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FINAL REPORT

SPACE STATION VENTILATION STUDY

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By

Biotechnology and Power Department
McDonnell Douglas Astronautics Company
Huntington Beach, California

For

George C. Marshall Space Flight Center
National Aeronautics and Space Administration
Marshall Space Flight Center, Alabama 35812

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Final Report

SPACE STATION VENTILATION STUDY

February 1972

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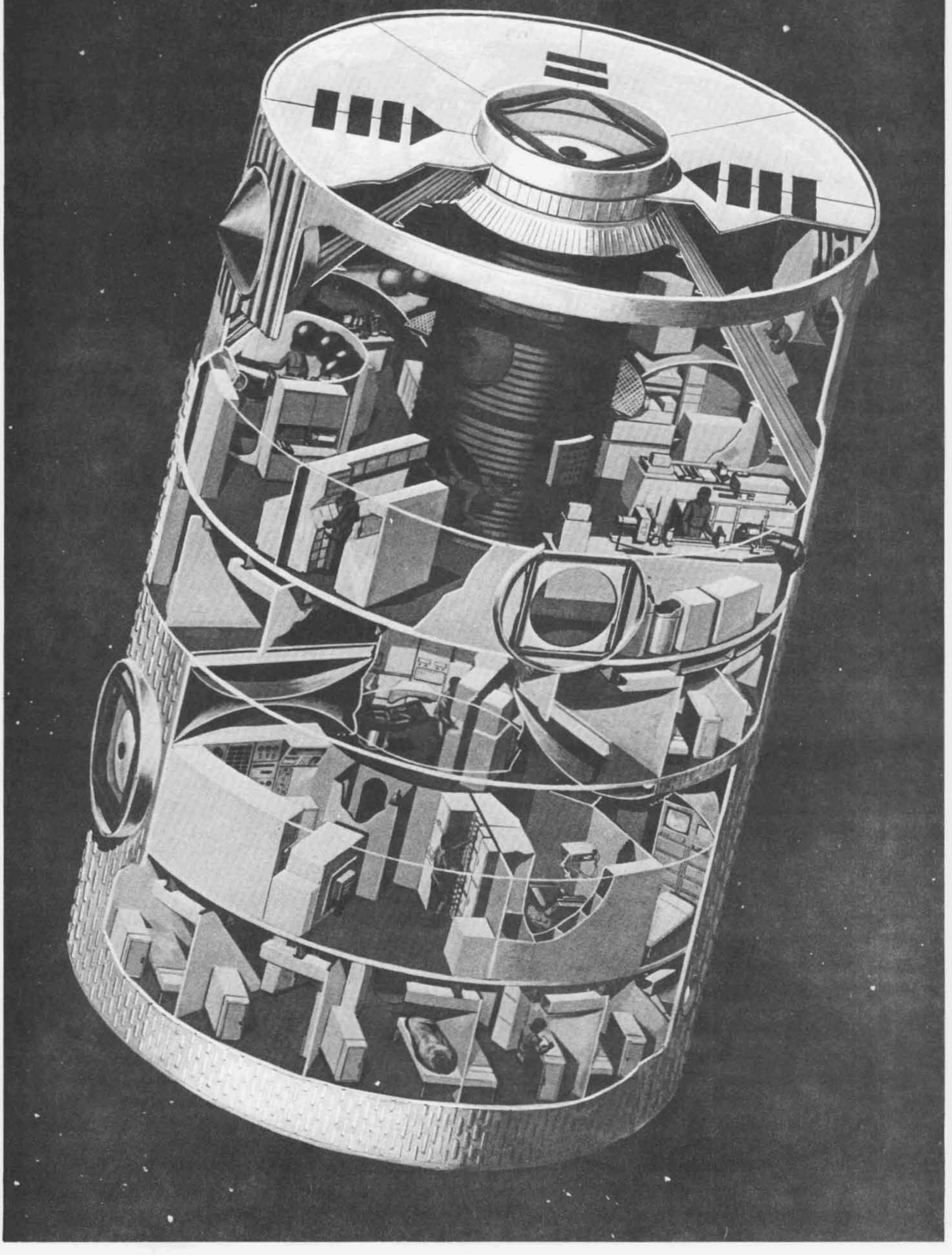
ABSTRACT

This report presents the study results of Contract No. NAS8-26267 in two parts. Part I includes the development of a ventilation system design and selection method which is applicable to any manned vehicle. This method was used to generate design options for the NASA 33 foot diameter space station, all of which meet the ventilation system design requirements. System characteristics such as weight, volume and power were normalized to dollar costs for each option. Total system costs for the various options ranged from a worst case $8 million to a group of four which which were all approximately $2 million. A system design was then chosen from the $2 million group and presented in detail in the report. In addition, a ventilation system layout was designed for the MSFC space station mockup which provided comfortable, efficient ventilation of the mockup thus confirming the adequacy of the design.

Part II of the report presents a conditioned air distribution system design for the 14 foot diameter modular space station. This system was designed using the techniques developed in Part I. The tradeoff study resulted in the selection of a system which costs $1.9 million, as compared to the alternate configuration which would have cost $2.6 million.

PART I, 33 FOOT DIAMETER SPACE STATION



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PART I
NOMENCLATURE

SYMBOLS	DEFINITION
C	SPEED OF SOUND
C_l	LOSS COEFFICIENT
C_p	SPECIFIC HEAT
C_{pc}	SPECIFIC HEAT OF COLDER FLUID
C_{ph}	SPECIFIC HEAT OF WARMER FLUID
D	EQUIVALENT DIAMETER
d	DISTANCE BETWEEN ENTRANCE AND EXIT
D_E	EFFECTIVE DIAMETER AT OUTLET
f	DARCY FRICTION FACTOR
g	ACCELERATION DUE TO GRAVITY
ΔH	ENTHALPY CHANGE OF MOIST ATMOSPHERE
K	PROPORTIONALITY CONSTANT FOR ORIFICE OR NOZZLE
L	LENGTH
M_c	MASS FLOW RATE OF COLDER FLUID
M_h	MASS FLOW RATE OF WARMER FLUID
P_r	AVERAGE EFFECTIVE SOUND PRESSURE DUE TO REVERBRATED SOUND
Q	DIRECTIVITY FACTOR
q_L	LATENT HEAT LOAD
q_s	SENSIBLE HEAT LOAD
R_q	ENTRAINMENT RATIO
S_e	PLENUM OR TRAP EXIT AREA

PART I

SYMBOLS	DEFINITION
S_w	PLENUM OR TRAP WALL AREA
t_{ci}	INLET TEMPERATURE OF COLDER FLUID
t_{hi}	INLET TEMPERATURE OF WARMER FLUID
t_{ho}	OUTLET TEMPERATURE OF WARMER FLUID
ΔT	TEMPERATURE DIFFERENCE BETWEEN SUPPLY AND RETURN
V_a	AVERAGE VELOCITY
V_o	EFFECTIVE VELOCITY OF JET AT OUTLET
V_R	CENTERLINE RESIDUAL VELOCITY OF THE JET
W	SOUND POWER OF THE SOURCE
X	DISTANCE FROM SOUND SOURCE
X_1	THROW
ρ	MASS DENSITY
α	ABSORPTION COEFFICIENT OF THE LINING
Θ	ANGLE OF INDENCE AT EXIT
ζ	ACOUSTICAL CONSTANT

SECTION 1.0

INTRODUCTION AND SUMMARY

This study has formulated a design for a ventilation system which will provide selectable comfort conditions throughout key space station areas. The design has been developed for the 33 foot space station as defined in the Phase B Program Definition Study under NASA contract NAS8-25146. Prior to selecting a design, trade-off studies were made on eight (8) configuration combinations for Module 1 and four (4) configuration combinations for Module 2. These trade-off studies provided a basis for comparing weight, volume and power characteristics of the various feasible configurations. Additional comparative studies were made on each configuration to determine if unique advantages existed in the area of performance, reliability, and maintainability.

The design concept chosen is a workable ventilation system which provides eight (8) zones of control for each module. Each crew compartment has individual temperature control. The configuration has low weight, low volume and minimum power requirement. High reliability is achieved as a result of system simplicity and state-of-the-art component usage. A key feature of the system is that minimum auxiliary heat is required in any area to provide the upper design range temperatures (i.e., $75^{\circ}F$ to $85^{\circ}F$). This system characteristic exists due to the ability of the controls to allow air to bypass the main heat exchanger. Although the system was designed to operate most efficiently at a space station pressure of 14.7 psia, satisfactory operation can be achieved at a pressure of 10 psia with increased blower power.

Recommendations for future investigations as a result of this study include the following:

- o Develop an analytical model which can be used to make transient and steady-state studies based on a changing heat and moisture dissipation level in various areas of a space station.
- o Perform detailed analytical studies on condensation possibilities in highly stagnant areas.

- Conduct tests which will verify key system design concepts and provide data for upgrading analytical model.

SECTION 2

DESIGN REQUIREMENTS AND ANALYTICAL APPROACH

The design requirements and analytical procedures that were used during the study are reviewed in this section. This description includes a definition of design conditions, criteria, and requirements in addition to a brief discussion of the analytical tools utilized to accomplish the design.

