITY	5	3	3	4	4	3
COMPLEXITY	5	3	3	3	4	4
FIXED WEIGHT	5	4	3	3	3	4
	40	21	23	23	26	28

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Figure 25

O_2 RECOVERY SYSTEM CHARACTERISTICS

Processes for oxygen recovery from CO_2 selected for the LESA application involve two steps: first, CO_2 reduction by the Bosch process followed by electrolysis of the product water; second, provision of oxygen for breathing and hydrogen necessary for the Bosch process. A schematic diagram of the system is shown in Figure 26.

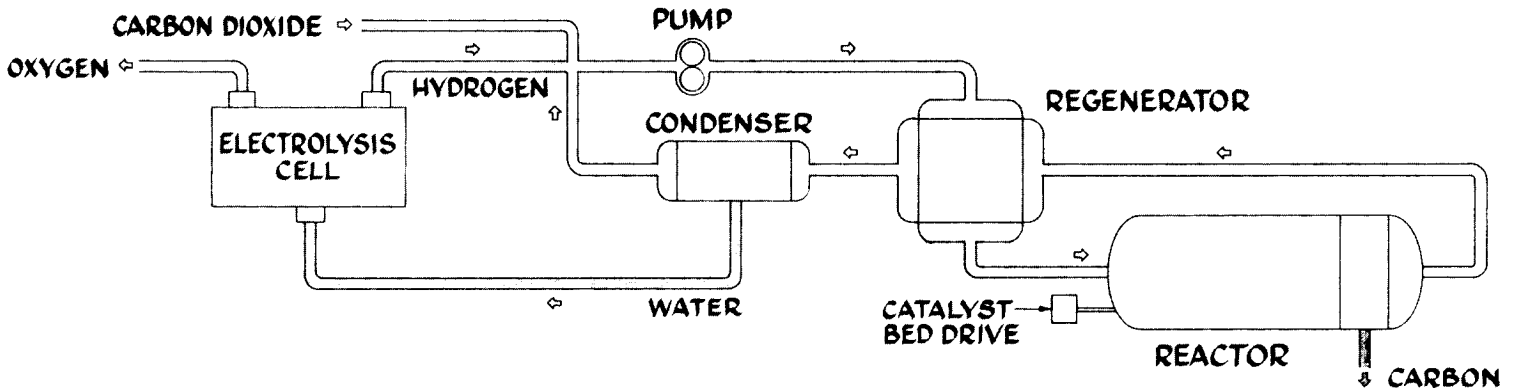
The penalties associated with these two steps also are listed in Figure 26. The system characteristics given are for a 6-man, 6-month shelter. All the catalyst required for the 6-man, 6-month mission is contained in the reactor at the beginning of operation and is spent during the 6-month period. Since the reactor-catalyst is by far the heaviest system component, the complete system is assumed expended after six months.

In estimating the performance of the CO_2 reduction system, it was assumed that considerable care will be given to engineering details in the design of the reactor, particularly with regard to reduction of power requirement. A highly efficient regenerator must be used to minimize thermal energy input to the system.

The system was designed for operation at a nominal pressure of 20 psia. Use of an elevated operating pressure reduces the pressure drop through the system and improves effectiveness through overall reduction in size. The system energy requirements are the following: 170 w for pump and reactor operation and for circuit control; 900 w (thermal energy at 1400°F) to make up for regenerator inefficiencies and heat leaks. Here the use of a radioisotope heat source would appear advantageous, since it would reduce the system penalty by as much as 315 lb.

The electrolytic cell data presented is fairly conservative, in that an overall cell efficiency of about 60 percent was assumed. Conceptually, the electrolysis cell consists of eight modules which can be operated separately. Each module has a capacity of about 1.5 times its normal load. Cell performance under overload is expected to drop slightly; however, the life of the cell should not be affected by the overload condition if suitable means of cooling are provided. This feature is considered of prime importance for the Base 2, 3 and 4 oxygen supply design.

O_2 RECOVERY SYSTEM CHARACTERISTICS



ELECTROLYSIS CELL

OPERATING PRESSURE	30 PSIA
OPERATING TEMPERATURE	175°F
WATER ENTRAINED BY GAS STREAMS	5.1 LB/DAY
CONDENSER TEMPERATURE	65°F
CONDENSER HEAT LOAD	230 BTU/HR
FIXED WEIGHT	100 LB
ELECTRICAL POWER REQUIREMENT (INCLUDING CONTROL)	1270 WATTS
HEAT REJECTION LOAD (TO AMBIENT)	860 BTU/HR

REACTOR LOOP

OPERATING PRESSURE	20 PSIA
REACTOR TEMPERATURE	1400°F
HEATING REQUIREMENT AT 1400°F	900 WATTS
CONDENSER TEMPERATURE	60°F
CONDENSER HEAT LOAD	530 BTU/HR
ELECTRICAL POWER REQUIREMENT (INCLUDING CONTROL)	170 WATTS
FIXED WEIGHT	200 LB
EXPENDABLE WEIGHT	0.05 LB/DAY
HEAT REJECTION	4100 BTU/HR

Figure 26

O_2 RECOVERY

On the basis of the system characteristics previously given, the actual savings to be obtained with oxygen recovery were estimated. In addition, for the systems using oxygen recovery from CO_2, the thermal energy requirement (approximately 600 w for a 6-man system) for the CO_2 removal system was included in the system power consumption estimate in determining the weight penalties chargeable to energy use. The result of the analysis for actual weight savings is shown in Figure 27 for the Base Concepts 2, 3, and 4. Two power systems, nuclear and solar cell-fuel cell, were considered for Base 2. The savings shown for nuclear powered bases are those resulting from oxygen recovery from the CO_2 only.

Because of the large amounts of material and the time dependence of cryogenic storage penalties, the weight savings obtainable with oxygen recovery are particularly important for the longer-duration LESA missions. Figure 27 also indicates the advantage to be realized by use of a radioisotope heat source for the advanced system concepts. It should be emphasized that this conclusion does not consider the availability of radioisotopes or the possibility of nuclear power availability at low weight penalty.

O_2 RECOVERY

ACTUAL SAVINGS

DAYTIME WASTE WATER RECOVERY AND ELECTROLYSIS

POTENTIAL SAVINGS	1620 LB	BASE 2
ACTUAL SAVINGS	710 LB	

CONTINUOUS O_2 RECOVERY FROM CO_2

	BASE 2	BASE 3	BASE 4
POTENTIAL SAVINGS, LB	2650	10,600	23,900
ACTUAL SAVINGS, LB			
NUCLEAR POWER	620	6120	16,500
NUCLEAR POWER AND RADIOISOTOPE HEAT SOURCE	1220	7300	18,400

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Figure 27

V LIFE SUPPORT

by W. L. Burriss

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LIFE SUPPORT REQUIREMENTS

The life-support requirements are given in Figure 28 in terms of the material balance for man, representing the most important material inputs and waste outputs. The water balance implied by the material balance is based upon an average latent heat load of 230 Btu per hr, which is somewhat higher than the insensible level. Water is obviously the most important material requirement for life support. In addition to the water needed by man for food preparation and drinking purposes, additional water is used for sanitation. The amount of water needed for personal hygiene is estimated to be approximately 5.0 lb per man-day; this may be considerably greater if water reclamation can be provided at low cost. The water management system will have a number of significant interfaces with other water-using or -producing systems. If wash water for clothing is required it will impose a significant load on the water reclamation system. The Initial Concept study concluded that use of expendable clothing was preferable to laundering. This selection did not include consideration of the undergarment used with the extravehicular suit. The present extravehicular suit undergarments require laundering or replacement after every use. Based upon extensive use of extravehicular suits in the lunar bases, expendable undergarments would not appear practical, thereby indicating need for laundering provisions in the LESA shelters. This conclusion may be modified somewhat by use of liquid-loop suit cooling techniques that reduce the sweat rate inside suits and possibly eliminate the need for absorbent undergarments.

LIFE SUPPORT REQUIREMENTS

MATERIAL BALANCE

INPUT		OUTPUT	
FOOD	1.5 LB/MAN-DAY	WATER VAPOR	5.3 LB/MAN-DAY
WATER	7.6	URINE	3.2
OXYGEN	2.0	FECES	0.3
	11.1	CO_2	2.3
			11.1

PERSONAL HYGIENE

WASH WATER 5.0 LB/MAN-DAY

CLOTHING

EXTRAVEHICULAR SUITS

EVS UNDERGARMENTS
FLIGHT GARMENTS
UNDERGARMENTS
} EXPENDABLE VS WASHABLE

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Figure 28

WATER RECLAMATION

The requirements for water recovery from waste products in the LESA shelter involve careful consideration of water and oxygen balance. Figure 29 illustrates some of these considerations. Daily water consumption includes the water necessary for drinking and food preparation, and also water leaving the shelter as part of atmosphere leakage. In addition, water is also involved in the material balance for the oxygen recovery systems used in the advanced LESA bases.

Sources of water include waste products (feces, urine, and condensate); for Base Concepts 1 and 2, another source is water produced by the fuel cell as a byproduct of power production. The water necessary for metabolic use on Base Concept 1 and 2 can be derived from fuel cell water and from processing a small proportion of the condensate. If oxygen production from excess water is considered during daytime operation, a larger portion of the condensate must be processed for electrolysis. In all cases, however, water recovery from urine is not required for material balance in Base Concepts 1 and 2.

Base Concepts 3 and 4 involve the use of a nuclear power supply; consequently, all waste water must be recovered for complete material balance, including oxygen production. Highly efficient processes will, therefore, be necessary to reduce resupply requirements to a minimum. A tradeoff between material supply and waste reclamation provisions will help determine the fecal processing provision to be used. In this case, the incentive for use of systems providing recovery of water from feces will be determined by fixed weight, manpower, and power requirements, as well as expendable consumption requirements for the waste reclamation process relative to the material recovery and the relative cost of supply or resupply.

WATER RECLAMATION

SYSTEM REQUIREMENTS

WATER REQUIREMENT, LB/DAY	
METABOLIC	45.6
LEAKAGE	0.3
TOTAL	45.9

WASTE MATERIAL WATER CONTENT, LB/DAY	
FECES	1.2
URINE	18.0
CONDENSATE	31.8
TOTAL	51.0

BASE CONCEPTS 1 AND 2 (FUEL CELL - SOLAR CELL POWER)

FUEL CELL WATER PRODUCTION (AVERAGE)	41.0 LB/DAY
WATER RECOVERY FROM CONDENSATE	4.9 LB/DAY

BASE CONCEPTS 3 AND 4 (NUCLEAR POWER)

WATER FOR ELECTROLYSIS (O_2 BALANCE)	5.1 LB/DAY
TOTAL WATER REQUIREMENT	51.0 LB/DAY
EXCESS WATER	NONE

WATER RECOVERY FROM ALL SOURCES AT MAXIMUM EFFICIENCY

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Figure 29

WATER RECLAMATION

Depending upon the source of the waste water and the use of the purified product water, a variety of different processes can be used for water reclamation. Consequently, the LESA shelter water management systems probably will incorporate more than one process for water recovery. As will be seen, some of the waste water will be relatively pure, requiring little processing to make it suitable for human consumption. The key problem in the water management system will involve processing of urine for water recovery; the process evaluation discussed here is based upon this process.

A number of different processes were evaluated and compared for use in the LESA water reclamation systems. Figure 30, summarizing the evaluation of urine processing, shows the most important competitive processes. System characteristics were assigned figures of merit based upon a relative scale from 1 to 4. No weighting factors were used in the comparison. Each of the systems shown is capable of meeting the basic performance requirements. In some cases, however, extensive pre-treatment and post-treatment may be necessary to provide water of acceptable purity.

On the basis of this evaluation, all of the processes listed are shown to be more or less competitive, with air evaporation being somewhat favored. An unknown factor that may greatly influence process selection involves the water quality standards required for long-duration missions. In closed recycling water systems, trace materials could build up to toxic levels. Water reclamation systems using pyrolysis appear to provide highest purity water. Therefore, a distillation system (vacuum or vapor compression) provided with a pyrolysis reactor may be preferred because of the quality of the product water.

It appears expedient to use a multiple-step purification system. That is, the water recovered from the urine is used for sanitation purposes. Drinking water can be obtained from additional treatment of the sanitation water. This approach somewhat alleviates the purity requirements for urine processing.

WATER RECLAMATION

PROCESS EVALUATION

	VAPOR COMPRESSION	ELECTRODIALYSIS	AIR EVAPORATION	VAPOR COMPRESSION AND PYROLYSIS	DISTILLATION ATM	DISTILLATION VACUUM
STATE-OF-THE-ART DEVELOPMENT	4	3	4	4	4	4
FIXED WEIGHT	4	3	4	2	4	4
EXPENDABLE USAGE	3	1	3	4	2	3
POWER REQUIREMENT	3	2	4	1	2	4
MAINTENANCE	3	3	3	3	3	2
RELIABILITY	3	2	3	2	4	2
RECOVERY EFFICIENCY	3	3	4	4	3	3
TEMPERATURE LEVEL	3	4	3	1	2	4
WATER PURITY	2	3	2	4	1	2
	28	24	30	25	25	28

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Figure 30

WATER RECLAMATION

Figure 31 shows characteristics of three processes applicable to reclamation of water from waste products. Water obtained from the condensing heat exchanger used for cabin humidity control will be relatively pure and will require little treatment to be suitable for human consumption. On the other hand, water recovery from feces will be comparatively difficult. The process selected here involves dehydration by a recirculating hot-gas loop. Relative to the amount of water available, processing of feces for water recovery is comparatively expensive in terms of the energy requirements. Therefore, water recovery from feces appears to be advantageous for mission durations in excess of one yeat. If waste incineration is incorporated into the more advanced LESA systems for waste disposal, however, predrying of the feces before burning would help combustion. Waste disposal methods may be affected by national policy. For health and safety reasons, it is probably undesirable to store wastes inside the shelters for long-duration missions. Alternative methods would involve external disposal or processing.