Design Conditions, Requirements, and Criteria

The study was based on the 33 foot diameter Phase B Space Station configuration which was designed to handle 12 men within the two modules. Table 2-1 (Reference 2-1) presents the pertinent conditions and constraints which were adhered to in formulationg the configuration and sizing the Thermal Conditioning Unit. Criteria established during the study included formulation of an acceptable noise level (based on Reference 2-2) which would not intefere with normal speech levels of communication. This allowed an evaluation of the amount of attenuation which could be utilized effectively to reduce the fan and air noise to acceptable levels.

Prior to performing design studies a review of ventilation systems developed for Skylab, Space Station Simulator, and MOL was made. Based on indicated performance from these programs calculations were begun for the Phase B Space Station Configuration. Results of these calculations, shown on Figure 2-1 and 2-2, are based on the following assumptions:

- Conditioned atmosphere delivery temperature is at constant 58°F for Figure 2-1. Initial atmosphere delivery temperature is 58°F in Figure 2-2.
- Wall temperature is the same as the atmosphere temperature.
- Equipment heat dissipation equals 1500 watts per deck.
- Crewman sensible metabolic rate equals 500 BTU/HR.

TABLE 2-1 SPACE STATION VENTILATION STUDY

DESIGN REQUIREMENTS - PHASE B

DESIGN PARAMETER	DESIGN RANGE	COMMENTS
ATMOSPHERE		
TEMPERATURE	65 - 85°F	Selectable
DEW POINT	45 - 85°F	Transients to 40°F Allowed
VELOCITY	20 - 50 FT/MIN	Occupied Region Only
PRESSURE	10 - 14.7 PSIA	Selectable
MEAN RADIANT WALL TEMPERATURE	65 - 85°F	
METABOLIC LEVEL	Normal - 465 $\frac{\text{BTU}}{\text{HR/MAN}}$	Range - 300 - 600 BTU/HR/MAN
	Peak - 1200 $\frac{\text{BTU}}{\text{HR/MAN}}$	
HEAT DISSIPATION		
SENSIBLE	Crew metabolic + 20% of net electrical power output	Consider wall adiabatic Average Dissipation - 11,490 $\frac{\text{BTU}}{\text{HR}}$
LATENT	122 BTU/HR/MAN + 78 $\frac{\text{BTU}}{\text{HR}}$	The 78 BTU/HR represents shower and laundry
HEAT EXCHANGER		
COOLANT FLOW	0 - 1650 lb/hr	825 lb/hr nominal
COOLANT TEMP.	44°F	Minimum

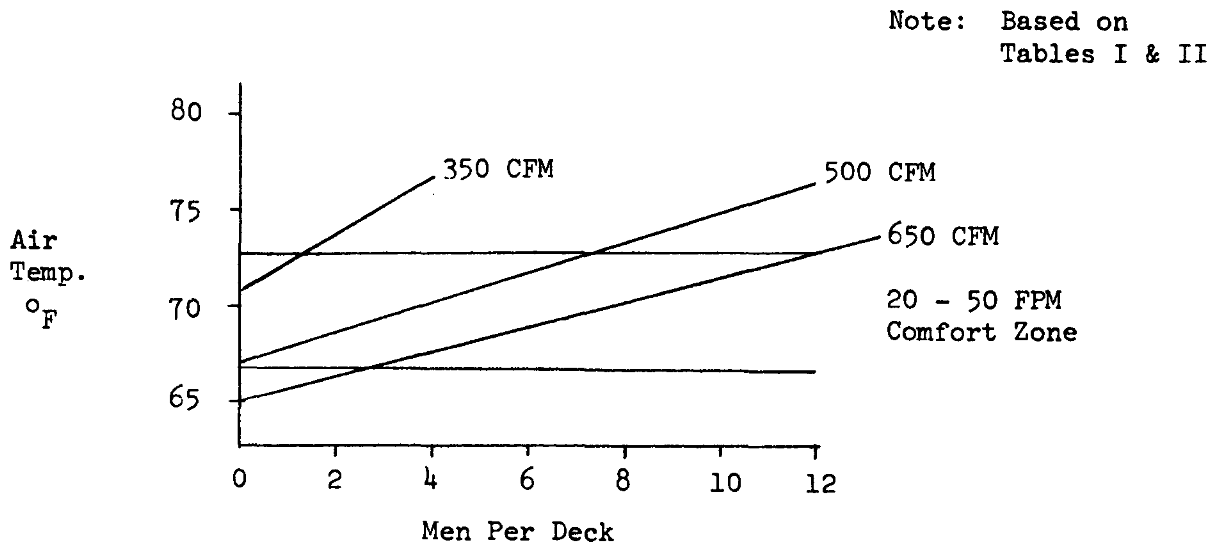

FIGURE 2-1 STEADY STATE ATMOSPHERE TEMPERATURE VS. DECK OCCUPANCY

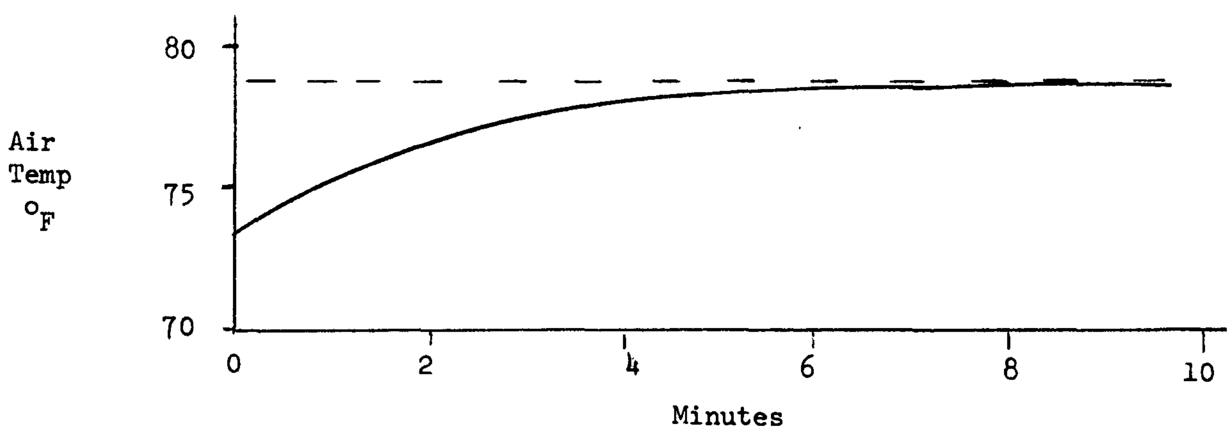

FIGURE 2-2 TRANSIENT EFFECT OF INCREASING DECK OCCUPANCY FROM 6 TO 12 MEN WITH 500 CFM VENTILATION RATE

- Initial conditions for Figure 2-2 are based on six crewmen occupying one deck with an atmospheric flow rate of 500 CFM. Heat transfer to equipment and deck walls is negligible.

Conclusions reached as a result of these initial calculations are listed below.

- Figure 2-1 indicates that if 500 CFM of 58°F air is supplied to a deck the temperature can be maintained within a comfort zone of 67°F - 73°F with a man loading of zero to seven.
- Figure 2-2 indicates that the deck temperature will rise from an initial temperature of 73°F to 78°F if deck occupancy is increased from six men to twelve men. Steady state conditions would be achieved within ten minutes after increasing the man loading.

Analytical Approach

Conventional analytical methods were used to configure and size the various components within the system. These methods are discussed briefly in the following text.

Sizing the Fan and Ducts

Atmospheric flow rate for sizing the fan and transport ducts is based on the crew metabolic load, equipment heat dissipation and requirements for a minimum atmosphere movement rate to prevent contaminant buildup and provide comfort. The flow rate required for sensible heat removal is calculated from equation (1).

$$(\text{Flow Rate})_s = \frac{q_s}{\rho \cdot C_p \, \Delta T} \qquad (1)$$

and compared against the flow rate required for latent heat removal expressed in equation (2) [Reference 2-3].

$$(\text{Flow Rate})_L = \frac{q_t}{\Delta H} \qquad (2)$$

The higher of the two values represent the minimum atmosphere flow rate required for sensible and latent heat removal. This minimum value known as primary atmosphere is then divided among the compartments of each deck based on the expected total heat load for that area.

Transport ducts were used to carry the conditioned atmosphere to its point of discharge. They were sized based primarily on the pressure drop deemed allowable from a fan power basis. Pressure drop calculations for flow thru straight ducts were based on equation (3) [Reference 2-4].

$$(\text{Heat Loss})_{ST} = f\ {}^{L}/D\ \frac{V_a^{\ 2}\ \rho}{2g} \qquad (3)$$

Losses for flow thru elbows and turns were calculated from equation (4) with the loss coefficient (C_1) taken from Reference 2-4.

$$(\text{Head Loss})_{Elbow} = C_1\ \frac{V^2\ \rho}{2g} \qquad (4)$$

Atmospheric Diffuser Design

Atmospheric diffusion utilizes the kinetic energy contained in a jet of the primary supply to provide movements ranging from 20 - 50 ft/min. throughout the occupied areas. The motion created by the jet promotes mixing of the supply (primary) atmosphere with compartment (secondary) atmosphere. Velocity profiles of isothermal jets issuing from diffusers can be calculated as a function of the distance from the opening by equation (5) [Reference 2-5].

$$V_R = \frac{V_o\ D_e}{X\ K} \qquad (5)$$

The velocity profile is used to determine the entrainment ratio (i.e., ratio of total moving atmosphere to primary atmosphere supplied) at various locations within the compartments. The entrainment ratio is calculated from equation (6).

$$R_q = 0.314^{\,V_R/V_o} (1.12 + 0.395\,K^{\,V_o/V_R})^2 - 1 \qquad (6)$$

Diffuser selection is based on a design which provides the necessary entrainment ratio in occupied areas.

Heat Exchanger Performance

Heat rejected from each module of the space station will be removed by a condensing heat exchanger. The heat exchanger efficiency must be sufficiently high to allow a close approach between the cooled atmosphere and the leaving fluid. This efficiency is expressed in terms of effectiveness (Equation 7) for a cross-flow heat exchanger with the fluid unmixed (Reference 2-6).

$$\varepsilon \text{ (EFFECTIVENESS)} = \frac{t_{hi} - t_{ho}}{t_{hi} - t_{ci}} \qquad (7)$$

where $M_c C_{p_c} > M_h C_{p_h}$

Actual heat exchanger design was not a part of this study, however, a relizable effectiveness was assumed to determine a minimum supply atmosphere temperature.

Acoustics

Noise at any point in the space station is a combination of direct and reverberated sound. The average effective sound pressure due to reverberated sound is a function the sound power level (SPL) of the source, the characteristic impedance of the medium, and the acoustic properties of the room. Sound pressure is defined by equation (7) where sound is radiated uniformly in all directions,

$$\bar{P}_r^2 = W \rho c\, ^4/\zeta \qquad (7)$$

and by equation (8) where more sound is radiated in one direction than another.

$$P_r^{\,2}(\mathrm{dir}) = \frac{W}{1/_{\rho c}\ [\frac{1}{Q/_{4\pi x^2} + 4/_{\zeta}}]} \tag{8}$$

The expression of sound pressure in the more familiar form of sound pressure level (SPL) is accomplished by equation (9).

$$(\mathrm{SPL})_{db} = 10\ \mathrm{LOG}_{10}\ (p_r/.002)^2 \tag{9}$$

Attenuation of excessive noise is achieved primarily by altering the characteristics of the acoustical path. In the atmospheric distribution system this is accomplished by use of sound traps or lined plenums (Reference 2-7). Calculation of attenuation resulting from use of acoustical material within ducts can be made by use of equation (10).

$$\text{ATTENUATION (db)} = 10\ \mathrm{LOG}_{10} \left[\frac{1}{S_e\ [\frac{\mathrm{Cos}\Theta}{2\pi d^2} + \frac{1-\alpha}{S_w}]}\right] \tag{10}$$

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Section 3.0

SYSTEM DESIGN AND TRADEOFFS

This section deals with the various configurations investigated in formulating a specific ventilation system design for each module. A method of investigation in the form of a trade off analysis was utilized which evaluated the effects of weight, volume and power required on each system design. Results of the tradeoff study and optional considerations are tabulated.

Trade Method and Philosophy

The tradeoff procedure considers all feasible combinations of configuration options listed in Table 3-1. (See Appendix A for deck layouts.) By calculating option penalties (See Appendix C for sample calculation) for configurations on each floor on an individual basis and summing, all attractive combinations were investigated without the tedious computation of all possible permutations and combinations. Weight and volume penalties and contribution to fan pressure drop were calculated for each deck by completing Table 3-2. Following this, module configurations were compared on Table 3-3.

Various methods of sizing ducts were investigated prior to starting the tradoff analysis. Common sizing methods used in designing duct systems are: constant pressure drop, velocity reduction, and static regain. Each method has advantages and disadvantages when used to optimize a duct design from a power, weight and volume standpoint. Based on the planned tradeoff studies, the velocity reduction method yields sufficient accuracy, while minimizing duct volume and weight. The static regain method was used on any constant volume portions of the duct system when a detailed configuration was established, to validate the sizes selected by the velocity reduction method.

Trade Off Results

Trade-off studies of various ventilation configurations were completed according to the method outlined above. Penalty data for the 28 candidate configurations are presented in Table 3-1 thru 3-3. The most promising combinations of these options are then presented as Deck options in Table 3-2. Schematics of the configurations which appear to be attractive based on the results of the trade off analyses are included in Appendix A. Table 3-3 shows the most attractive combinations for Module 1 and Module 2, not including maintenance and spares penalties. The primary difference between the penalties of Module 1 and 2, is the requirement for bacteria filters and maintaining the Biomedical laboratory, Dispensary and Isolation room at a slightly negative pressure on Deck 2. The crew compartments have individual temperature control capabilities by means of thermostatically controlled mixing of up to 75 cfm of $53^{o}F$ air with 55 cfm of bypass or unconditioned air. No auxiliary fans are used in any of the options.

A single design for the thermal conditioning unit was assumed in all configurations. Figure 3-1 shows the general component arrangement expected. Table 3-4 indicates estimated weight and volume for components or component groups which were derived from data obtained from other aerospace programs.

Duct sizes for the various configurations were established to stay within the fan power guidelines established in Reference 3-1. Performance characteristics of a typical fan (Reference 3-2) were investigated over a range of differential pressures as a basis for determining the noise and power penalties involved with higher pressures and smaller ducts. Figure 3-2 indicates these performance characteristics.

Design Options

As an optional design approach higher duct velocities were considered in the trade off studies. Overall penalties were recalculated on the selected configuration using higher velocities and smaller areas on transport ducts where minimal acoustical treatment would suffice in attenuating the resulting increase in noise level. Duct velocities were increased from approximately 1000 FPM to 3000 FPM in the main duct transporting atmosphere between decks

TABLE 3-1 OPTION PENALTIES

Option	Duct Volume ft^3	Penalty (1)	Duct Weight, lb	Penalty (2)	Diffuser Weight lb.	Penalty (2)	Design $\triangle P$, in H_2O	Total Vol. & Weight Penalty
Decks 1 and 3								
Conditioned Air Supply								
13 AC	6.4	84,500	9.6	9,980	2.0	2,080	0.25	96,560
13 BC	16.9	223,000	32.0	33,300	3.3	3,430	0.30	259,730
13 CC	12.0	158,000	22.6	23,500	3.6	3,750	0.30	185,250
Crew Compartment Air								
Conditioned								
13 ACCC	31.1	410,000	52.2	54,200	3.2	3,300	0.40	467,500
13 BCCC	33.1	437,000	55.5	57,700	3.2	3,300	0.45	498,000
Bypass								
13 ACCB	0	0	0	0	3.2	3,300	0.35	3,300
13 BCCB	17.1	225,000	39.7	41,200	3.2	3,300	0.45	269,500
13 CCCB	14.9	197,000	35.0	36,400	3.2	3,300	0.45	236,700
Return Air								
13 AR	0	0	0	0	1	1,040	0.15	1,040
13 BR	36.3	479,000	45.0	46,800	1	1,040	0.20	526,840

Space Station Normalization Factors: (1) Launch Volume \$13,200/ft^3 (2) Launch Weight \$1,040/lb

TABLE 3-1 OPTION PENALTYS

Option	Duct Volume ft^3	Penalty (1)	Duct Weight, lb	Penalty (2)	Diffuser Weight lb.	Penalty (2)	Design $\triangle P$, in H_2O	Total Volume and Weight Penalty
<u>Decks 1 and 3</u>								
Return Cont.								
13 CR	71.2	940,000	60.2	62,600	1	1,040	0.2	1,002,600
13 DR	28.6	378,000	36.0	37,400	1	1,040	0.2	416,440
13 ER	62.1	820,000	58.8	62,200	1	1,040	0.2	883,240
13 FR	9.4	124,000	10	10,400	1	1,040	0.15	135,440
<u>Deck 2</u>								
Conditioned Air								
2 AC				---DELETED ----				
2 BC	42.1	555,000	79.2	82,400	9	9,360	0.35	646,760
2 B'C	69.6	918,000	91.1	94,700	9	9,360	0.45	1,022,060
2 B"C	69.6	918,000	91.1	94,700	9	9,360	0.45	1,022,060
2 CC	33.8	446,000	59.5	61,800	7.4	7,700	0.35	515,500
Return Air								
2 AR	30.0	396,000	46.8	48,700	20*	20,800	0.8	465,500
2 BR	21.2	280,000	30.7	31,900	20*	20,800	0.75	332,700

** Included Bacteria Filters

Space Station Normalization Factors: (1) Launch Volume $13,200/$ft^3$ (2) Launch Weight $1,040/lb

TABLE 3-1 OPTION PENALTYS

Option	Duct Volume ft^3	Penalty (1)	Duct Weight, lb	Penalty (2)	Diffuser Weight lb.	Penalty (2)	Design ΔP, in H_2O	Total Volume and Weight Penalty
Deck 4								
Conditioned Air								
4 AC	63.3	836,000	111.9	116,000	4.1	4,270	0.45	956,270
4 A'C	51.6	672,000	95.1	98,900	4.1	4,270	0.42	775,170
4 BC	49.5	653,000	92.7	96,400	9	9,360	0.35	758,760
4 CC	59.5	785,000	89.6	93,200	9	9,360	0.38	887,560
4 D	28.6	378,000	53.7	56,700	4.7	4,890	0.33	439,590
Return Air								
4 R	3.6	49,000	3.6	3,740	0.3	310	0.05	53,050

Space Station Normalization Factors: (1) Launch Volume $13,200/$ft^3$ (2) Launch Weight $1,040/lb