WATER RECLAMATION

SYSTEM CHARACTERISTICS

WATER RECOVERY FROM CONDENSATE

- CHARCOAL FILTRATION AND UV EXPOSURE

FIXED WEIGHT	2.5 LB
EXPENDABLE WEIGHT	2 LB/6 MONTHS
POWER	3 WATTS

(TANKAGE NOT INCLUDED)

WATER RECOVERY FROM FECES

- DRIED WITH HOT AIR PLUS CHARCOAL

FIXED WEIGHT	5.5
EXPENDABLE WEIGHT	15 LB/6 MONTHS
POWER	10 WATTS
COOLING REQUIREMENTS	94 BTU/HR
HEATING REQUIREMENTS	60 BTU/HR

WATER RECOVERY FROM URINE

- AIR EVAPORATION (2 STAGES TO 98% RECOVERY)

FIXED WEIGHT	22
EXPENDABLE WEIGHT	40 LB/6 MONTHS
POWER	15 WATTS
HEATING REQUIREMENTS AT 120°F	1100 BTU/HR
COOLING REQUIREMENTS AT 50°F	920 BTU/HR
HEAT LOAD TO CABIN	230 BTU/HR

Figure 31

MAJOR INTERFACES

A primary task in the human factors studies has involved establishing the constraints imposed by pressure suits. Although normal operation inside the LESA shelters is in a shirtsleeve environment, it is anticipated that pressure suits will find extensive usage for extravehicular operations. Also, pressure suits may be used to effect repairs in event of shelter depressurization. Consequently, provision will be required in shelter interior design for pressurized suit operation. This will impose certain limitations on installation of equipment and controls where these are to be operable by men in suits. In addition, there will be a considerable amount of activity, inside the LESA shelters, associated with support of extravehicular operations, which will involve checkout, donning, and doffing of extravehicular suit and life support assemblies. Figure 32 illustrates these considerations.

VI HUMAN FACTORS

by Dr. E. C. Wortz

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MAJOR INTERFACES

SUIT, ACCESSORIES, LIFE SUPPORT PACK, BASE

SUIT / LIFE SUPPORT PACK

SUIT ASSEMBLY / ENVIRONMENT

BASE / SUIT ASSEMBLY / LIFE SUPPORT PACK

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Figure 32

MAJOR INTERFACES

Figure 33 lists some of the support and operational requirements and the resulting tasks for the extravehicular suit life support assembly. The requirements for accessible suit storage and adequate space for suit donning have received particular attention because of their importance to both crew safety and efficient base operation. The support requirements for servicing the life-support packs and for suit maintenance have been analyzed to provide necessary information for the time line analyses. The limitations imposed by the suit with respect to reduced mobility and dexterity have been considered in air lock design and operating procedures.

MAJOR INTERFACES

SUIT, ACCESSORIES, LIFE SUPPORT PACK, BASE

BASE/SUIT ASSEMBLY/LIFE SUPPORT PACK

- STORAGE OF PORTABLE E.C.S.
- STORAGE OF SUIT ASSEMBLY
- DONNING SPACE
- O_2 TANK FILLING
- WATER TANK FILLING
- SWITCHING FROM PORTABLE TO FIXED ECS
- AIRLOCK OPERATION
- SUIT LEAKAGE CHECKOUT EQUIPMENT
- PORTABLE ECS CHECKOUT
- INTEGRATION OF EXTRA AND INTRA-SHELTER SUIT REQUIREMENTS
- BACTERIOLOGICAL DECONTAMINATION
- COMMUNICATION SYSTEM
- FOOD SUPPLY STORAGE (ZERO G TYPE FOOD FOR EMERGENCY)
- MOBILITY REQUIREMENTS FOR TASK
- FINGER DEXTERITY REQUIREMENTS FOR INSTRUMENT AND EQUIPMENT OPERATION
- WASTE HANDLING AND STORAGE
- UMBILICAL SUPPORT ATTACHMENT
- SUIT BIOMEDICAL INSTRUMENTATION
- BATTERY RECHARGING

Figure 33

MAJOR INTERFACES

The extravehicular suit will be used inside the shelter during preparations for extravehicular excursions. For this phase of operation and for egress through the air lock, the extravehicular suit will be supported by shelter systems. Therefore, depending upon extravehicular suit assembly design, there will be a number of different methods and operating procedures that can be adopted. Figure 34 lists some of the physical interfaces between the suit and life support system. In developing shelter egress procedures, it will be necessary to consider these requirements and provide suitable means for their accomplishment. During air lock operation, for example, it will be necessary to provide (a) oxygen for suit pressurization and breathing, (b) cold heat transport fluid for suit cooling, and (c) electrical circuits for communications and instrumentation. The portable life-support pack can be put into operation once the air lock is depressurized. It is evident that the shelter must provide suit loop systems that function independent of the cabin for air lock operation.

MAJOR INTERFACES

SUIT, ACCESSORIES, LIFE SUPPORT PACK, BASE

- THERMAL EXCHANGE
- MECHANICAL CONNECTION
- ELECTRICAL CONNECTION
- PNEUMATIC CONNECTION
- TOOLS AND ACCESSORIES PLACEMENT
- LIQUID LOOP CONNECTION

SUIT ASSEMBLY / ENVIRONMENT

- EXTRA SHELTER EQUIPMENT (TOOLS APPARATUS)
- THERMAL EXCHANGE
- METEORITIC PROTECTION
- RADIATION PROTECTION

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Figure 34

LUNAR SUIT ASSEMBLY OPERATIONS

The gross task description of pressure suit usage as depicted in Figure 35 shows the four elements essential to this operation. The variety of secondary tasks necessary to assure their reliable accomplishment are shown in Figures 36 to 40. Each gross task entry is reduced to the support activities associated with them. Although these tasks have been arrived at in an analysis of soft pressure suits, they are applicable to the hard suit concept as well.

LUNAR SUIT ASSEMBLY OPERATIONS

CHECKOUT AND DONNING → USAGE → DOFFING → STORAGE AND MAINTENANCE

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Figure 35

LUNAR SUIT ASSEMBLY OPERATIONS

Checkout and donning the pressure suit, at least during the early phases of the mission, will in all likelihood include monitoring of various physiological parameters of the suited personnel. In turn, this requires the placement of sensors and the use of telemetry and recording devices. Basically, the suited men will require the assistance and support of another cremember for this monitoring. The additional requirement of the buddy system for lunar surface activities points out the limiting factors associated with Base Concepts 1 and 2, due to the small number of men in the crew.

The ready condition of the pressure suit must be maintained at all times for emergency use. The requirements associated with donning must be by-passed for the most part under such circumstances. Due to the short response times anticipated for emergency procedures, suit design must include the provision for rapid donning.

Figure 36 illustrates these approaches.

LUNAR SUIT ASSEMBLY OPERATIONS

CHECKOUT & DONNING

↓

- ATTACH & SECURE PHYSIOLOGICAL SENSORS
- PRETREAT INNER GARMENT

↓

UNSTORAGE AND DONNING

- UNLATCH STORAGE RESTRAINTS
- DON UNDER GARMET
- CHECK WASTE REMOVAL DEVICES
- ORIENT SUIT FOR DONNING
- DON SUIT; CHECK MOBILITY & INTERNAL STRAP RESTRAINTS ← EMERGENCY ONLY LOSS OF BASE PRESSURIZATION
- SEAL ZIPPER; PRESSURIZE SUIT; ADJUST EXTERNAL COMFORT CINCH
- CHECK LIFE SUPPORT SYSTEM PERFORMANCE, OR UMBILICAL PERFORMANCE
- DON ADDITIONAL EXTERNAL ACCESSORIES FOR SPECIFIED MISSION, GLOVES, BOOTS, TOOLS, THERMAL GARMENT, ETC

↓

USAGE

Figure 36

LUNAR SUIT ASSEMBLY OPERATIONS

During the performance of egress and ingress procedures, pressure suit limitations must be taken into consideration (Figure 37). Vision is restricted in both up and down planes due to helmet and visor cutoff. Mobility is also restricted as torso bending is prohibited; the wearer must crouch instead of bending at the waist to go through hatchways. Hatch coamings also must be limited in height as leg movement is restricted and this motion also compensates for torso bending.

Pressure suit restrictions must be included as design constraints in the layout of the shelter, especially air lock operations. Crew performance will be adversely affected and more seious consequences may result if the shelter interior does not include provisions for pressure suit restrictions.

LUNAR SUIT ASSEMBLY OPERATIONS

The present suit usage concept includes the storage of the majority of suits in the living module and maintaining them in a ready condition as an emergency provision (Figure 38).

An additional requirement is that the suit exterior be cleaned to avoid contamination of the base interior. It is presently planned to include a vacuum cleaner in the air lock to assist in performance of this task.

LUNAR SUIT ASSEMBLY OPERATIONS

USAGE

↓

BASE EGRESS

ENTER AIR LOCK
CHECK COMMUNICATIONS
LOCK INNER HATCH
PRESSURIZE SUIT
CHECK SUIT ΔP DURING PRESSURIZATION
DEPRESSURIZE AIR LOCK
OPEN OUTER HATCH

↓

BASE INGRESS

CHECK AIR LOCK PRESSURE
OPEN AND ENTER AIR LOCK
CHECK AIR LOCK SEAL
CLOSE OUTER HATCH
PRESSURIZE AIR LOCK
OPEN INNER HATCH

↓

DOFFING

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Figure 37

LUNAR SUIT ASSEMBLY OPERATIONS

DOFFING

↓

POSTMISSION CONDITIONING

DEPRESSURIZE; DISCONNECT UMBILICAL OR PACK
DOFF PACK AND ACCESSORIES
OPEN ZIPPER PRESSURE SEAL
DISCONNECT PHYSIOLOGICAL SENSORS
REMOVE WASTE REMOVAL DEVICES
DRY INTERNAL SUIT WITH FORCED AIR

DOFFING AND STORAGE

[redacted]

STORAGE AND
MAINTENANCE

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Figure 38

LUNAR SUIT ASSEMBLY OPERATIONS

The storage and maintenance requirements for the LESA extravehicular suits will substantially affect EC/LSS design, shelter interior design, and mission time lines. The EC/LSS must include provisions for recharging the portable environment control system. These provisions include supply of water, oxygen, and CO_2 absorbent. The storage provisions should keep the suits out of the way when not required but must provide ready accessibility for maintenance or rapid donning. It is anticipated that each crewmember will have responsibility for maintenance of his suit. Therefore, it will be necessary to identify the tasks associated with suit and portable environmental control system maintenance in order to establish the manpower requirements for these functions in the mission time lines. Figure 39 illustrates these considerations.

LUNAR SUIT ASSEMBLY OPERATIONS

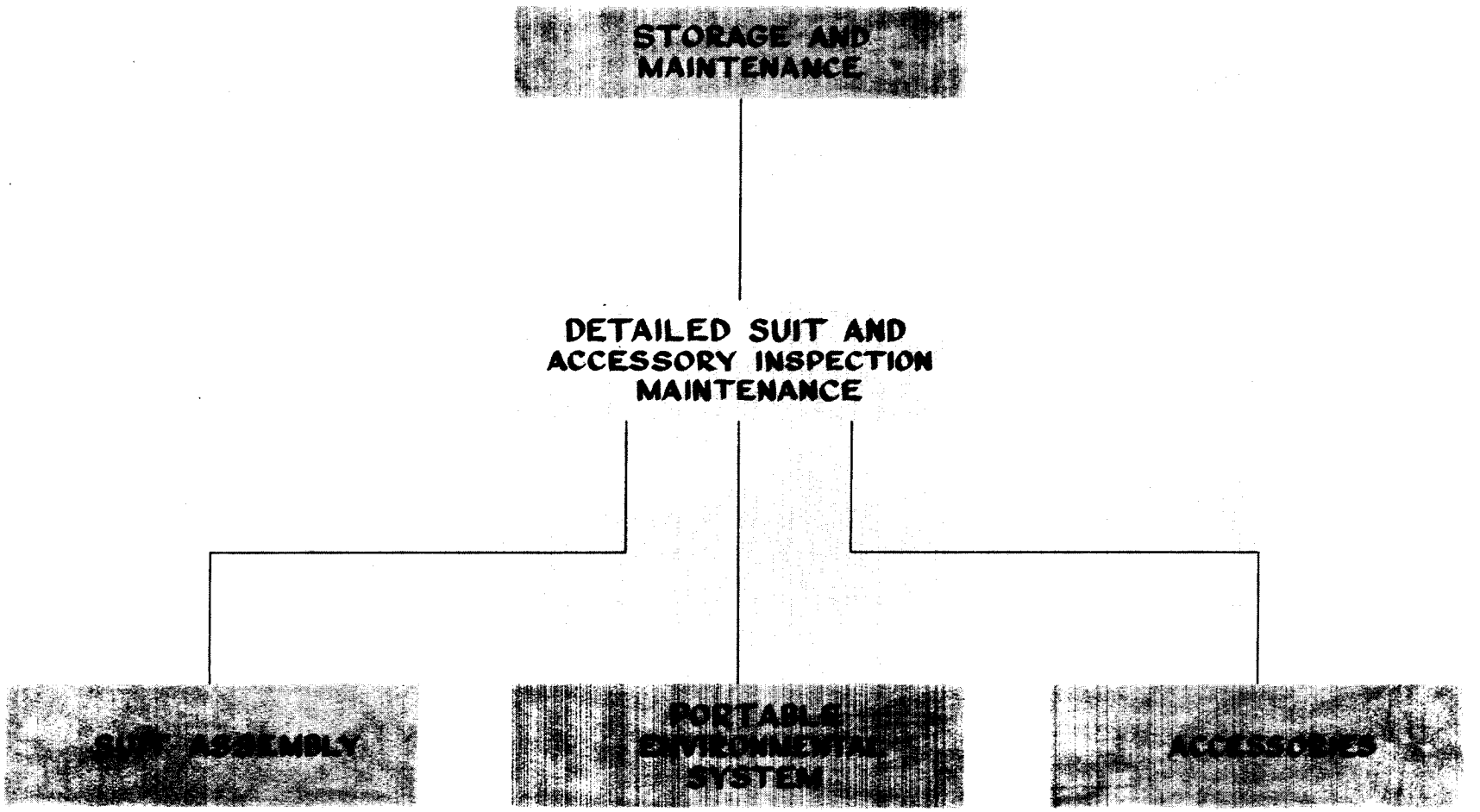

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Figure 39

LUNAR SUIT ASSEMBLY OPERATIONS

Identification of tasks associated with the support activities of the pressure suit system points out the time-consuming activities required in pressure suit use (Figure 40). Actual performance times for these tasks must yet be determined, but preliminary estimates anticipate a ratio of 2 hours of support for each extravehicular operation.

LUNAR SUIT ASSEMBLY OPERATIONS

SUIT ASSEMBLY

SUIT FUNCTION	SUIT ACTION
LEAKAGE	MAKE REPAIRS (IF POSSIBLE)
RESTRAINT	REPLACE CINCH STRAP
ENVIRONMENT AND SERVICE CONNECTOR	REPLACE OR REPAIR MODULE
TRANSDUCERS AND DOSIMETERS	REPLACE OR REPAIR MODULE
WASTE DISPOSAL	REPLACE DISPOSABLE MODULE

HEAD ENCLOSURE

HEAD ENCLOSURE FUNCTION	HEAD ENCLOSURE ACTION
VISOR	CHECK SEAL
ELECTRONIC AND PRESSURE TRANSDUCERS	REPLACE QUICK-DISCONNECT MODULE
ORAL SERVICING FUNCTIONS	CLEAN

ACCESSORIES

[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible] AND REPLACE
[illegible]	[illegible] PER MISSION
[illegible]	[illegible]EMENTS

PORTABLE ENVIRONMENT SYSTEM

[illegible]	ACTION
OXYGEN [illegible]	[illegible] QUANTITY; FILL TANK
[illegible]	[illegible] CIRCUIT AND [illegible]; REPLACE MODULE
WATER [illegible]	FILL TANK BY PRESSURE TRANSFER
LiOH	REPLACE CARTRIDGE

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Figure 40

METABOLIC ENERGY REQUIREMENTS

Figure 41 depicts metabolic rates, in Btu per hr, as a function of walking speed (mph) for subjects exercising on a level treadmill. The maximum walking speed shown is 2.0 mph, which testing has shown to be the greatest speed practicable in a pressurized space suit. The bottom line represents the metabolic load for subjects walking nude in a normal, sea-level pressure environment; it provides a base-line with which to compare the performance of subjects walking similarly in pressurized suits. A second curve (circled notation) represents the mean for metabolic data acquired with subjects walking at earth gravity in the most mobile of the current suits, under pressurized conditions representative of those to be encountered. The spread of these data is indicated by the adjacent lines, which are drawn one standard deviation away from the mean. The standard deviation (σ) shown includes the "Q_{10}" effect, which is the increase in metabolic rate due to heat storage in the body. Heat storage acts to increase the subject's metabolic rate by approximately 13 percent for each $1^{\circ}C$ elevation in body temperature. In addition, there is a large difference in metabolic rates, heat storage, etc., found between individual subjects for given rates of exercises. The effects of walking on the lunar surface in a pressurized suit have not been adequately studied; estimates of the mean requisite energy requirements range between the maximum and minimum depicted by the curves with the "diamond" shaped notation.

METABOLIC ENERGY REQUIREMENTS

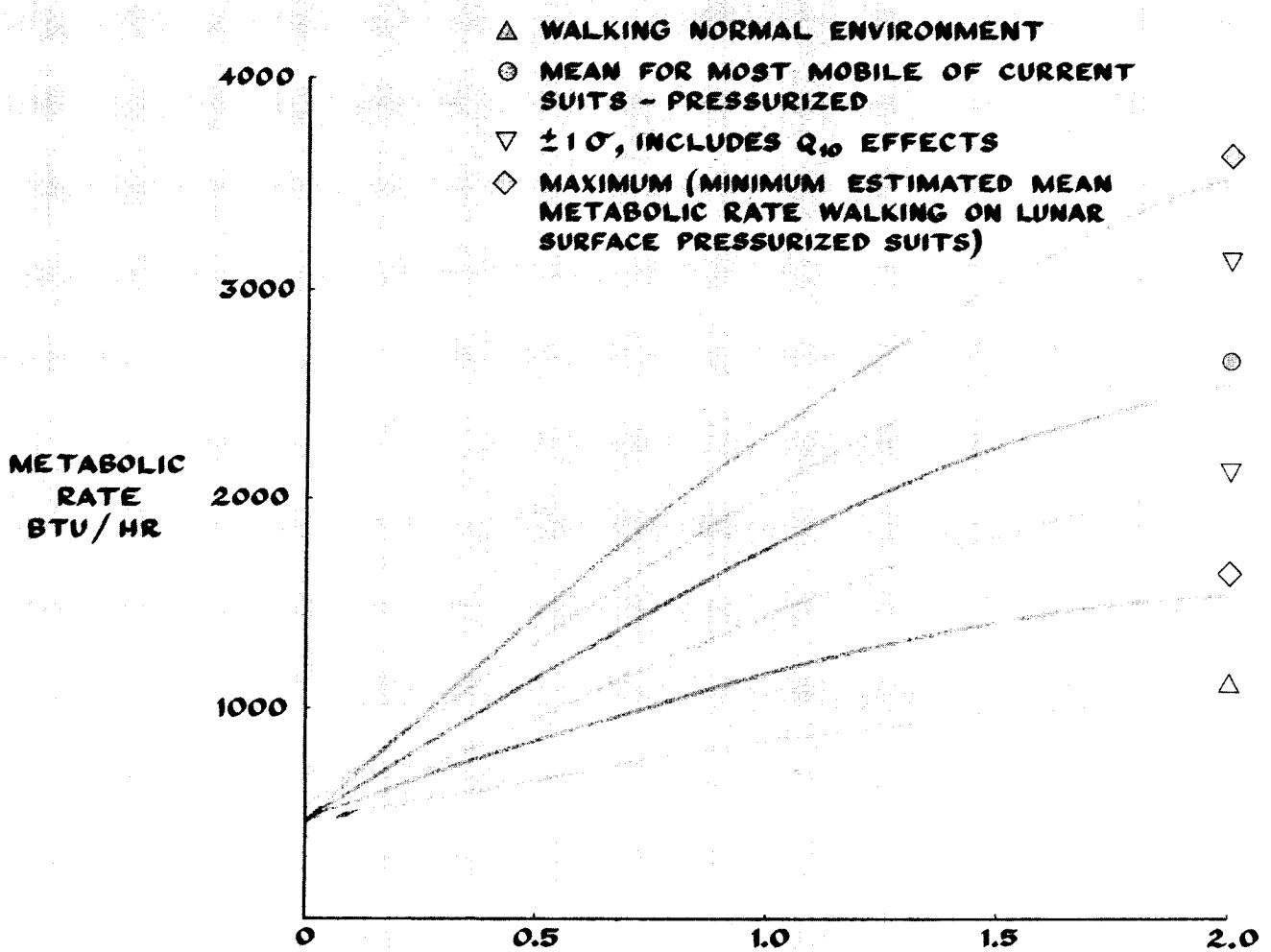

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Figure 41

TASKS AND BODY MOTIONS

The information depicted in Figure 42 represents data accumulated on pressurized state-of-the-art soft suits. The essential body motions for each task indicated in this figure are those indicated by prosthetic studies as the minimal motion required for each task. The column entitled "Cannot be done in pressurized suit" lists those motions that are impossible or severely limited in a pressurized suit with the wearer standing erect.

TASKS AND BODY MOTIONS

ESSENTIAL BODY MOTIONS	Cannot be done in pressurized suit	Donning/Doffing Suit	Base Operation	Scheduled Maintenance	Human Functions	Inside Repairs	Air Lock Exit Entrance	Outside Repairs
	TYPICAL TASKS							
HEAD								
Rotation		X	X		X			X
Sagittal Nodding	■							
PREHENSION								
Three Finger		X	X	X	X	X	X	X
Gross Grasp		X	X	X	X	X	X	X
WRIST								
Flexion		X	X	X	X	X	X	X
Extension		X	X	X	X	X	X	X
Rotation								
FOREARM								
Flexion		X	X	X	X	X	X	X
Extension		X	X	X	X	X	X	X
UPPER ARM								
Flexion		X	X	X	X	X	X	X
Extension		X		X		X	X	X
Abduction	■							
Adduction								
Rotation		X	X	X		X		X
SHOULDER								
Depression	■							
Elevation	■							
THIGH								
Flexion		X	X	X		X	X	X
Extension		X		X		X	X	X
Abduction								
Adduction								
KNEE								
Flexion		X	X	X		X	X	X
Extension		X		X		X	X	X
ANKLE								
Flexion/Extension	■							
TRUNK								
Bending							X	
Backward/forward	■							
Bending left/right	■				X			X

Figure 42

VII CREW TASKS

by W. Schreck

Item	Page
Functional Flow Data	98
Detail Functional Flow Diagram	100
Typical Functional Data	102
Typical Task Data	104
Personal Activities	106
Crew Support Activities	108
Facility and Communication Control	110
Base Task Composite	112
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FUNCTIONAL FLOW DATA

Preliminary human factors studies for LESA were related to human behavioral requirements for the shelter module under LESA Base Concept 2. Since specific task detail was an objective, the operational phase was selected as the most amenable to later extrapolation for other base concepts.

The first step was to determine the system elements required for the mission. These elements were then further defined as to the primary functions necessary to support the system elements. Each of these functions in turn was more definitively described to establish "second level functions."

Graphically displayed, this information provides a functional flow diagram for the LESA mission, as shown in Figure 43. Illustrated are the elements and functions required during the mission operational phase.

The functional flow diagram provides a structure for the overall study as well as a framework for the human factors analysis. Such a procedure makes systematic methodology possible by limiting the study effort to specific definitions: the procedure for working from the general to the specific; the "man orientation" of a human factors study; minimized presuppositions about hardware during the conceptual study; and additional definition of the mission arrived at by logical procession.

FUNCTIONAL FLOW DATA

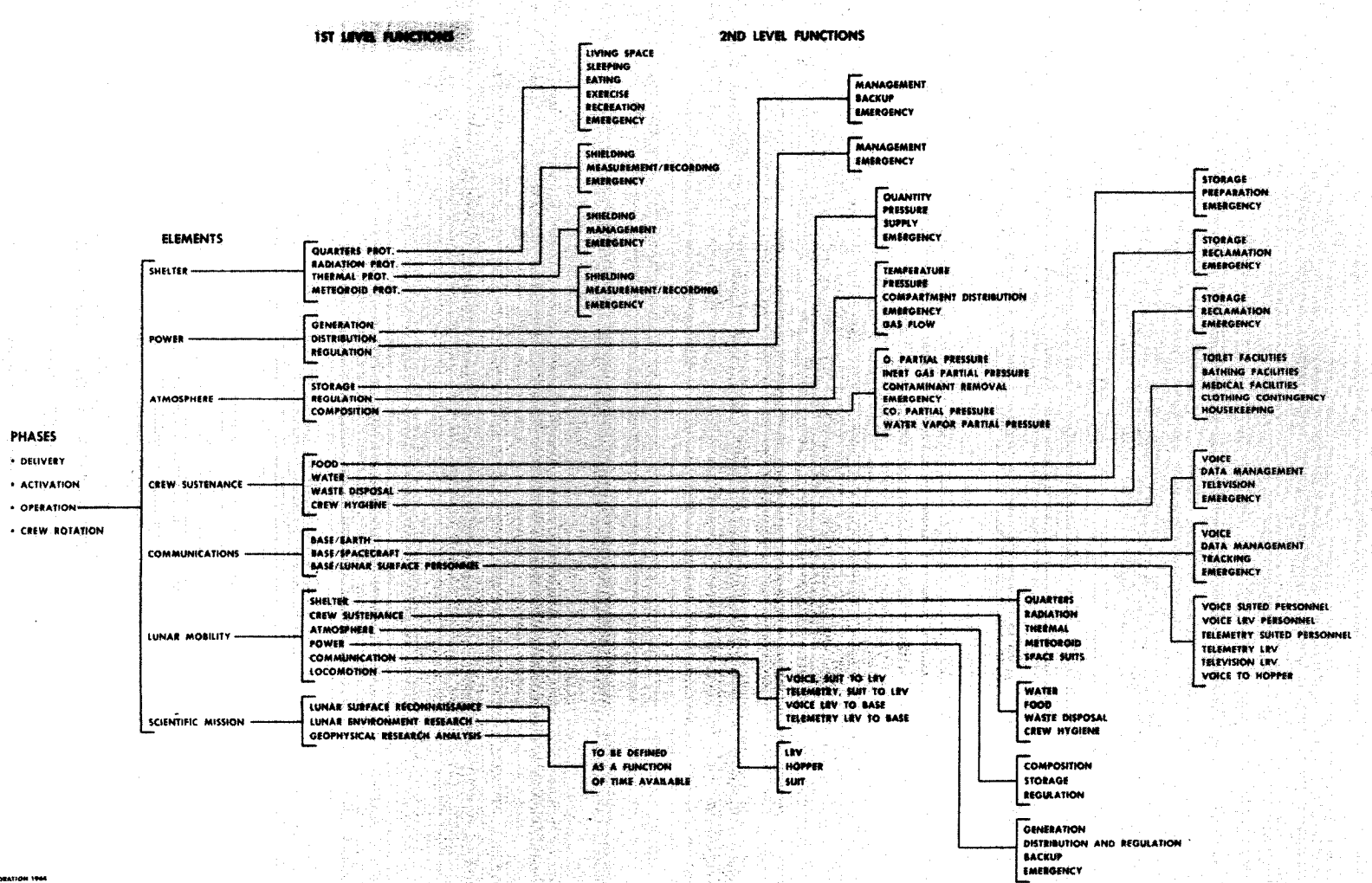

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Figure 43

DETAIL FUNCTIONAL FLOW DIAGRAM

Figure 44 is included in this presentation to illustrate a specific example of human factor methodology. The first-level function is storage; second level functions are quantity, pressure, supply, and emergency.