TABLE 3-2 OPTION COMBINATIONS

Combinations	Total Duct Penalty	Max. Supply Duct ΔP	ΔP Return Duct
<u>Decks 1 & 3</u>			
13A 13 AC + 13 ACCC + 13 ACCB + 13 AR	568,400	0.40	0.15
13B 13 AC + 13 ACCC + 13 ACCB + 13 FR	702,800	0.40	0.15
13C 13 CC + 13 ACCC + 13 ACCB + 13 AR	657,394	0.40	0.15
13D 13 CC + 13 ACCC + 13 ACCB + 13 FR	781,490	0.40	0.15
<u>Deck 2</u>			
2A 2 CC + 2 BR	848,200	0.35	0.75
2B 2 CC + 2 AR	981,000	0.35	0.80
2C 2 BC + 2 AR	1112,260	0.35	0.80
2D 2 BC + 2 BR	979,460	0.35	0.75
<u>Deck 4</u>			
4A 4 BC + 4R	811,810	0.35	0.05
4B 4 DC + 4R	492,640	0.33	0.05

TABLE 3-3

MODULE OPTIONS

	Module 1	Total Duct Penalty	ΔP In. Wg. [1]	Power, Watts [2]	Penalty $ [3]	Total Penalty $ [4]
1-1	13 A + 2 B	1,549,400	1.80	555	672,000	2,610,400
1-2	13 A + 2 C	1,680,700	1.80	555	672,000	2,741,700
1-3	13 C + 2 B	1,638,400	1.80	555	672,000	2,699,400
1-4	13 C + 2 C	1,769,700	1.80	555	672,000	2,830,700
1-5	13 B + 2 A	1,551,000	1.75	546	663,000	2,603,000
1-6	13 B + 2 D	1,682,300	1.75	540	663,000	2,734,300
1-7	13 D + 2 A	1,629,700	1.75	540	663,000	2,681,700
1-8	13 D + 2 D	1,761,000	1.75	540	663,000	2,813,000
	<u>Module 2</u>					
2-1	13 A + 4 A	1,380,200	1.15	355	437,000	2,206,200
2-2	13 A + 4 B	1,061,000	1.15	355	437,000	1,887,000
2-3	13 C + 4 A	1,469,200	1.15	355	437,000	2,295,200
2-4	13 C + 4 B	1,150,000	1.15	355	437,000	1,976,000

1. Includes 0.6" Wg. Thermal Control Unit Penalty
2. Assuming 40% Fan Efficiency
3. Power Penalty at $1,230 Per Watt
4. Includes $389,000 Weight and Volume Penalty from TC Unit
5. A worst case system compromised of 2 each of 13 BCC, 13 BCCC, 13 BCCB, 13 CR, and one each of 2B6, 2AR, 4AC, and 4R have a total penalty of $8,052,700.

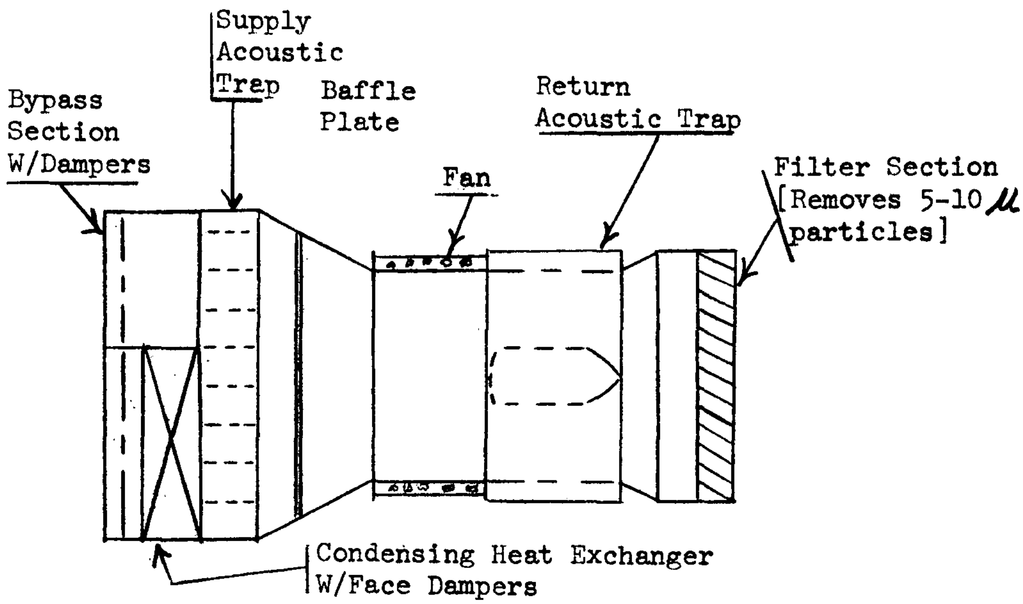


FIGURE 3-1 THERMAL CONDITIONING UNIT

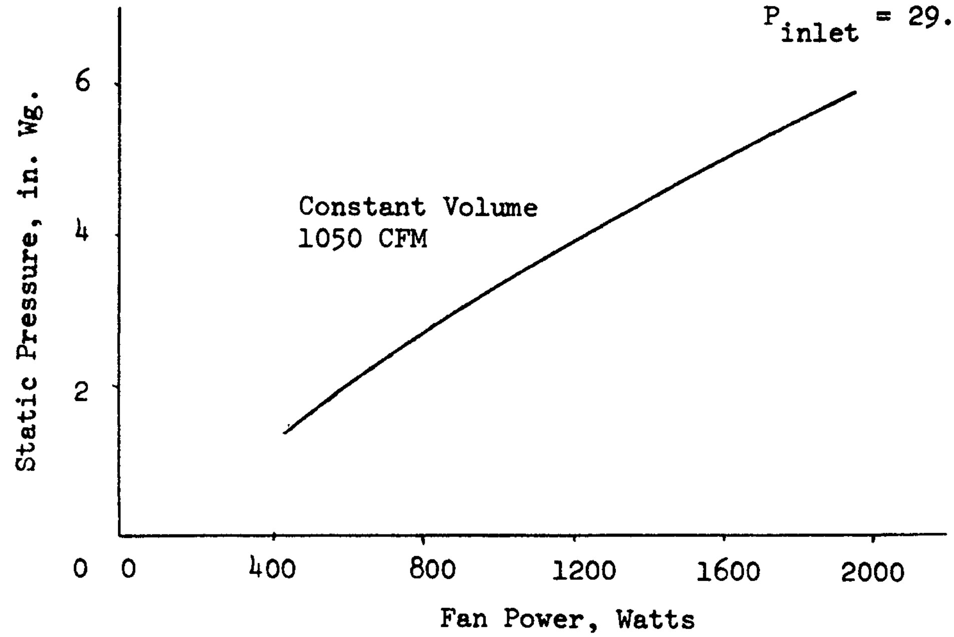
Component	Weight	Volume
Fan	12 lbs	.8 Ft^3
Heat Exchanger W/Face Damper	140 lbs (Dry)	1.7 Ft^3
Return Acoustic Trap	3 lbs	3 Ft^3
Supply Acoustic Trap. Bypass Section Bypass Damper, Transition Section, and Baffle Plate	8 lbs	10 Ft^3
Filter Section W/Filters and Blower Filter Transition	1 lb	1 Ft^3

TABLE 3-4 THERMAL CONDITIONING UNIT COMPONENTS ESTIMATED WEIGHT AND VOLUME

NOTE: Data based on AiResearch Mfg. Model MDF 44 Axial Fan

$\rho = .075\ lb/ft^3$

$P_{inlet} = 29.92''$ Hg



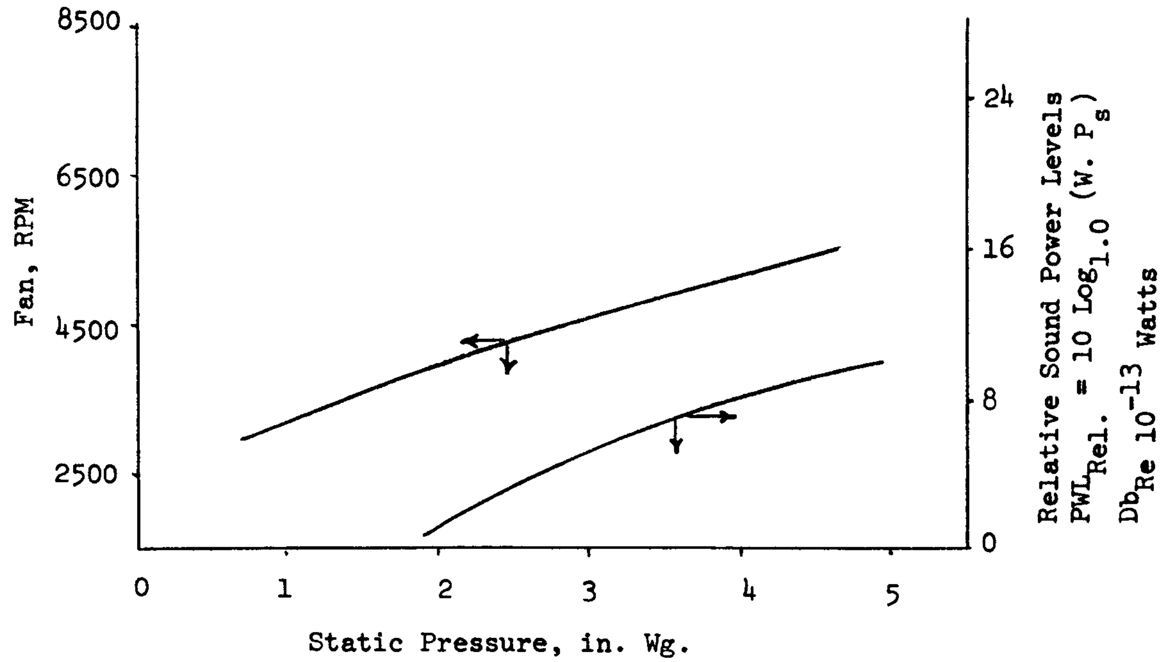


FIGURE 3-2 TYPICAL FAN PERFORMANCE CHARACTERISTICS

while velocity in the branch duct around the periphery of the inner core was increased to 1800 FPM from approximately 700 FPM. Velocity was not changed in ducts with attached diffusers since an acoustical plenum would be required for velocity reduction and noise control prior to each outlet. Added acoustical treatment to ducts without attached diffusers consists of three feet of lining material on both sides (i.e., before and after each turn) of each elbow.