The entry used for illustration in the text is base total pressure, which is carried to the functional data sheet for further analysis.

DETAIL FUNCTIONAL FLOWDIAGRAM

PHASE	[redacted]	FIRST LEVEL FUNCTION	SECOND LEVEL FUNCTION
OPERATION	SHELTER	STORAGE	QUANTITY PRESSURE SUPPLY EMERGENCY
	POWER		
	ATMOSPHERE	REGULATION	TEMPERATURE PRESSURE COMPARTMENT DISTRIBUTION EMERGENCY GAS FLOW
	CREW SUSTENANCE		
	COMMUNICATION	COMPOSITION	O_2 PARTIAL PRESSURE INERT GAS PARTIAL PRESSURE CONTAMINANT REMOVAL EMERGENCY CO_2 PARTIAL PRESSURE WATER VAPOR PARTIAL PRESSURE
	LUNAR MOBILITY		
	SCIENTIFIC MISSION		

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Figure 44

TYPICAL FUNCTIONAL DATA

The study procedure analyzes the second-level functions and subjects them to a descriptive itemization through the use of the Functional Data sheet, illustrated in Figure 45. The frame of reference is kept man-oriented for this and all subsequent steps. Certain state-of-the-art hardware concepts are used, but these are deliberately referred to in general terms to avoid the tendency to delineate hardware as opposed to man's requirements. Where human behavior is associated with the second-level functions, it is identified and described.

The entries are analyzed in the light of man's requirement for information and control to efficiently operate the system. In this manner, the tasks represent information necessary for the crew members to perform the mission, as well as knowledge of equipment performance.

TYPICAL FUNCTIONAL DATA

CODE

FUNCTIONAL DATA

PHASE _____ Operation

ELEMENT _____ Atmosphere

FIRST LEVEL FUNCTION _____ Storage

SECOND LEVEL FUNCTION _____ Quantity, pressure, supply, emergency

FUNCTIONAL DESCRIPTION	Pressure control of stored O_2 It is assumed that the required oxygen makeup of leakage and metabolic consumption shall be obtained from cryogenic storage tanks; where temperature and pressure control shall be required.
PRIMARY SYSTEM	Liquid storage containers with pressure regulator valve, with heat and possibly refrigeration control.
MAN/MACHINE INTERFACE	Facility display and control panel
PRIMARY TASK	Monitor and control, manual overrides for the automatic provision. Switching supply source
COMMUNICATION	Not required.
TASK ENVIRONMENT	Storage will not be in an area where the atmosphere is controlled. Base interior for facility control panel.
CREW NUMBER	Operation one man.
REMARKS	

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Figure 45

TYPICAL TASK DATA

The tasks associated with the second-level functions and identified on the Functional Data sheet are analyzed to further define the human behavioral requirements. To accomplish this, the task and associated information are entered on the Task Data sheet, illustrated in Figure 46, where the itemization procedure provides further task definition and description.

The procedure is the first step in the determination of the machine output to man, the human output in response, the safety and performance criticality of the task, task initiation, task time, task frequency, and other elements entered on a Task Data sheet.

TYPICAL TASK DATA

CODE

TASK DATA

SECOND LEVEL FUNCTION ____ Atmosphere storage temperature and pressure

PRIMARY TASK _____ Monitor and control oxygen

TASK DESCRIPTION	Monitor and control pressure and quantity at the facility control and display panel.
	Excessive storage tank pressure. Low cabin pO_2 ;empty tank.
	Provide atmospheric and fuel cell oxygen and provide control capability.
	Facility display and control panel.
	Storage tanks pressure and quantity.
HUMAN OUTPUT	Monitor and control condition of atmospheric stored gases. 1. Switch tanks on line. 2. Provide additional thermal installation. 3. Initiate additional cooling techniques. 4. ADO heat to cryo tanks.
	Displays- Pressure, liquid level and flow from tanks in use.
	Monitor; 1 minute Control; 5 minutes
	Monitor hourly Control estimated once every 4 hours.
	High criticality
REMARKS	Emergency action; 1. Provide additional thermal shield for cryogenic tanks. 2. Provide additional heat to cyro tanks.

Figure 46

PERSONAL ACTIVITIES

The associated tasks and those tasks that necessitate logical grouping to identify their frequency, duration, interfaces, location, and display and control requirements, are grouped together as task composite sheets. These composites are then utilized to establish the crew's task sequences and duration as system requirements. Data on these activities are shown in Figure 47.

Their initial use is most apparent in arriving at time totals for classes of activities. The task times associated with each crew member's various roles are examples of these classes; they are primarily (1) to maintain his health, safety and well being; (2) to operate and maintain the facility; and (3) to perform the scientific mission.

Personal activities are presented as an anticipated average for the crew members. The feasibility of the shower, an advisable item, will be determined by the amount of water available for washing and the water management penalty incurred for purification. The pressure suit checkout time period is based on the importance of maintaining this equipment for immediate emergency use. It is assumed that the pressure suit will be handled as personal property, each crew member being responsible for his own suit.

PERSONAL ACTIVITIES

24 HOUR CYCLE

CONTACT	DAILY FREQUENCY	TIME MINUTES	TIME HOURS
TOILET	1	20	
URINAL	5	15	
WASH BASIN	5	15	
SHOWER	1	15	
GROOMING	2	15	2
WASHING MACHINE	½	10	
CLOTHING	1	10	
PRESSURE SUIT CHECKOUT	1	20	
EXERCISE	1	20	0.33
SLEEPING	1 OR 2	480	8.00
EATING	3	90	1.50
TOTALS	23	710	11.83 = 11 HRS 50 MIN

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Figure 47

CREW SUPPORT ACTIVITIES

Figure 48 depicts four task groups required to support various phases of crew activities. The task groups comprising Handling Food, Physiological Monitoring, and Housekeeping are essential to the health, safety, and well-being of the crew. Scheduled System Support Activities are associated with maintaining the facility. Test, checkout, and maintenance activities are based on state-of-the-art hardware and anticipated requirements for future systems. The present analysis indicates that these tasks will be assigned on a regular schedule.

The task composite total of 6-1/2 hr represents the time devoted to support activity for a 24-hr cycle. Where skills and scheduling permit, the tasks will be shared equally by the various crew members.

Food Handling tasks anticipate meal preparation and serving by one man. Under this procedure, all crew members will eat together, except for the operator at the communication console. This arrangement has obvious psychological benefits.

Physiological data necessary to evaluate crew health, including effects of lunar environment upon their physiological or psychological well-being, will be required. Although each member will participate in this activity, the three crew members assigned to the facility and communication console will have primary responsibility for these data. Tentative scheduling provides that each of these men will be doing this work at a specific time during each 24-hr cycle.

Housekeeping will require a minimum of one hour each 24-hr cycle, assuming that each individual will normally keep his work station clean and in order.

The time required for system support, i.e., test, checkout, and maintenance of system equipment, obviously depends upon the specific hardware involved. At mid-term of a conceptual study the awareness of these requirements requires time allocation for their performance. Should this estimate prove to be inadequate the increased time deviation shall have to be gained at the expense of the available scientific mission time.

As the conceptual study progresses, time estimates for these tasks can be refined. Adjustment in time allotments for these tasks should not detract from the time available for scientific aspect of the mission.

CREW SUPPORT ACTIVITIES

TASK GROUP	DAILY FREQUENCY	TIME (24 HR CYCLE)
FOOD		1 HR 30 MIN
PROCURE	3	
PREPARE	3	
SERVE	3	
SANITATION	3	
PHYSIOLOGICAL MONITORING		1 HR
BASE INTERIOR	2	
PRESSURE SUIT	2	
HOUSE KEEPING	1	1 HR
SCHEDULED SYSTEM SUPPORT		3 HRS
TEST	AS REQUIRED	
CHECKOUT	AS REQUIRED	
MAINTENANCE	AS REQUIRED	
		6 HRS 30 MIN

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Figure 48

FACILITY AND COMMUNICATION CONTROL

Many system functions set up to protect the crew from hostile lunar environment require immediate corrective action in case of malfunction. Such action requires ready knowledge of system performance within established tolerances. This requirement established a monitor and control task for these critical survival parameters. Constant manning of certain communication links was also advantageous. These two task groupings were combined in a monitor and control/communication task composite. Preliminary analysis indicated that these tasks should be time-shared by one operator for a duty period of 4 hr to appropriately utilize the available manpower. Figure 49 illustrates this requirement.

Of this 4-hr duty period, a total of 31 min is undesignated time. It can be safely regarded, however, as contingency time since monitoring requirements will more than likely increase than decrease. Moreover, even the intervals established for this task are regarded as minimal time allocations.

A special consideration here is that the work load at the facility and communication console will decline during the rest period of the 24-hr cycle and also when the LRV is not on reconnaissance. It is anticipated that these "slack" periods will be devoted to data handling.

Crew time could be saved with complete automation of the facility monitoring function and display of these parameters as hazard warnings for out-of-tolerance performance or malfunctions. This approach would, however, require considerable equipment with exceptional reliability.

At this point of the human factors analysis it appears that critical facility parameters should be monitored by the crew rather than simply automated. If during the conceptual study effort it becomes apparent that the communication task is too complex for manual and visual monitoring, serious consideration must then be given to automated transmission. Any alternative that detracts further from scientific tasks is, of course, to be avoided if at all possible.

FACILITY AND COMMUNICATION CONTROL

TASK SUMMARY

FACILITY DISPLAY & CONTROL CONSOLE

ELEMENTS	MONITOR & CONTROL TIME, MINUTES
AIR LOCK	10
POWER	21
BASE EXTERIOR	22
THERMAL	
RADIATION	
METEOROID	
ECS	18
WATER	18
	89

COMMUNICATION CONSOLE

LINKS	MONITOR & CONTROL TIME, MINUTES
VOICE TO EARTH	30
VOICE TO LRV	40
TELEMETRY TO EARTH	20
LRV TELEMETRY	10
LUNAR SUIT TO BASE	20
	120

ONE OPERATOR TASK SHARER
FOR 4-HOUR DUTY CYCLE

Figure 49

BASE TASK COMPOSITE

Personal Activities, Crew Support Activities, and Facility and Communication Control have been combined in a base task composite to depict the crew time expenditure (Figure 50). Time remaining after these essential tasks are accomplished is available to perform the scientific mission. This scientific mission time is presently estimated 46.3 man-hours per day.

Obviously, in the conceptual study phase, specific task times will be modified as task requirements change. Iterative analysis lends itself effectively to this continuing modification.

Present estimates, by percentages, are as follows:

Sleeping	32 %	Duty	24 %
Monitor & Control/Communication	16 %	Personal Activities	7 %
Unscheduled (Potential Mission) Time	7 %	Eating	5 %
Scheduled System Support	6 %	Meal Preparation	1 %
Exercise	1 %	Housekeeping	0.5%
Physiological Monitoring	0.5%		

Duty and unscheduled time, 31 percent, represents the time available for pursuit of the scientific mission.

Figure 47 is the logical grouping of tasks associated with sleeping, personal health, safety, and well-being. They are expected to occupy almost 50 percent of a man's time during a 24-hr cycle.

BASE TASK COMPOSITE

	DAILY CREW ACTIVITIES, HOURS																								EXPERIMENTS TIME AVAILABLE
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	
COMMANDER				S					E		P			C & C							X				12 HRS 30 MIN
CREWMAN NO. 1				S					E		P			M/C & C						M	X				●3 HRS 10 MIN
CREWMAN NO. 2				S					E		P			M/C & C						H	B	X			●3 HRS 10 MIN
CREWMAN NO. 3				S					E		P			M/C & C						S.S.S			X		●3 HRS 10 MIN
CREWMAN NO. 4				S					E		P	X		LRV											12 HRS 10 MIN
CREWMAN NO. 5				S					E		P	X		LRV											12 HRS 10 MIN
																									46 HRS 20 MIN TOTAL

CODE

S = SLEEP
E = EATING
P = PERSONAL
X = EXERCISE
H = HOUSEKEEPING

C & C = COMMAND AND COMMUNICATION
M/C&C = MONITOR AND CONTROL, AND COMMUNICATION
M = MEAL PREPARATION
SSS = SCHEDULED SYSTEM SUPPORT
B = PHYSIOLOGICAL MONITORING
LRV = LUNAR ROVING VEHICLE

● ROTATION EVERY 3 DAYS
31 MIN. PER M/C&C EXPTL. TIME

DUTY, EXPTL. & UNSCHED. = DAILY AVERAGE OF 4 HRS. 12 MIN.

Figure 50

DUTY CYCLE

Duty cycles assume a continuation of the earth-oriented day on the lunar surface, and that the crew will be performing many activities concurrently, e.g., eating, conducting experiments, and resting at the same times. The exception to this procedure is the requirement for continuous monitoring and control of the Facility and Communication console. The console is monitored in 4-hr duty periods which will be interspersed by shift breaks every fifth period. At the shift breaks, two duty periods of 2-hr each are scheduled. When these monitoring periods occur at other than regular working hours, such as during sleep time, they are considered additional work periods above and beyond the regular duty. The two men who will man the LRV during reconnaissance of the lunar surface will be exempt from the monitor duty, thus avoiding cross-training of skills.

It is also assumed that the base commander (command function) will not have regular monitoring duty. He will thus be available as a backup for monitoring as well as to provide general flexibility as crew activities require.

Illustrating these concepts graphically and displaying them in time sets the job requirements and duty periods as depicted for the Base 2, 6-man concept.

Figure 51 depicts duty cycle allocations based upon the Base 2, 6-man concept.

DUTY CYCLE

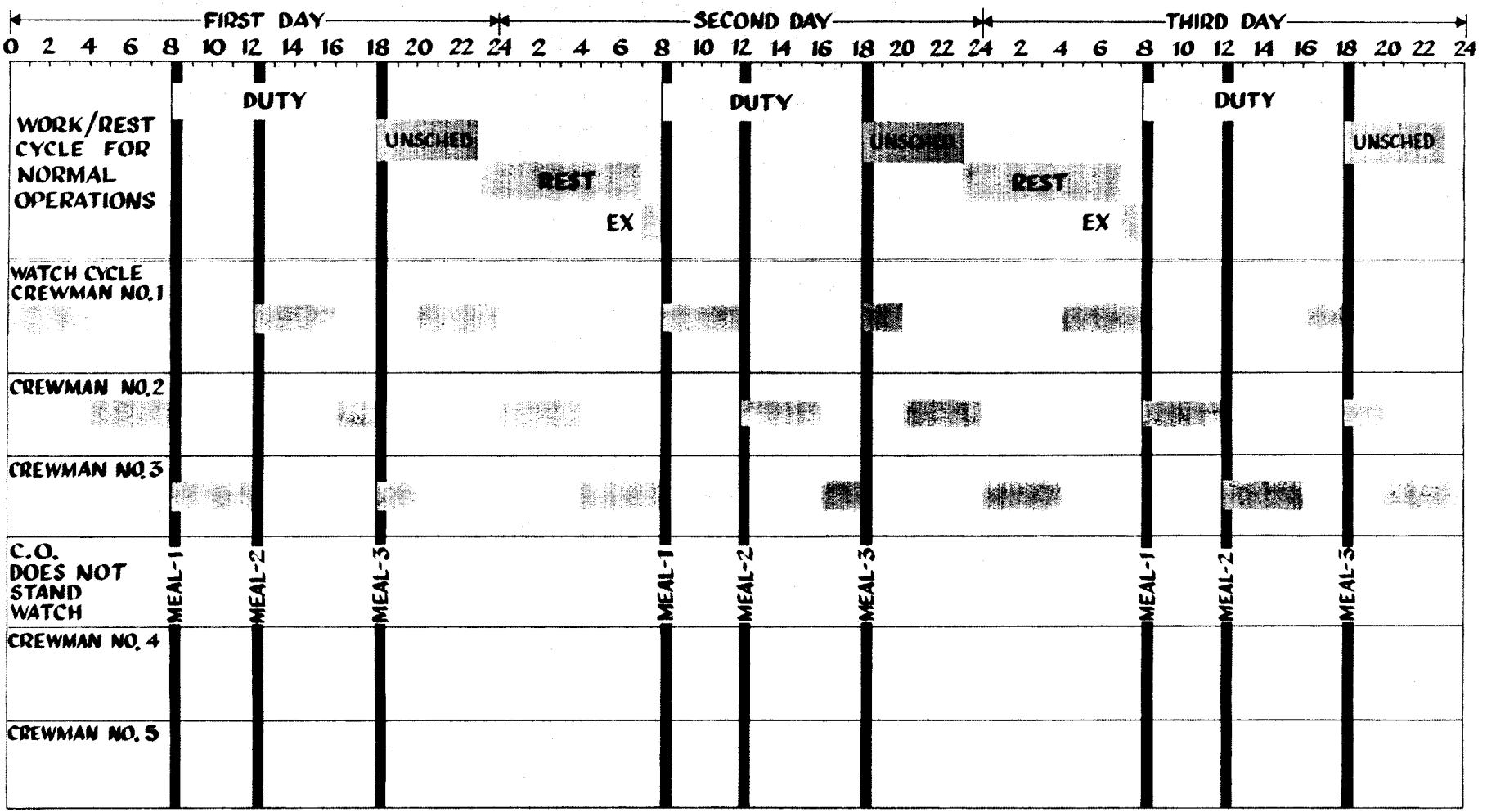

Figure 51

TIME LINE

Duty cycle structure and task composite information are reflected in the crew activity time-line provided in Figure 52. The time line represents most of the information arrived at through the analytical steps described. Graphically presented are the task times, groupings, and priorities, as well as a crew schedule depicting the events, sequences, frequencies, times and individual work loads.

The time line thus provides a specific analytical tool for the conceptual study phase. This initial time-oriented breakdown provides a comparison with the original systems concept.

The study effort methodology provides:

1. A means of organizing system concept tasks and task requirements into a manageable and uniform framework

2. An organized body of task requirements across system concepts that permits comparison across the mission requirements

3. A means of comparing system requirement interchangeability where man is treated as a system component

4. A means of defining man's requirements as a system component and the subsequent further delineation of the design envelope

5. A means of systematic updating of human behavioral sequences in the system as they are identified and for establishing the effect on the design

6. A means of identifying per sonnel skill requirements

7. A means of determining task loading and tradeoffs involving personnel

8. A mea s of standardizing the level of human behavior detail to establish realistic time requirements

9. A means of identifying problem areas where man is involved

TIME LINE

TIME	HOURS →	14	15	16	17	
	MINUTES →	30 40 50 60	10 20 30 40 50 60	10 20 30 40 50 60	10 20 30 40 50 60	10 20 30
COMMANDER		DUTY		DUTY		EATING
			PERSONAL		PERSONAL	
CREWMAN ONE		FACILITY MONITOR & CONTROL AND COMMUNICATION		DUTY		EATING
			PERSONAL		PERSONAL	
CREWMAN TWO			EXERCISE	FACILITY MONITOR & CONTROL AND COMMUNICATION		
		DUTY	PERSONAL			EATING
CREWMAN THREE		SCHEDULED SYSTEM SUPPORT		DUTY	PERSONAL	M/C & C
			PERSONAL	EXERCISE	MEAL PREPARATION	
CREWMAN FOUR			PERSONAL		PERSONAL	
		DUTY		DUTY		EATING
CREWMAN FIVE			PERSONAL		PERSONAL	
		DUTY		DUTY		EATING

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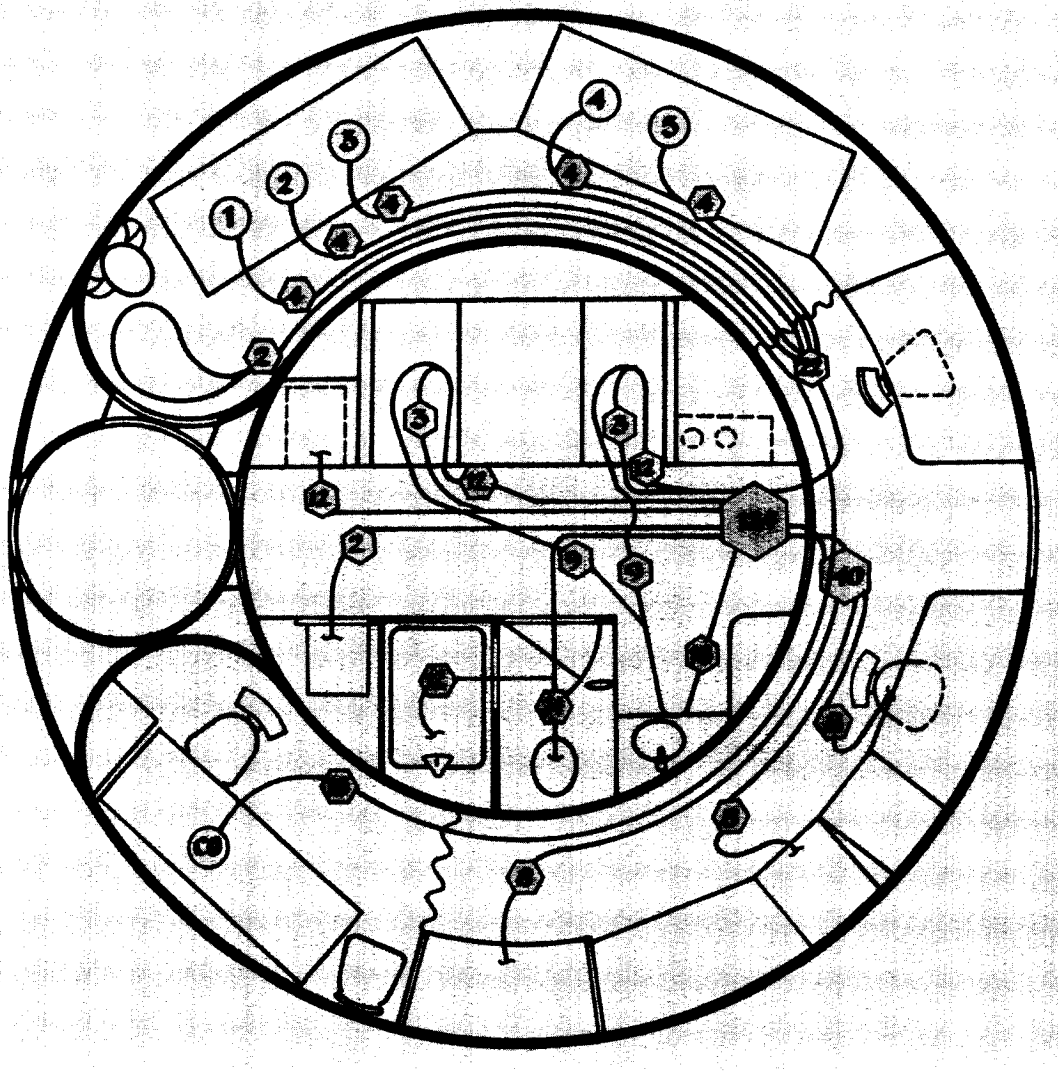
Figure 52

TRAFFIC FLOW THRU SHELTER

For an optimum arrangement of equipment, one factor that must be considered is the traffice flow and duty stations of the crew members. Some requirements must be compromised. For example, expediting service, control, and maintenance of equipment will conflict with providing freedom of movement through the inner and outer c mpartments. Additional restrictions involving confined volume, structually imposed traffic patterns, work place layout, crowding, and equipment location involve other restrictions. The traffic link analysis provides a means for making comparison, tradeoffs and compromises to obtain the optimum arrangement for full utilization of the facility. As problem areas are defined, the crew schedule and various interior arrangements may be modified as required. The traffic link analysis provides a systematic approach to location of personnel and work areas; this analysis will be an integrating function to assist in establishing the design envelope and in programming the crew. Figure 53 illustrates traffic patterns in the shelter.

TRAFFIC FLOW THRU SHELTER

COMPOSITE



CREW MEMBERS

WALK LINKS

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Figure 53

VIII INTERIOR DESIGN

by C. Righter

Item	Page
Volume Allocation Comparison	122
Plan View of LESA Shelter	124
Living and Recreation Area	126
Duty Stations	128
Pressure Suit Storage	130

VOLUME ALLOCATION COMPARISON

Long-term occupancy in a confined shelter requires optimum use of space by the crew. The very small spatial allocation per man in certain types of aircraft and spacecraft is justified largely by the brief mission time. In the LESA shelters, the extent of the missions, crew size, and mission complexity require that careful attention be given to interior design in order to provide acceptable arrangements consistent with minimum shelter volumes.

A correlation of living volume per man vs confinement time for different types of craft and shelter is shown in Figure 54. The LESA shelter volume per man falls slightly below the projected curve of similar shelters. It is higher than the minimum allowable for New York State jails (245 cu ft) but below that for the modern submarine. Of course, LESA crew members have the advantage of being able to leave the shelter for various tasks. Consequently, the volume allotted per man, plus the opportunity to leave the shelter, would indicate that the Initial Concept study shelter design can satisfactorily accommodate six men for the specified 6-month crew rotation period.

It must be noted, however, that comparisons of volume are not completely definitive in establishing minimum volume requirements. Usable floor area may be a more valid criterion in determining minimum shelter volume. Correlations involving psychological factors and based upon experience in submarines, jails, balloon and bathyscape gondolas, Antarctic bases, confinement experiments, etc., may not be applicable to LESA because of the selection standards and high motivation necessary for LESA personnel, as well as the nature of the work which will occupy the crew: while certain routine (personal maintenance, housekeeping, etc.) will be followed, much time will be devoted to more purposeful and exacting tasks, both inside and outside of the cabin.