Table 3-5 shows the calibrated system duct volume and weights and design pressure drop for the higher velocity arrangement. Table 3-6 furnishes a comparison of the penalties for both the high and low velocity arrangement. It can be noted from Table 3-6 that overall penalties are less for the low velocity arrangement if configuration B for Module 2 is selected. Configuration A, Module 2 overall penalty tabulation indicates the high velocity duct arrangement to be less than the low velocity arrangement. However, configuration A, Module 2 has a higher penalty in both cases than its alternate configuration B. System duct volume and weight is reduced by its alternate configuration B. System duct volume and weight is reduced by 28% and 10% respectively when increased velocity is utilized. Power consumption on the other hand increased 30% with the high velocity arrangement due to increased static pressure loss within the ducts. Increased duct velocity with the corresponding decrease in duct volume and weight could prove feasible if the power penalty was reduced 12% or the volume and weight penalty were to increase 6%.

System Performance

Selectable temperature between $65^{o}F$ and $85^{o}F$ can be provided within each zone by the proposed system using minimum auxiliary heat. The system is designed to allow a portion of the heat from a warm zone to be utilized in a cooler zone which requires heat. This considerably reduces the need for auxiliary heat in providing a higher zone temperature (i.e., $75^{o}F$ - $85^{o}F$). Requirement for auxiliary heat will most often occur in the crew compartment. The box shown in Figure 3-3 includes the attainable temperatures in each crew compartment assuming a heat load of 750 BTU/hr from metabolic and equipment. Based on the

TABLE 3-5

SELECTED CONFIGURATION PENALTYS BASED ON

HIGHER VELOCITY AIR IN VARIOUS DUCTS

Deck	Duct Volume Ft^3	Penalty (1)	Duct* Weight lbs.	Penalty (2)	Diffuser Weight lbs.	Penalty (2)	Design ΔP Inches H_2O
Deck 1 and 3							
(Fig. 13 ACCC)	31.1	410,000	52.2	54,200	3.2	3,320	0.45"
(Fig. 13 AC)	6.4	84,500	9.6	9,980	2.0	2,080	0.25"
(Fig. 13 AR)	0	0	0	0	1.0	1,040	0.15"
(Fig. 13 ACCB)	0	0	0	0	3.2	3,300	0.35"
Deck 2							
(Fig. 2BC)	28.6	377,000	64.1	66,900	9.0	9,360	1.2"
(Fig. 2 AR)	30.0	396,000	46.8	48,700	20.0	20,800	0.8"
Deck 4							
(Fig. 4 BC)	28.4	374,000	63.5	66,000	9.0	9,360	1.0
(Fig. 4 R)	3.6	49,000	3.6	3,740	0.3	310	0.05
Fig. 4 DC	23.2	306,000	47.7	49,500	4.7	4,890	0.51

* Includes internal liners at elbows of high velocity ducts.

TABLE 3-6

MODULE PENALTY BASED ON SELECTED CONFIGURATION

Module No.	Configuration	Total Volume and Weight Duct and Thermal Conditioning Penalty	Max. Supply Fan ΔP	Power Penalty Watts	Power Penalty $	Total Module Penalty
LO VELOCITY						
1	Fig. 13 AC 13 ACCC 13 ACCB 13 AR 2 BC 2 AR	2,069,720	1.8	555	672,000	2,741,720
2	A Fig. 13 AC 13 ACCC 13 ACCB 13 AR 4 BC 4 R	1,769,270	1.15	355	437,000	2,206,270
2	B Fig. 13 AC 13 ACCC 13 ACCB 13 AR 4 DC 4 R	1,450,100	1.15	355	437,000	1,887,100
HIGH VELOCITY						
1	Fig. 13 AC 13 ACCC 13 ACCB 13 AR 2 BC 2 AR	1,876,180	2.6	795	980,000	2,856,180

TABLE 3-6 (Continued)

MODULE PENALTY BASED ON SELECTED CONFIGURATION

Module No.	Configuration	Total Volume and Weight Duct and Thermal Conditioning Penalty	Max. Supply Fan ΔP	Power Penalty Watts	Power Penalty $	Total Module Penalty
2	A: Fig. 13 AC, 13 ACCC, 13 ACCB, 13 AR, 4 BC, 4 R	1,459,830	1.65	500	615,000	2,074,830
2	B: Fig. 13 AC, 13 ACCC, 13 ACCB, 13 AR, 4 BC, 4 R	1,370,960	1.45	450	555,000	1,925,960

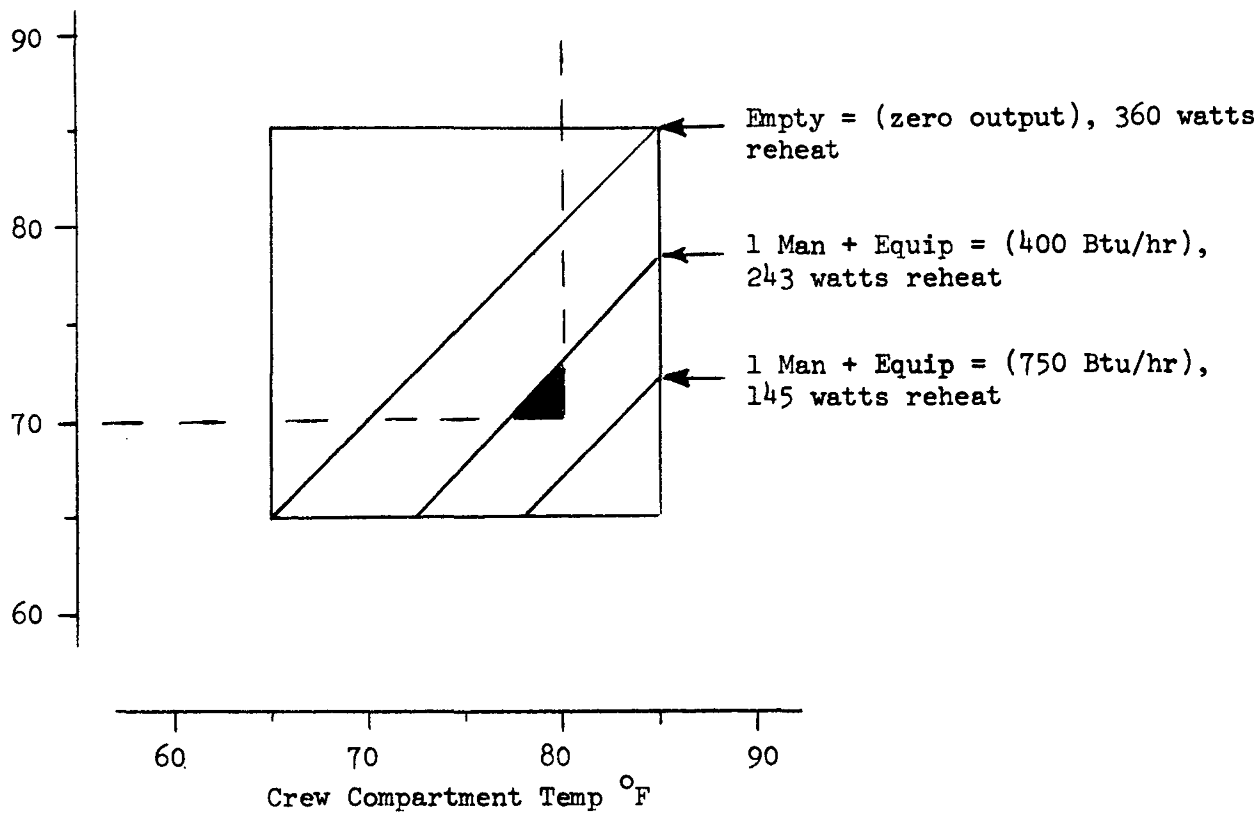


FIGURE 3-3 CREW COMPARTMENT TEMPERATURES ATTAINABLE BY MIXING 53°F ATMOSPHERE WITH DECK ATMOSPHERE

system design, $53^{o}F$ conditioned air is mixed with deck air at a total flow of 55 CFM per compartment. However, auxiliary heat is required to completely cover the box at some of the lower deck temperatures.

Assuming that heating an unoccupied compartment is not desired, a 250 watt heater in each compartment would appear to be sufficient to make all areas of the box attainable. Since it is conceivable that all 12 heaters could be operating simultaneously, (during crew overlap), the energy requirement could reach 3,000 watts, with an attendent penalty of $3.7 million. This is the penalty of requiring each compartment temperature to be selectable between $65^{o}F$ and $85^{o}F$, regardless of the deck temperature.

If one takes a more realistic look and assumes that the deck temperature will never be operated below $70^{o}F$, and a crewman will not want his compartment above $80^{o}F$, we may ignore the area of the box below and to the right of the dashed lines. This means if one is further willing to give up the small shaded triangle, (including very low metabolic rate and a coincidental desire for a compartment temperature above $78^{o}F$ when the deck is below $72^{o}F$), no reheat is required with a substantial power savings in addition to equipment costs and improved reliability and safety.

REFERENCES

3-1 Space Station Preliminary Design, Volume 1, Book 3, McDonnell Douglas Astronautics Company-West, Report No. MDC-G0639, July 1970.

3-2 Jorgensen, Robert; Fan Engineering, 6th Edition, Buffalo Forge Company, Buffalo, New York, 1961.

Section 4.0

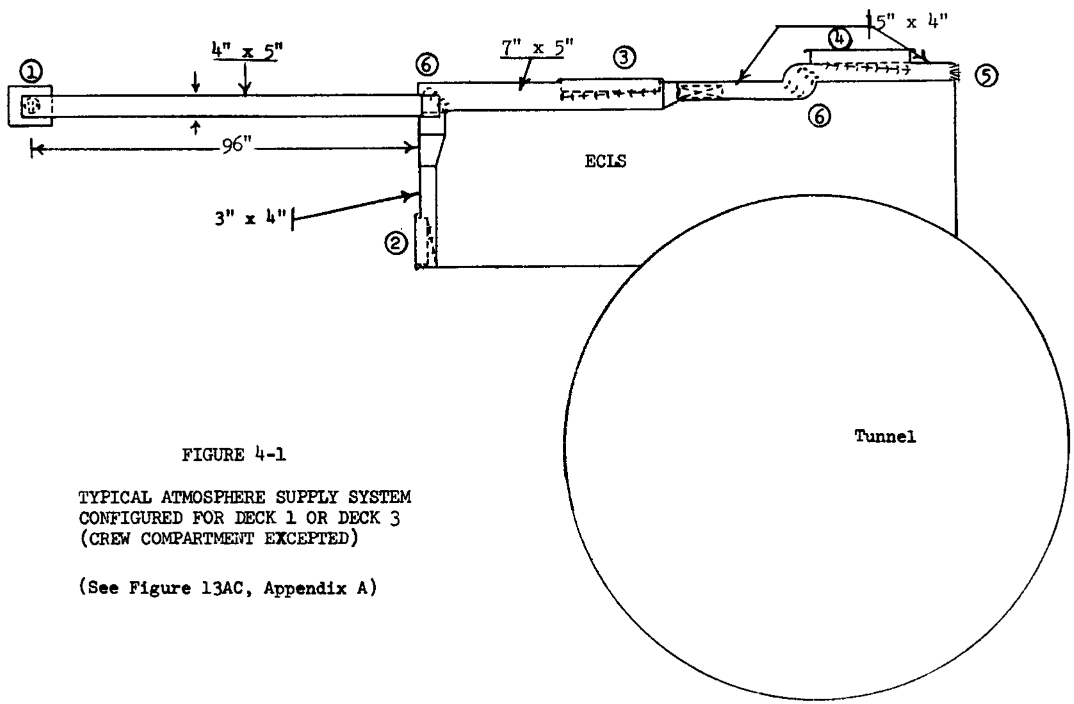
FLIGHT DESIGN

A flight design was formulated based on the best configuration found during the tradeoff study. This section includes a more detailed layout of the flight design and reports on the controls, diffusers and acoustical treatment required. In addition the system maintainability, pressure change effects and emergency operation performance is analyzed.

System Layout

The flight design selected from the trade off studies was configuration 1-2 (Table 3-3) for Module 1 and 2-2 for Module 2. These two configurations appear most feasible due to the calculated low penalty, good atmospheric distribution characteristics and a degree of commonalty between modules. A scaled layout of the assemblies and duct system for each deck is shown on Figure 4-1, 4-2, 4-3, and 4-4. Each deck layouts indicate the location of turning vanes and balancing dampers along with identification of diffusers grills and filters. Details are given on diffusers and grills in order to indicate the level of performance required and aid in developing working drawings for mockup testing.

The central station thermal conditioning unit installed in the ECLS area is shown on Figure 4-5. The ECLS compartment will function as a return plenum for the two decks in each module. It will utilize access door seals and operate at a slight negative pressure allowing only atmosphere from the return ducts to enter the area. This method of atmosphere return appears to offer several inherent advantages in addition to reducing required ducts. These advantages include lower noise level in decks 1 and 3, containment and localized removal of heat losses from life support systems, and centralized sensing of hazardous contaminants. The arrangement provides easy access to equipment which may require service and minimizes supply duct volume.



NOTES:

① Diffuser Type - Anemostat E-100-5 w/equalizing defleftor and volume control damper

② Diffuser Type - Anemostat Slad-F (Spec.) 2 slot - 1" w/opposed blade damper

③ & ④ Diffuser Type - Anemostat Slad-F-2 slot-2" w/opposed blade damper

⑤ Waterloo - Rotacore Grill - 8" x 4" w/volume control damper

⑥ Turning Vanes installed at each elbow

FIGURE 4-1

TYPICAL ATMOSPHERE SUPPLY SYSTEM
CONFIGURED FOR DECK 1 OR DECK 3
(CREW COMPARTMENT EXCEPTED)

(See Figure 13AC, Appendix A)

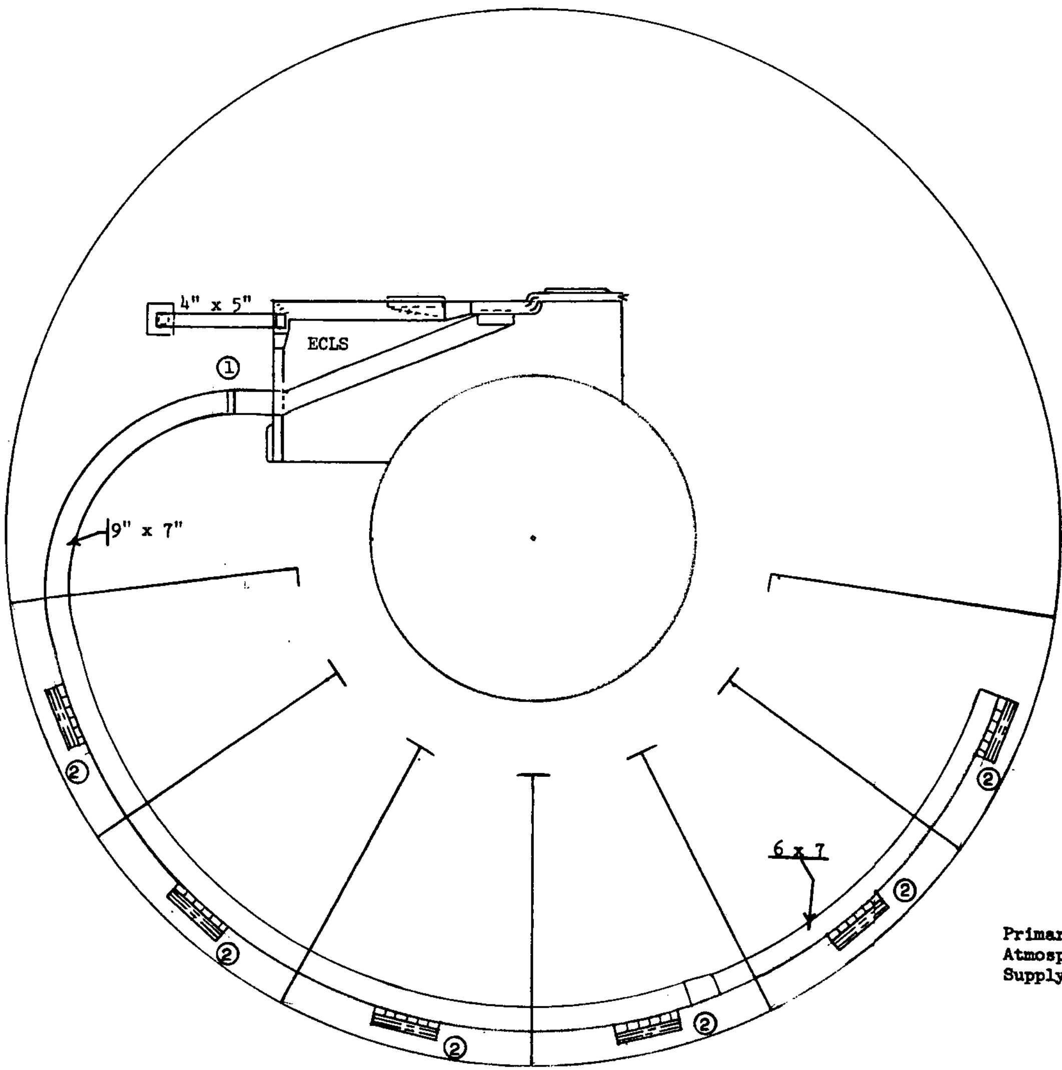


FIGURE 4-2 TYPICAL ATMOSPHERE SUPPLY SYSTEM FOR DECK 1 OR DECK3

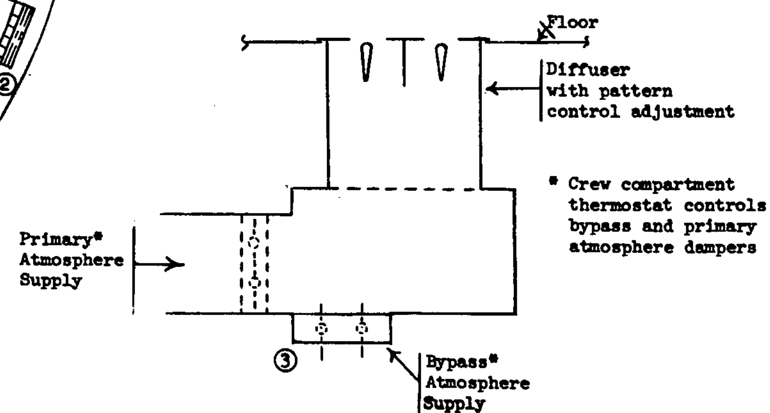
(See Figure 13ACCC and 13AC)
For detail layout on ECLS Unit, see Fig. 4-1 & 4-5.