VOLUME ALLOCATION COMPARISON

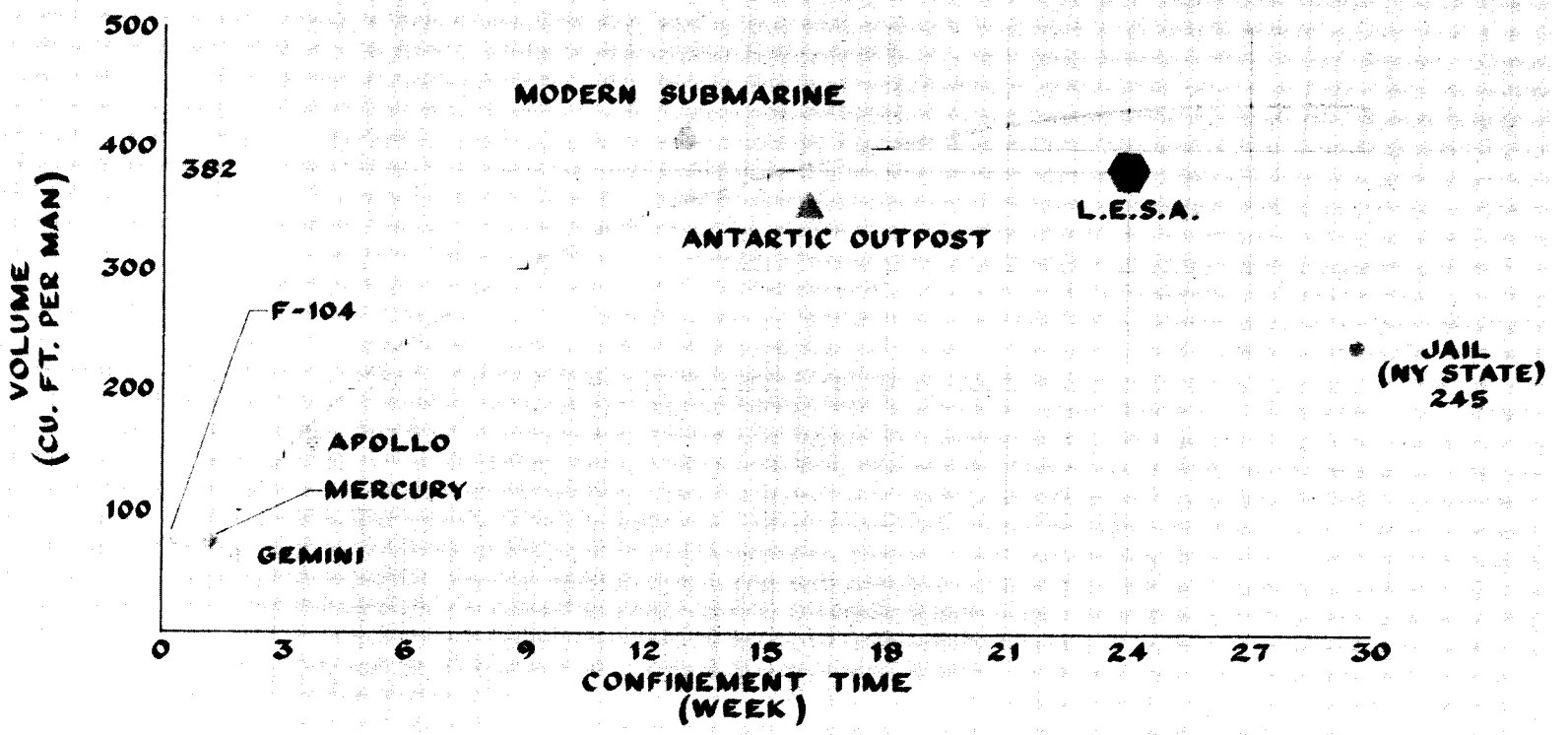

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Figure 54

PLAN VIEW OF LESA SHELTER

As illustrated in Figure 55, crew functions are divided according to six major areas within the shelter:

1. Living and Recreation Area
2. Rest Area
3. Work Area
4. Duty Station
5. CO's Quarters
6. Air Lock

Location of these areas within the shelter is dictated by mission requirements, task analyses, and traffic flow patterns.

In Area 1 are all items and services necessary to sustain life, including essential communications equipment and controls for creating an emergency shelter within the shelter. This area can be used as a radiation refuge during solar flares.

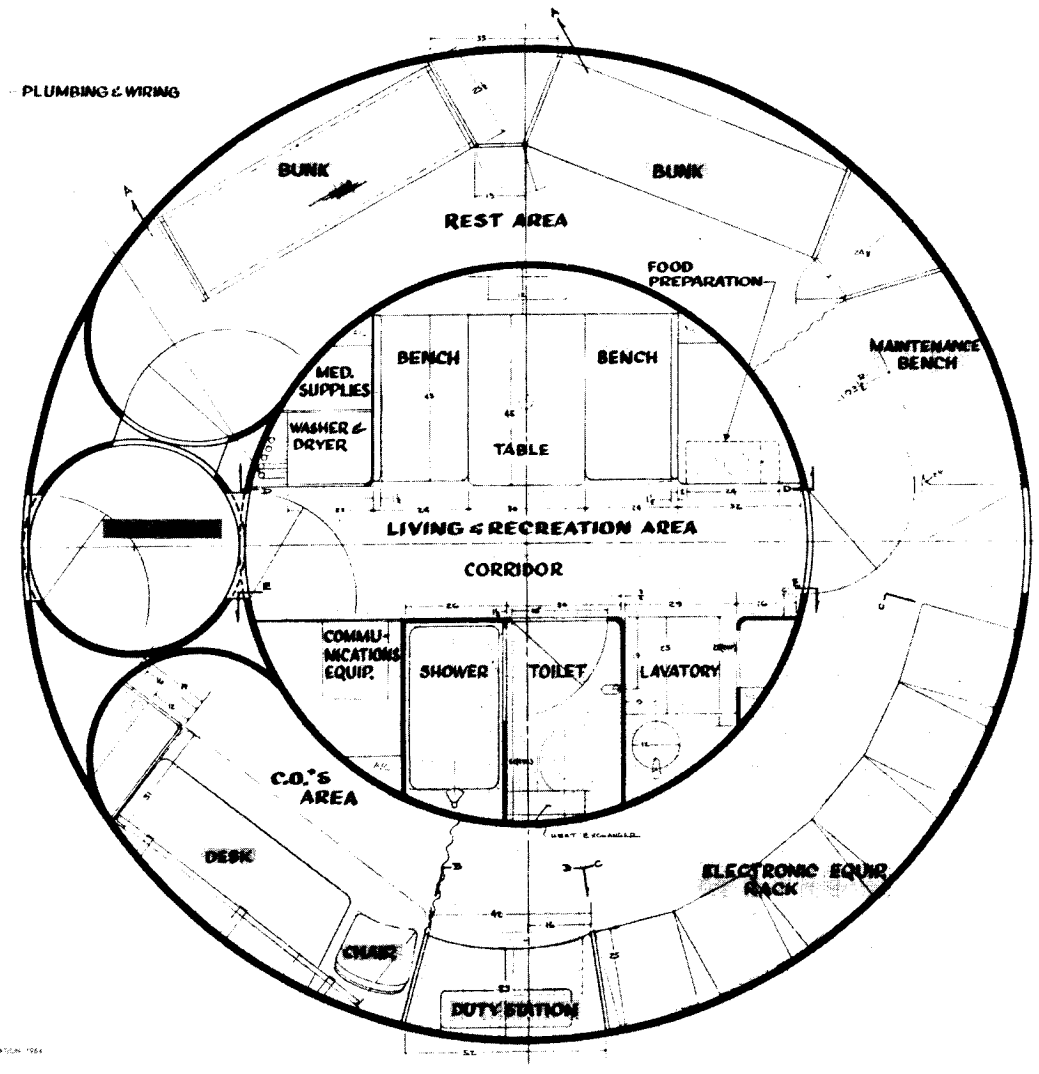
Area 2 includes five bunks isolated from the rest of the station to limit travel and sound and to provide a restful atmosphere. Closets are provided for storage of clothing and personal effects. This area contains an emergency hatch leading to the air lock.

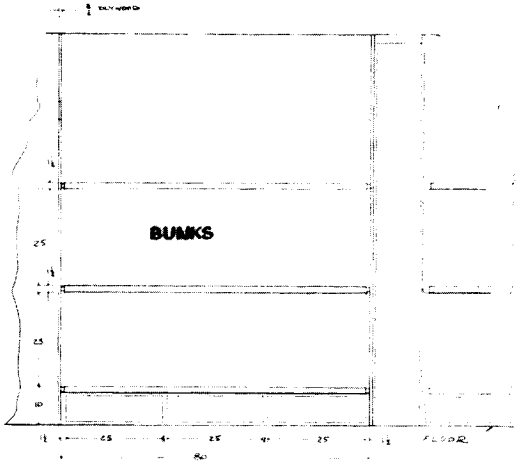
Area 3 is contained in the outer compartment. (A general maintenance workbench long enough for suit repair is located next to the rest area.) The scientific work area consists of a workbench and chair, with storage provided both overhead and under the work surface. Next to the scientific work area are two standard electronic racks and an additional workbench.

Area 4 is the command control and communications center for the base. It will be manned constantly.

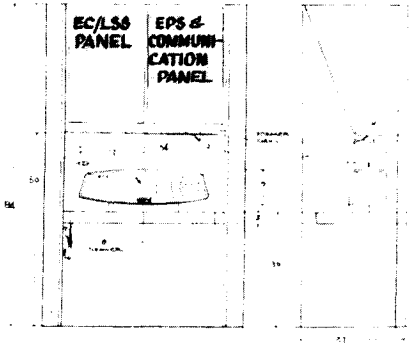
Area 5 is a combination living and work space for the base commander. Located next to the duty station to provide immediate access to the communication center, it includes a closet for storage of garments, charts, and maps, and a desk whose pedestal supports provide storage for logs and other documents. Separate quarters for the base commander are considered highly desirable due to the long-term confinement, the magnitude of the decisions to be made, and the type of data to be analyzed and transmitted to earth.

PLAN VIEW OF LESA SHELTER





SECTION A-A



SECTION B-B

Figure 55

LIVING AND RECREATION AREA

In the Living and Recreation area, space can be saved with multiple-function equipment, as illustrated in Figure 56. Flexibility of multi-purpose equipment is illustrated in the functions planned for the table area:

a. Dining: Table with extension can seat the entire crew at one time, facilitating ease of food preparation and saving time for other activities. A 25-day emergency food supply for six men is stored back of the food preparation equipment. The regular food supply is stored overhead in the outer torus.

b. Recreation: The arrangement of table and seating permits group participation in face-to-face games such as cards, chess, and checkers. Individual recreation such as writing, drawing, or model-making can be carried out at the work areas and maintenance bench.

c. Emergency Rest: The crew can use this area for sleeping in case of emergencies that require occupancy of the inner shell only. The table can be lowered on telescoping leg and the seats unhooked from the cabinets and placed flat to form a bed. Additional bunks can be placed overhead, since the distance between the cabinets is the same as the bunk length in the outer shell.

d. Medical Aid: Emergency medical aid can be administered to personnel by unhooking the table from the wall and sliding it to a clear position where it is free to rotate. A bright overhead light is provided for medical examination and operation. Medical equipment and supplies are stored in a cabinet behind the laundry.

e. Utility: Clear space is provided for crew activities such as suit donning and doffing by folding up the table and securing it and both benches flat against the cabinets.

Food Preparation--A food preparation center contains a hot- and a cold-water injector and two hot plates. The water injector is primarily for reactivating dehydrated foods. The hot plates are available to reheat leftover food or prepare bulk food in order to prevent waste of any food.

Laundry--A small closed-cycle washer and a dryer are provided for cleaning and drying garments. Separate units will save time: some crewmen may wash while the others dry.

Decor--Warm colors are used in this area as a visual relief from the cool colors used in the outer shell work-rest areas. The color scheme is basically that used in Apollo, except that it has been considerably reduced in intensity. Reducing the intensity of interior colors will provide brighter interiors with lower ambient illumination and, consequently, more efficient use of electrical power.

LIVING & RECREATION AREA

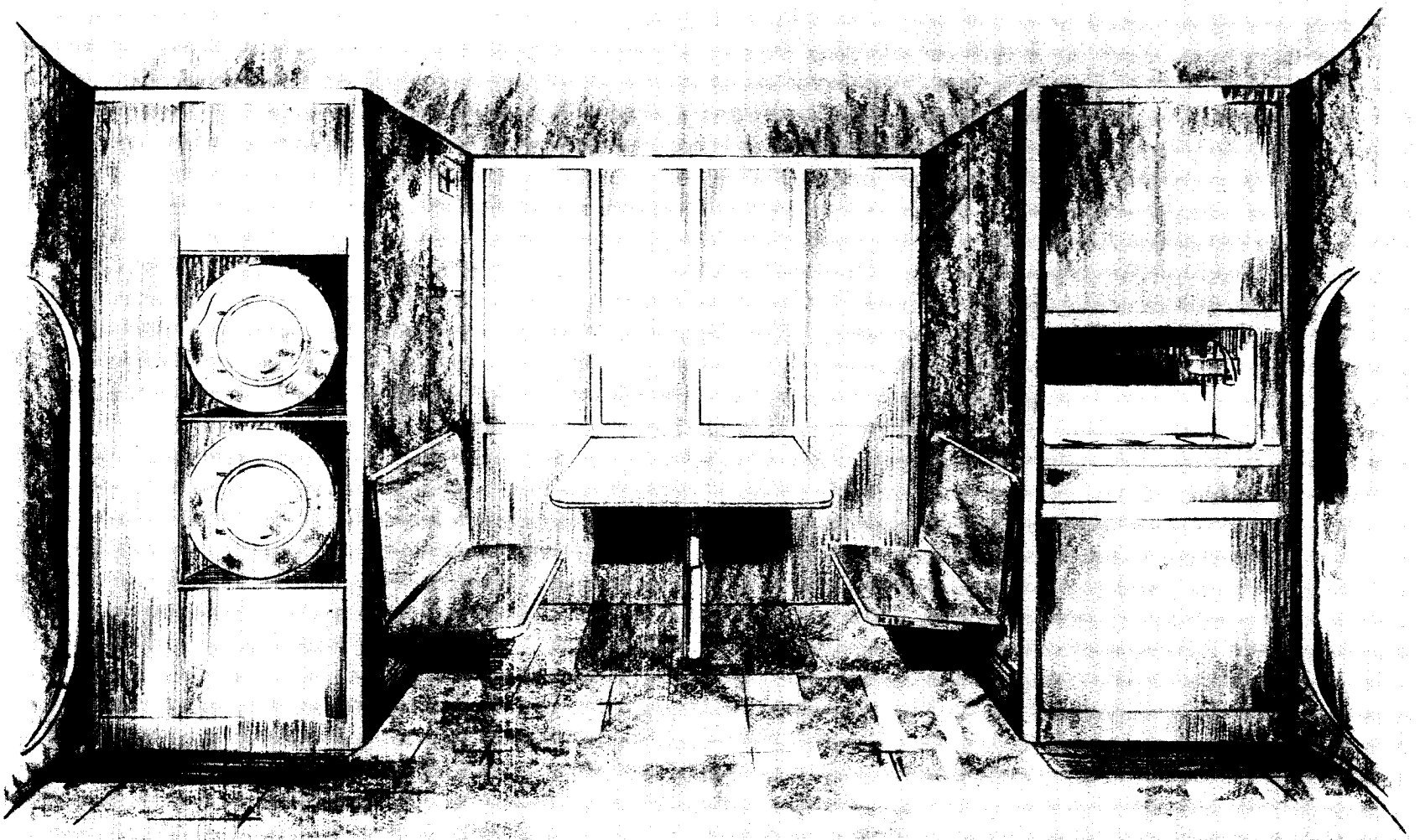


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Figure 56

DUTY STATIONS

Located in the outer shell next to the CO's quarters, the command control center provides for the rapid transmittal of information. Rapid communication and privacy in decision making are extremely important for the efficient and effective operation of the shelter during an extended mission. Figure 57 illustrates the duty station plan.