NOTES:

① Opposed blade blancing and shut-off damper

② Diffuser Type - Anemostat Slad-F
2 Slot 2' w/2 sets of motorized
opposed blade dampers (see detail A-A)

③ Bypass atmosphere transported in a pressurized plenum below floor



* Crew compartment thermostat controls bypass and primary atmosphere dampers

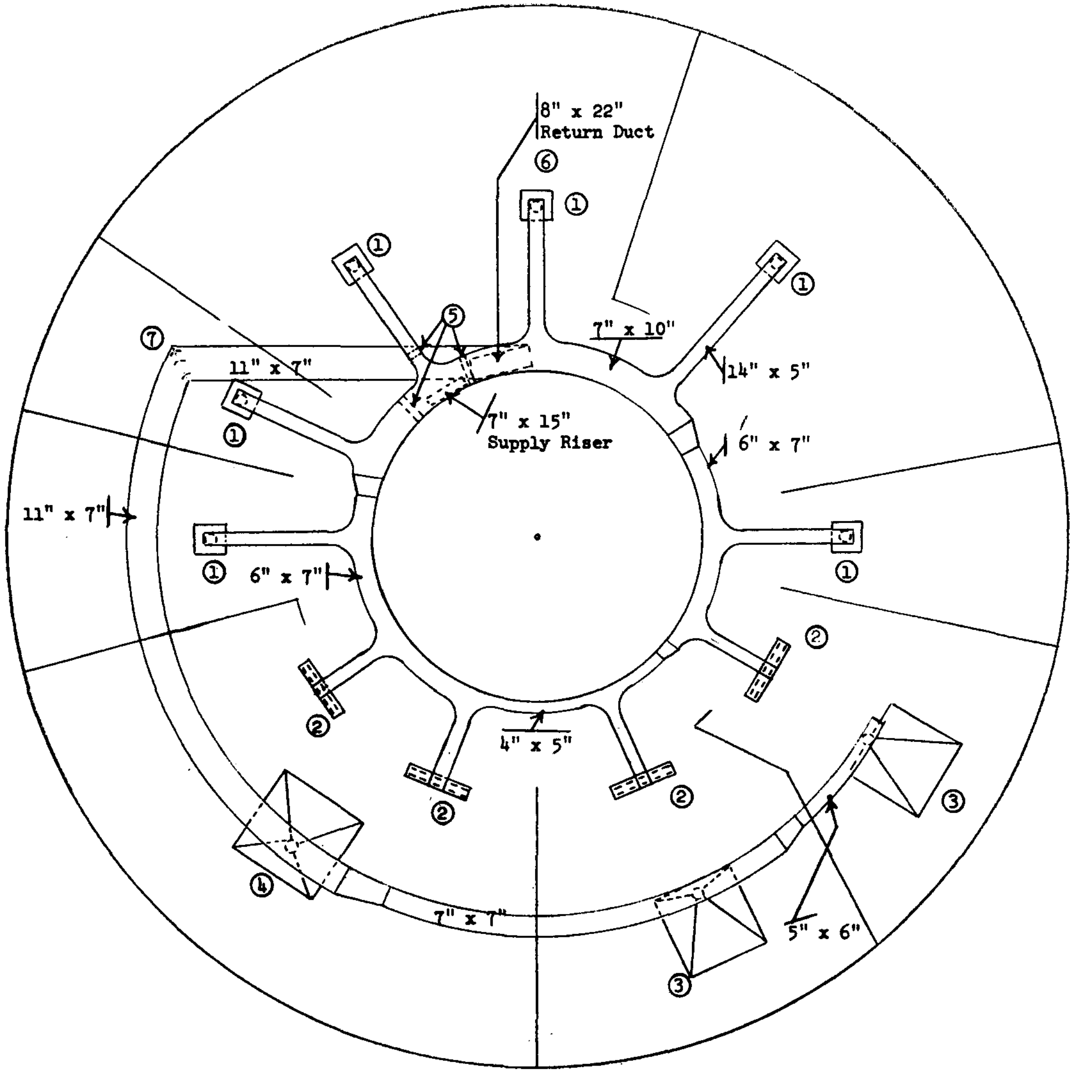


FIGURE 4-3 DECK 2 ATMOSPHERE SUPPLY AND RETURN SYSTEM
(See Figure 2BC and 2AR, Appendix A)

① Diffuser Type - Anemostat E-100-5 w/equalizing deflector and volume control damper

② Diffuser Type - Anemostat Slad-F 2 Slot 2' w/opposed blade damper

③ Bacterial Filters - Size 30" x 30"

④ Bacterial Filters - Size 40" x 40"

⑤ Opposed blade balancing and shut-off damper

⑥ Return Grill Type - Waterloo model 1HMV size 14" x 10" w/one-half inch thick 5-10μ particle filter attached

⑦ Turning vanes installed @ each elbow

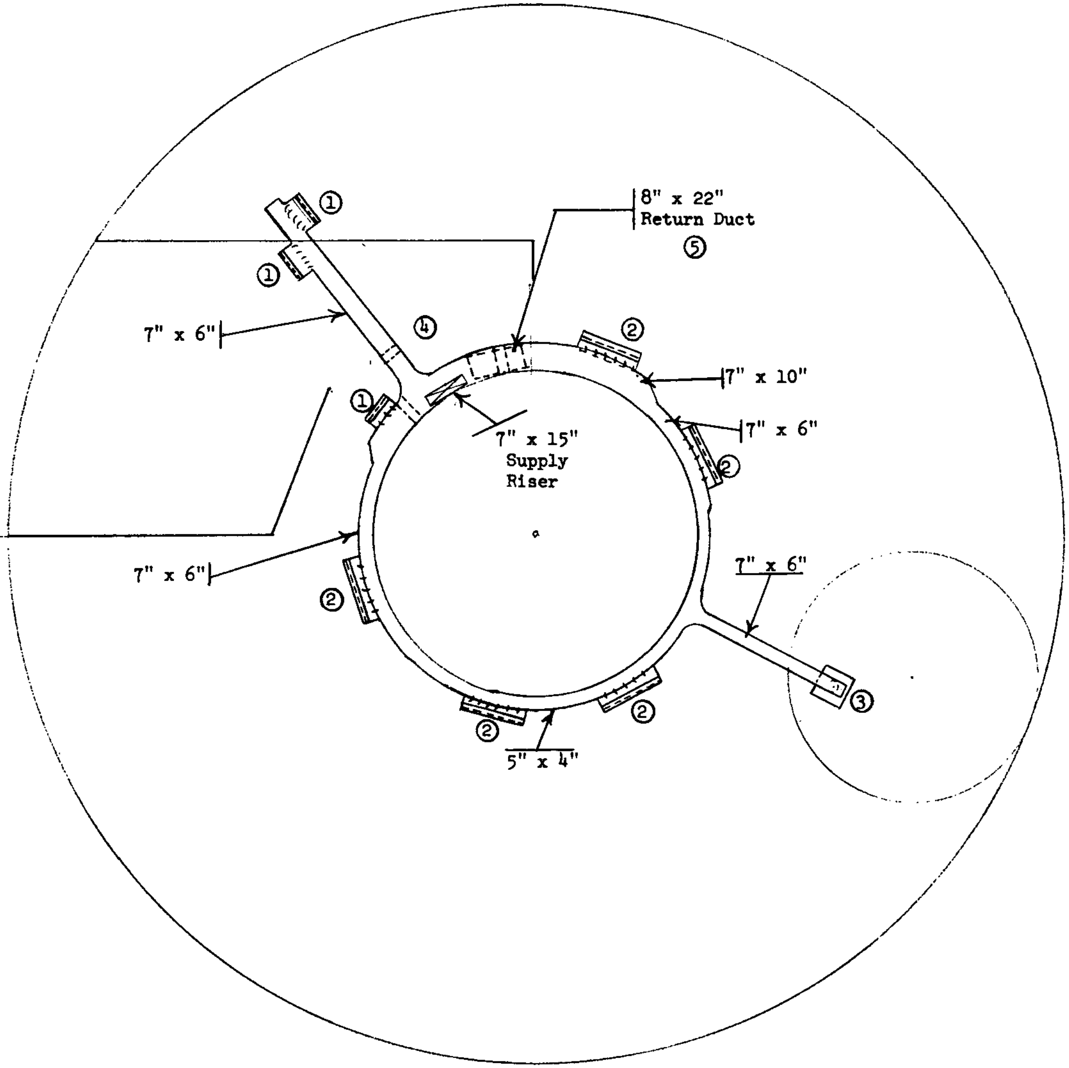


FIGURE 4-4 DECK 4 ATMOSPHERE SUPPLY AND RETURN SYSTEM

(See Figure 4DC and 4RA, Appendix A)