A display control console houses critical status summation displays, a TV monitor, and communications for frequently used contacts. Hazard displays for fire, radiation, toxic atmosphere, cabin leakage, cabin pressure and other emergency parameters will be contained in this panel. The TV monitor provides site surveillance, air lock monitoring, and LRV- and hopper visual contact.

ECS and Life-Support displays and controls will be mounted on the panel over the consule and to the left. The upper right panel will contain the power system displays and controls and additional communication equipment. Important but infrequently used controls will be placed on a recessed panel between the console and the overhead panels.

Since this station is constantly manned, cool colors have been used to make the confined area appear larger and to provide a restful atmosphere. A light-colored writing surface is provided to create an immediate environment that is close to the color value of paper and documents to lessen visual fatigue or eye strain.

DUTY STATIONS

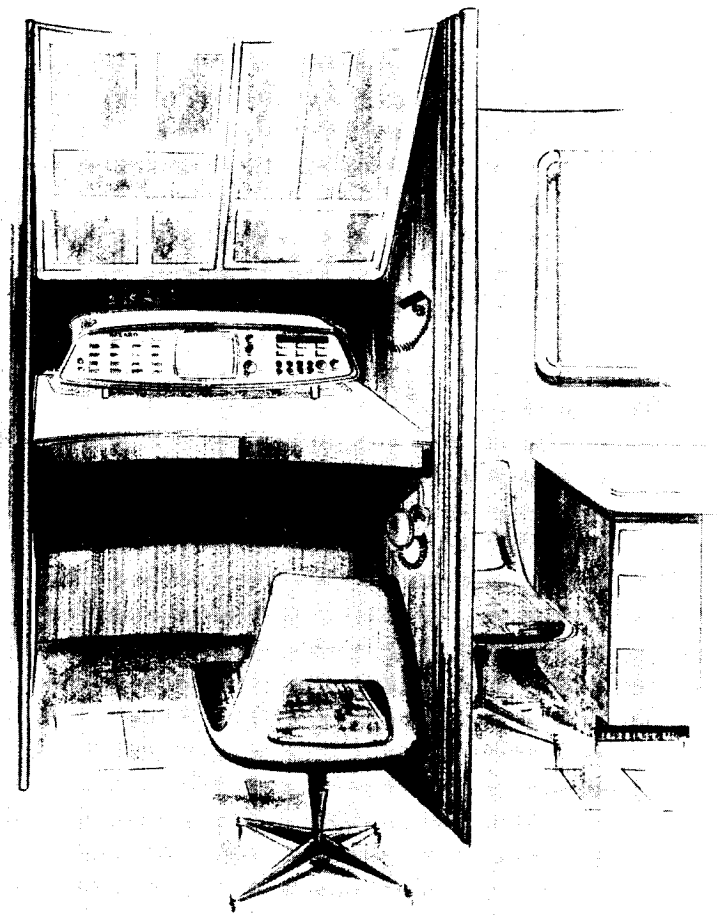

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Figure 57

PRESSURE SUIT STORAGE

Figure 58 illustrates a revolving rack, mounted in the dome of the Living and Recreation Area, which holds five pressure suits, along with helmets, backpacks, boots, gloves, and spare parts kits. This method of suit storage has two major advantages: first, quick and easy access to the suits, and, second, storage within the inner circle to provide additional protection as well as a maximum clear area for rapid donning.

Because it has not been a major design concern and because space is at a premium in spacecraft, space for suit donning is usually below minimum requirements. The large volume (4 ft by 6 ft by 8 ft) is perhaps the most important element of this design as it permits more than one man to suit up at a time. It also permits one man to assist another with accessories and adjustments. Much critical time thus can be saved in emergencies.

Placing the suits on an overhead rack provides safe, easily accessible storage within the inner shell. One suit is placed in the outer shell at the end of the bunk area. If the inner compartment is depressurized, this suit could be used for repairs or for obtaining suits from the inner compartment.

PRESSURE SUIT STORAGE

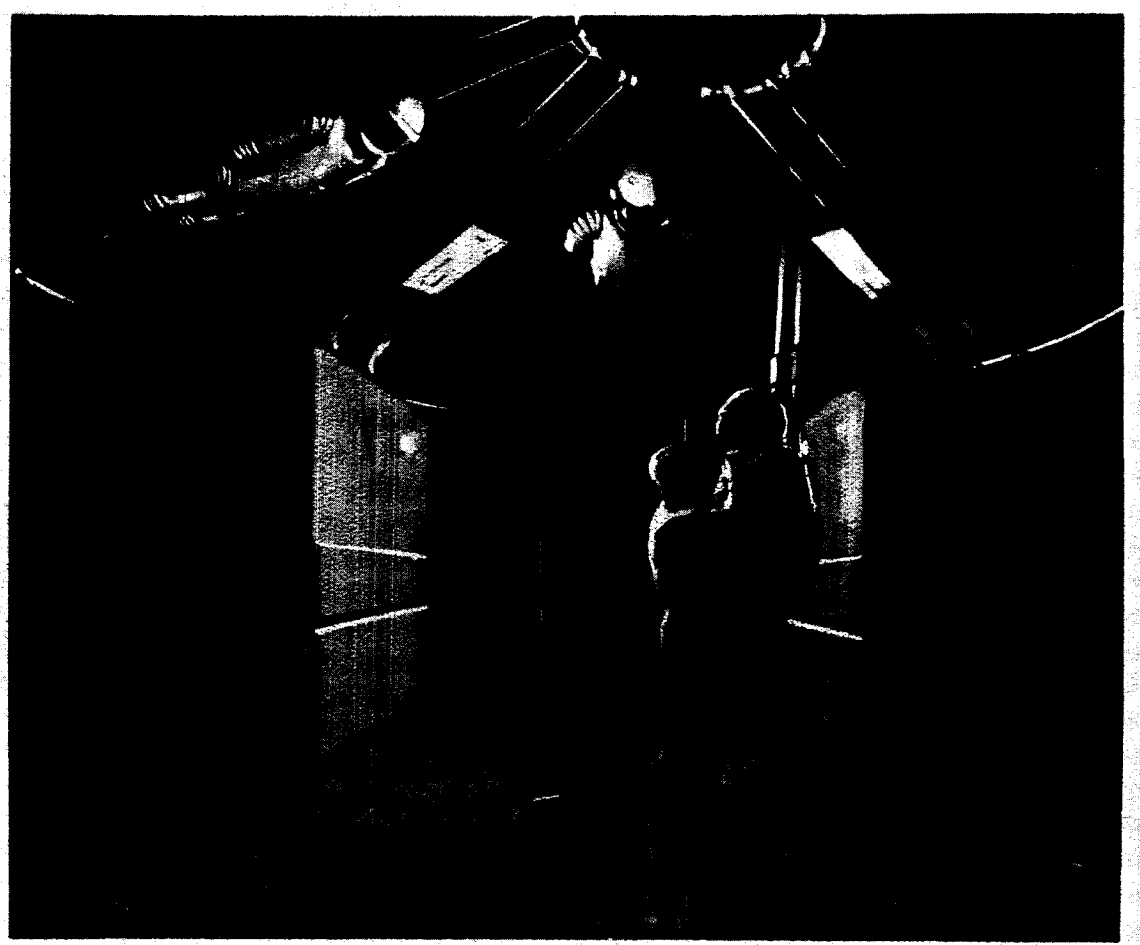

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Figure 58

IX SUMMARY AND CONCLUSIONS

by W. L. Burriss

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Process Selection Summary	140
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ATMOSPHERE CONTROL

Results of the studies in the two primary work areas (Human Factors and EC/LS Systems) have been described earlier in this report. Initial emphasis in this program has been in the subsystem area. System integration studies involve consideration of the interrelations between the two study areas illustrated in Figure 59 for the atmosphere control system. Here, human factors studies provide inputs concerning activities and interior design that influence atmosphere control system design. These inputs are connected to the system design by material and energy balances and by environmental design requirements. Atmospheric gas circulation will be provided for the three basic functions of carbon dioxide removal, humidity control, and body cooling (thermal control). In general, the flow requirements for these functions will be quite different, as will be the processing system. For example, thermal control may be provided by a high-flow, low-pressure-drop recirculating gas loop, while carbon dioxide removal is accomplished with a low-flow, high-pressure-drop processing loop. Although the flows will obviously depend upon the loads and environmental requirements, there is a less evident, although highly important, dependence upon interior design with regard to compartment arrangement, work station layout, scheduled activities in various areas, space available for equipment, etc. Figure 20, for example, illustrates the ventilating provisions used in different areas, in both cases shown to take advantage of available space for installation of ducting. Although tradeoff studies involving design parameters such as ducting size can be readily performed, unless they are related directly to other factors such as mentioned, the results of such tradeoff studies will not lead to realistic results. The results of such tradeoff studies will not lead to realistic results.

ATMOSPHERE CONTROL

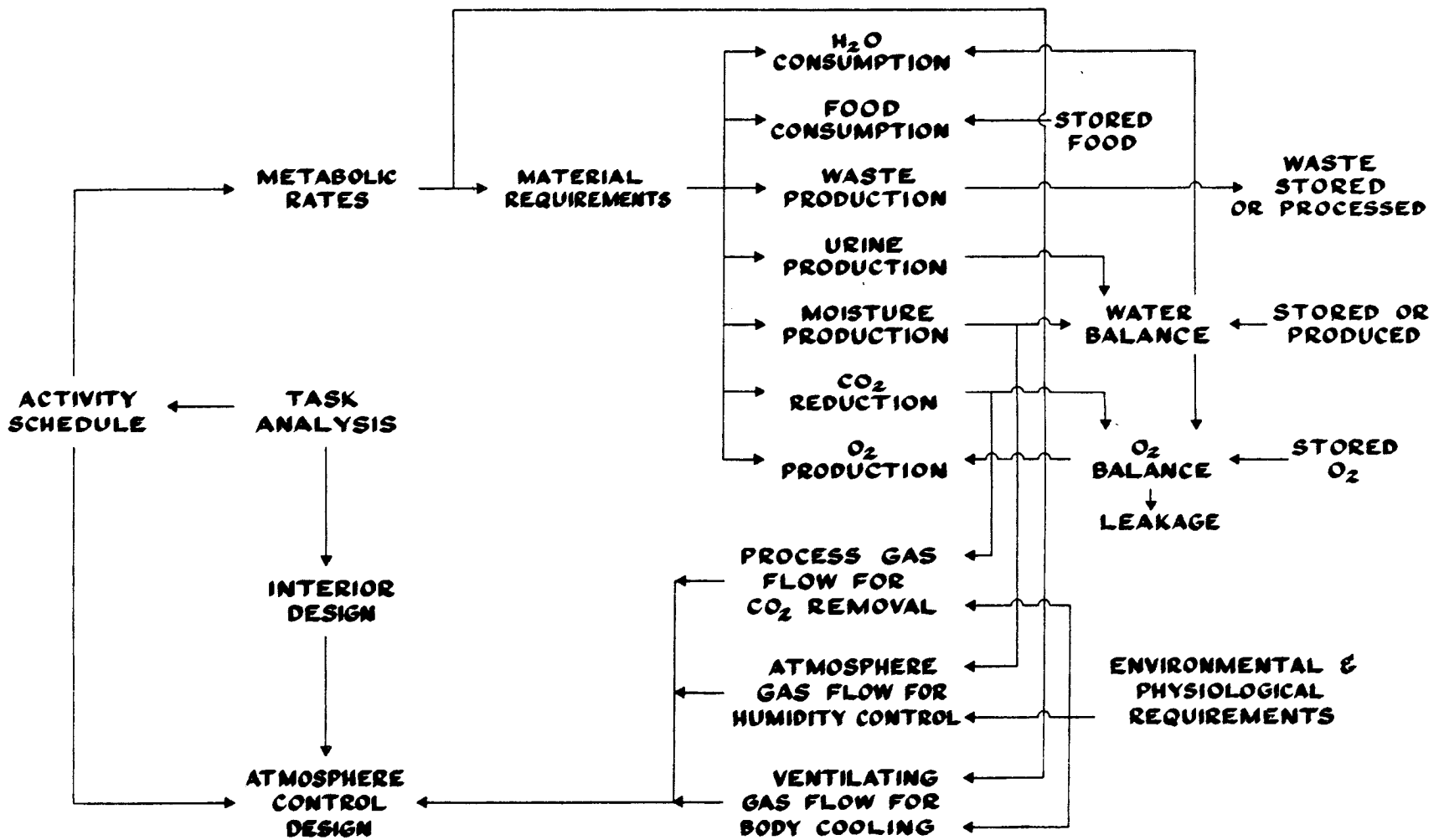

Figure 59

RELIABILITY

Environmental control and life support system design will be determined to a considerable extent by reliability considerations. Consequently, reliability studies, outlined in Figure 60, represent an important part of the present program. In work to date, reliability studies have been primarily concerned with subsystems, such as the carbon dioxide removal system reliability shown on a previous chart. It is important, at the start, to distinguish between two somewhat different reliability design criteria. The first of these is the reliability requirement for crew safety. The second, and perhaps most familiar, is the reliability requirement for mission success. A crew safety criterion frequently specified for EC/LSS design is based upon the requirement that no single failure mode may endanger human life. When this requirement is attained, the reliability for crew safety obtained with the resulting systems will usually be several orders of magnitude higher than that specified for mission success. The reliability goals for mission success to be applied to EC/LSS design will be determined through effectiveness studies later in the program.

Some of the reliability problems associated with the LESA missions will be similar to those obtained with long-duration systems of any type requiring high reliabilities for long operation. That is, to achieve high reliability with complex, long-duration systems at minimum cost to the mission, it will be necessary to use a combination of maintenance capability and redundancy with appropriate component design.

Frequently, component reliability can be enhanced by internal design, such as higher design safety margins, selection of superior materials, or use of unorthodox designs such as gas bearings. The LESA missions have several unique reliability factors as shown in Figure 60 that will be important in the reliability studies leading to optimum EC/LSS configurations.

RELIABILITY

CREW SAFETY ≡ PROBABILITY OF SAFE RECOVERY OF PERSONNEL IN EVENT OF FAILURE LEADING TO MISSION ABORT

FACTORS IMPORTANT TO CREW SAFETY
- BACKUP PROVISIONS (OTHER VEHICLES, COMPARTMENTS, ETC.)
- ALTERNATE OPERATING MODES
- ESCAPE TIME TO A SAFE HABITAT

MISSION RELIABILITY ≡ PROBABILITY OF SUCCESSFUL ACCOMPLISHMENT OF DESIGN MISSION

FACTORS IMPORTANT TO MISSION RELIABILITY
- SYSTEM AND COMPONENT REDUNDANCY
- REPAIR AND MAINTENANCE
- RESUPPLY

UNIQUE LESA RELIABILITY FACTORS

- PERSONNEL TRANSFER ACCOMPLISHED IN SEPARATE VEHICLES
- OTHER VEHICLES AND SHELTERS AVAILABLE FOR EMERGENCY USE IN ADVANCED BASES
- LUNAR SURFACE MATERIALS AVAILABLE FOR METEOROID AND RADIATION PROTECTION

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Figure 60

RELIABILITY ANALYSIS

Figure 61 illustrates the procedures used in the LESA reliability studies. The first step involves preparation of functional schematic diagrams of basic system configurations. The basic systems are nonredundant (except where redundancy is necessary for performance requirements) and represent the simplest arrangements to meet the required performance. The basic systems are analyzed for their safety characteristics; provisions needed for crew safety are then incorporated into the system. As mentioned previously, an important safety criterion is based upon offsetting failure modes potentially dangerous to human life. Another involves providing an adequate reliability margin for safe escape in event of mission abort.

The system is next subjected to reliability analysis for mission success. The mission reliability studies are iterative to determine the effects of various changes on reliability. These design changes can be classified as (a) redundancy, (b) maintainability, and (c) replacement. The effects on reliability are weighed against their cost to the mission by application of suitable value parameters. The curve illustrates the results of an analysis of this type for a LESA gas loop system used for atmospheric control. Since the analysis in this case involved application of selective redundancy, the cost parameter is given in terms of a percent increase in system fixed weight. The three modifications shown on the curve represent component additions to the initial system provided in the shelter. The trends shown by the curve are typical of those obtained in these studies. That is, a relatively large decrease in the probability of failure is initially obtained by component redundancy at relatively low cost. However, a reliability level is quickly reached where additional increases in reliability become comparatively expensive. The reliability goals for system design can be determined by application of suitable value parameters to the various cost factors.

RELIABILITY ANALYSIS

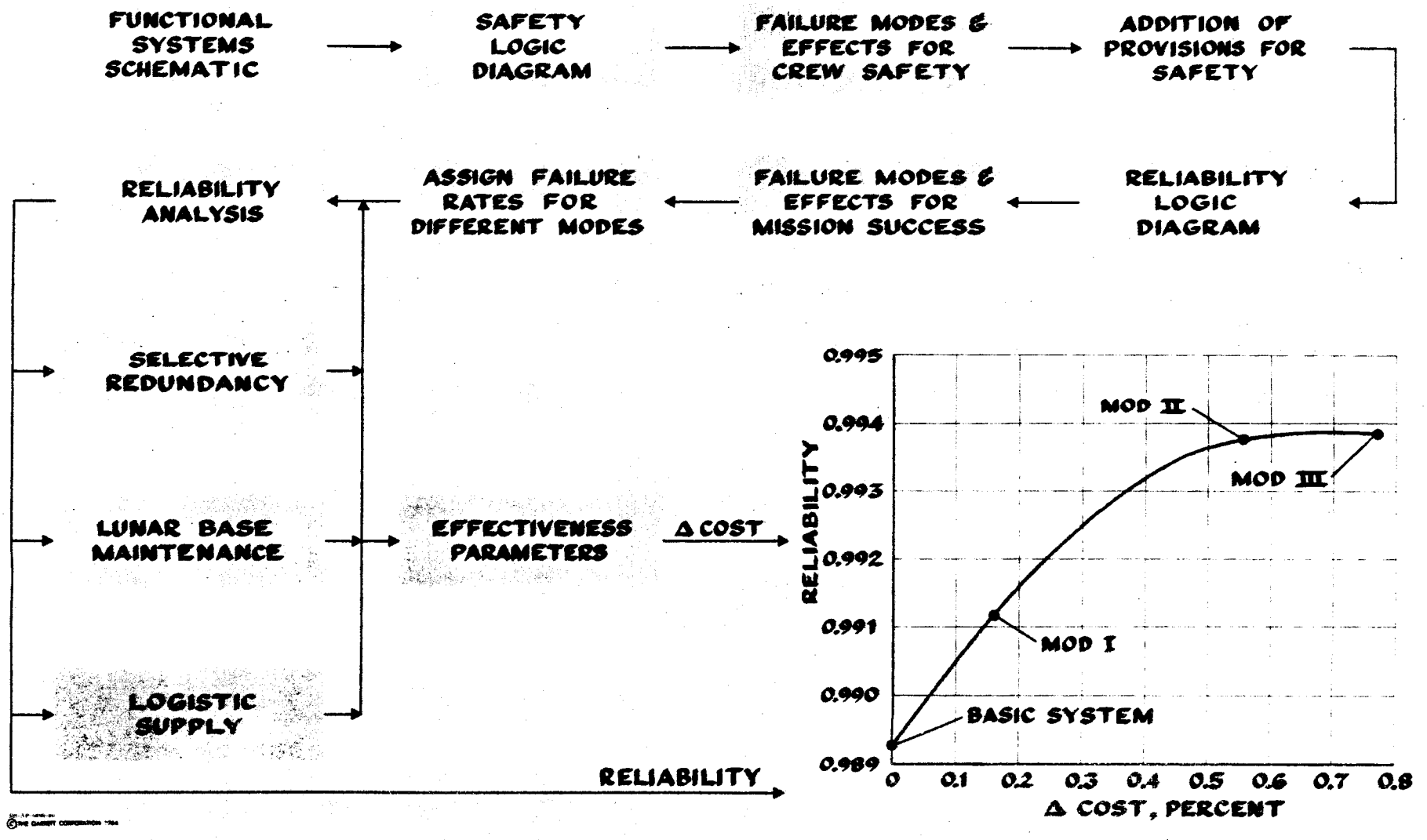

Figure 61

PROCESS SELECTION SUMMARY

Figure 62 summarizes the processes selected for various essential life-support functions for the various LESA bases. Many of the choices are based upon power system characteristics. For Base Concepts 1 and 2, where fuel cell-solar cell power systems are contemplated, the processes optimally used are characterized by low electric power consumption; some can operate on low-temperature waste heat. With Base Concepts 3 and 4, where nuclear power will be used, there will be considerably more incentive for use of systems providing reclamation of wastes.

PROCESS SELECTION SUMMARY

	LUNAR BASE CONCEPT			
	1	2	3	4
CO_2 REMOVAL	VACUUM-DESORBED MOLECULAR SIEVE		THERMAL-DESORBED MOLECULAR SIEVE	
O_2 SUPPLY	CRYO. STORED	STORED + DAYTIME H_2O ELECT.	H_2O ELECTROLYSIS	
POTABLE WATER SOURCE	FUEL CELL + CONDENSATE		RECLAIMED WASTE	
URINE PROCESSING	VENT OVERBOARD	DAYTIME AIR EVAPORATION	AIR EVAPORATION	
FECES PROCESSING	VACUUM DEHYDRATION		AIR DEHYDRATION	
CO_2 PROCESSING	VENT CO_2 OVERBOARD		REDUCE CO_2 TO C AND H_2O BY BOSCH PROCESS	
CONTAMINANT CONTROL	WHETLERITE + CATALYTIC BURNER + UV LAMP + PARTICULATE FILTRATION			
HUMIDITY CONTROL	CONDENSING HEAT EXCHANGER + GRAVITY SEPARATOR			
THERMAL CONTROL	DEPLOYABLE RADIATOR WITH REFLECTOR PANELS			
PROCESS HEAT SOURCE	EQUIPMENT WASTE HEAT		RADIOISOTOPE	

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Figure 62

EC/LSS POWER REQUIREMENTS

Figure 63 summarizes the EC/LSS power requirements for the four lunar base models. Where high-temperature thermal energy is suitable for process operation, radioisotope heat source can be used to provide the energy, at significant weight saving over use of electrical power (assuming electrical power to be available from a nuclear power plant at a weight penalty of 0.5 lb per w, for example). If electrical power is available at penalties less than about 0.15 lb per w, its use will be favored over radioisotopes. Radioisotope cost and availability have been neglected in this analysis; these considerations may limit application to relatively low energy levels.

Lunar Base 2 is shown with intermittent use of some of the equipment for daytime operation where relatively low weight penalties are obtained with solar cells. Thus, the solar cell system will be sized for an EC/LSS power requirement of 2.375 kw, while the fuel cell system used during the night will supply an EC/LSS power requirement of 0.485 kw. The EC/LSS power requirements for Lunar Bases 3 and 4 are divided between Base Concepts 2 and 3, respectively, used in these bases.

EC/LSS POWER REQUIREMENTS

POWER REQUIREMENTS (WATTS) FOR LUNAR BASE CONCEPT

	1	2	3	4
VENTILATION	120	120	240	360
HUMIDITY CONTROL	110	110	220	330
CO_2 REMOVAL (RADIOISOTOPE)	35 –	35 –	85 (1080)	125 (1620)
CONTAMINANT CONTROL (RADIOISOTOPE)	45 –	45 –	50 (40)	75 (60)
WATER ELECTROLYSIS	–	1860 (DAY)	3720	5580
CO_2 REDUCTION (RADIOISOTOPE)	– –	– –	440 (1800)	660 (2700)
WATER RECLAMATION	5	35 (DAY) 5 (NIGHT)	110	160
THERMAL CONTROL	50	50	150	225
CONTROLS AND INSTRUMENTATION	120	120	240	360
TOTAL	485	2375 (DAY) 485 (NIGHT)	5255 (2920)	7875 (4380)

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Figure 63

EC/LSS EXPENDABLES

Figure 64 summarizes some of the more important expendables used for life support in the four lunar bases. The material balance for atmospheric fluid makeup is based upon a shelter leakage rate of 4.0 lb per day, pressurization to 0.1 psia during 1-year inactive storage, air-lock operation twice a day during the design mission duration (with 90-percent recovery of the air-lock gas), and two complete shelter pressurizations during the design mission. With oxygen recovery used in the more advanced bases, the amount of stored oxygen in proportion to stored nitrogen is greatly reduced. The expendable atmospheric filters will be primarily activated carbon. The CO_2 reactor weight represents the high-temperature CO_2 processing gas loop and includes the catalyst required for the subsystem design life (6 months). The water treatment expendables are activated carbon and other chemicals used in processing of the waste water.

EC/LSS EXPENDABLES

EXPENDABLE WEIGHT (LBS) FOR LUNAR BASE CONCEPT

	1	2	3	4
FOOD	505	2,020	8,200	24,600
WATER	109	109	481	1,442
OXYGEN	949	1488	222	333
NITROGEN	355	601	2,260	6,284
ATMOSPHERIC FILTERS	35	35	138	438
CO_2 REACTORS	–	–	800	2,400
WATER TREATMENT	17	57	228	684

ASSUMPTIONS:

1. 10% RESERVE ALLOWANCE
2. 6.0 PSIA, 50% O_2 ATMOSPHERE
3. NEGLECTS PLSS AND LRV REQUIREMENTS

Figure 64

FUTURE WORK

The Initial Concept study shelter configuration appears to provide adequate space for a 6-man crew, with certain modifications in interior design. A 24-hr earth-oriented work/rest cycle is recommended for the LESA bases. Manpower requirements for personal activities (including sleeping), shelter systems monitoring, and facility support are high, representing approximately 52 percent of the mission time. Since the monitoring function is assumed to be time-shared with communications, part of this time can be considered related to mission performance. Greater reliance on automatic controls and warning devices may permit additional time-sharing of the monitoring function with experimental work.

The EC/LSS studies to date have concentrated on process selection and subsystem design. Tentative selections have been made for systems for the various LESA bases. The thermal studies have included investigations of inactive storage in the lunar environment and of heat rejection methods (including use of heat pumps) for the operational bases.

Future work will include the study areas listed in Figure 65. The studies will be on a system basis and will be concerned with mission integration and development of modular concepts for both the LESA shelters and roving vehicles. The operational, display, and control requirements for the LESA systems will be studied to permit refinement of shelter interior design and improvement of the projected time lines.

FUTURE WORK

- SYSTEM RELIABILITY STUDIES
- EFFECTIVENESS STUDIES
  - REDUNDANCY
  - MAINTENANCE PROVISIONS
  - LOGISTIC RESUPPLY REQUIREMENTS

  } TRADEOFFS
- DEFINITION OF EC/LSS OPERATING PROCEDURES
  - STARTUP AND SHUTDOWN
  - NORMAL AND EMERGENCY
  - MAINTENANCE AND REPAIR
- REFINEMENT OF SHELTER INTERIOR DESIGN
- INTEGRATION OF MODULAR CONCEPTS WITH LESA MISSIONS
- DEFINITION OF DEVELOPMENT PROBLEM AREAS

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Figure 65