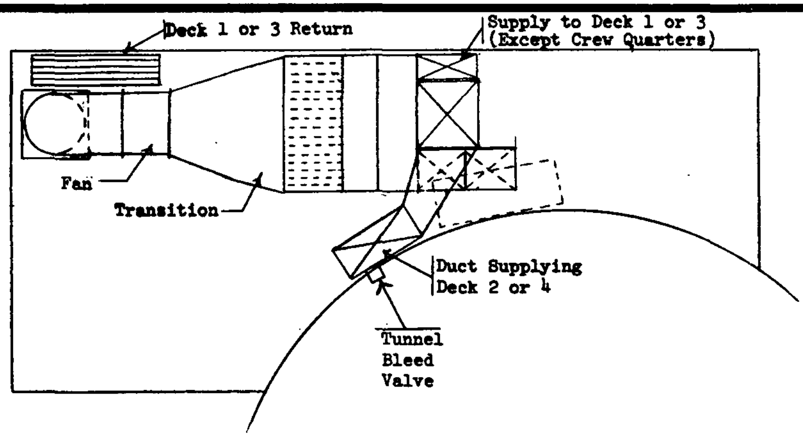
① Diffuser Type - Anemostat Slad-F (Spec.)
2 Slot - 1' W/Opposed Blade Damper

② Diffuser Type - Anemostat Slad-F 2 Slot -
2' w/opposed blade damper

③ Diffuser Type - Anemostat E-100-5
w/equalizing deflector
and volume control damper

④ Opposed blade balancing and shut-off damper

⑤ Return Grill Type - Waterloo model RC3HD-81
size 20" x 12" W/one-half
inch thick 5-10μ particle
filter attached



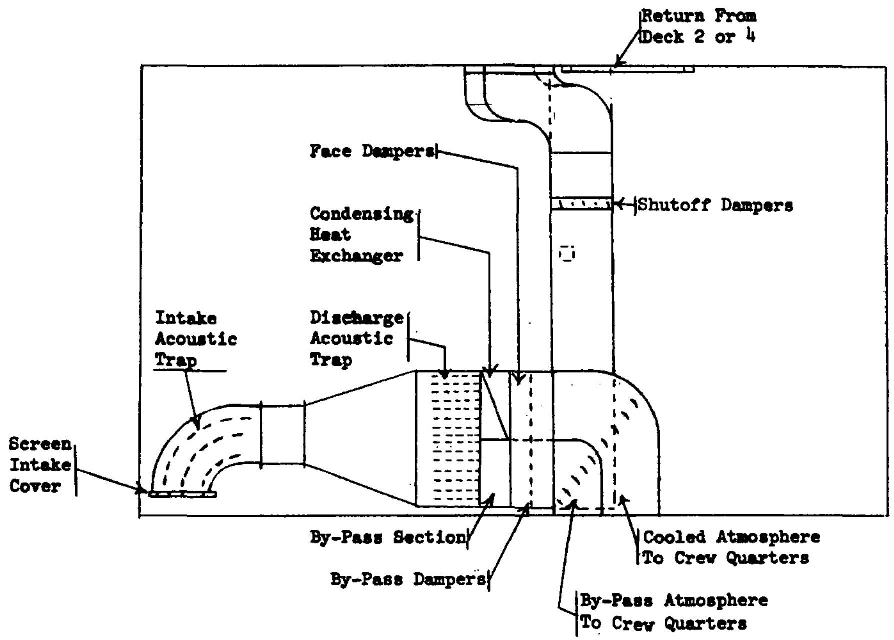


FIGURE 4-5 THERMAL CONDITIONING UNIT
CENTRAL STATION LAYOUT

NOTES: Compartment serves as a return atmosphere plenum. Access seals allow the compartment to operate at a slight negative pressure

System Fan Performance

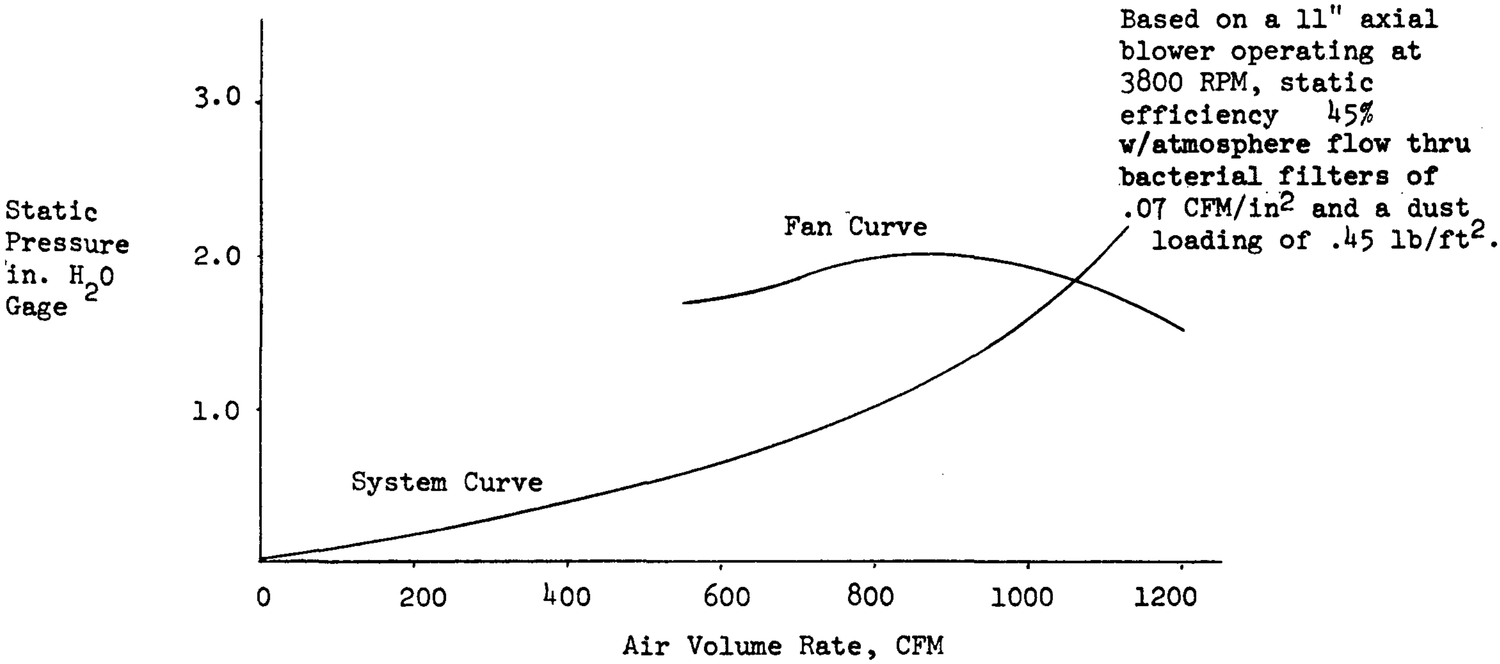
System fan performance characteristics curves for Module 1 and Module 2 are shown on Figure 4-6. Module 1 system curve reflects the added pressure drop, resulting from dust laden (i.e., 0.45 lb/ft^2) bacterial filters located on deck 2. Initial system pressure for Module 1 (based on clean bacterial filters) and Module 2 is 1.43 inches of water. Gradual filter loading occurs in Module 1 until the system pressure drop exceeds 1.8 inches of water where it is assumed the filters would be changed. Figure 4-7 shows the relationship between bacterial filter pressure drop and volume flow per unit area for both clean and loaded conditions.

The desired commonality between Module 1 and Module 2 blowers can be achieved using two approaches. One approach would be design and manufacture both blowers to operate on several current frequencies with selection depending on the impeller speed required to meet the system pressure characteristics. Filter loading resulting in an increase in the pressure drop could be adjusted for by changing the operating frequency. A second approach would be to utilize the same blower housing and impeller for both modules but install different motors. Outlet dampers would be used to provide an added pressure drop in Module 1 while the bacterial filters were clean. This would provide commonalty of blower assemblies for Module 1 and Module 2 in all components except motors.

Diffuser Evaluation

Diffuser designs were established for the flight configured ventilation system based primarily on commercial test data (Reference 4-1). A preliminary test was completed in an attempt to correlate commercial test data (developed using a floor to diffuser height of 9') with expected performance in a space station where the floor to diffuser height is only 6.5'. The three diffuser designs tested were: 1) modular cored unit with preforated plates (8" x 8"), 2) high induction circular unit (5" neck), and 3) wall mounted two-slot unit (3' long). The test was designed to simulate mounting locations typical of those that will exist for a space station.

Module 1*



* Module 1 system and fan curve will be identical with Module 2 when bacterial filters are clean.

Module 2

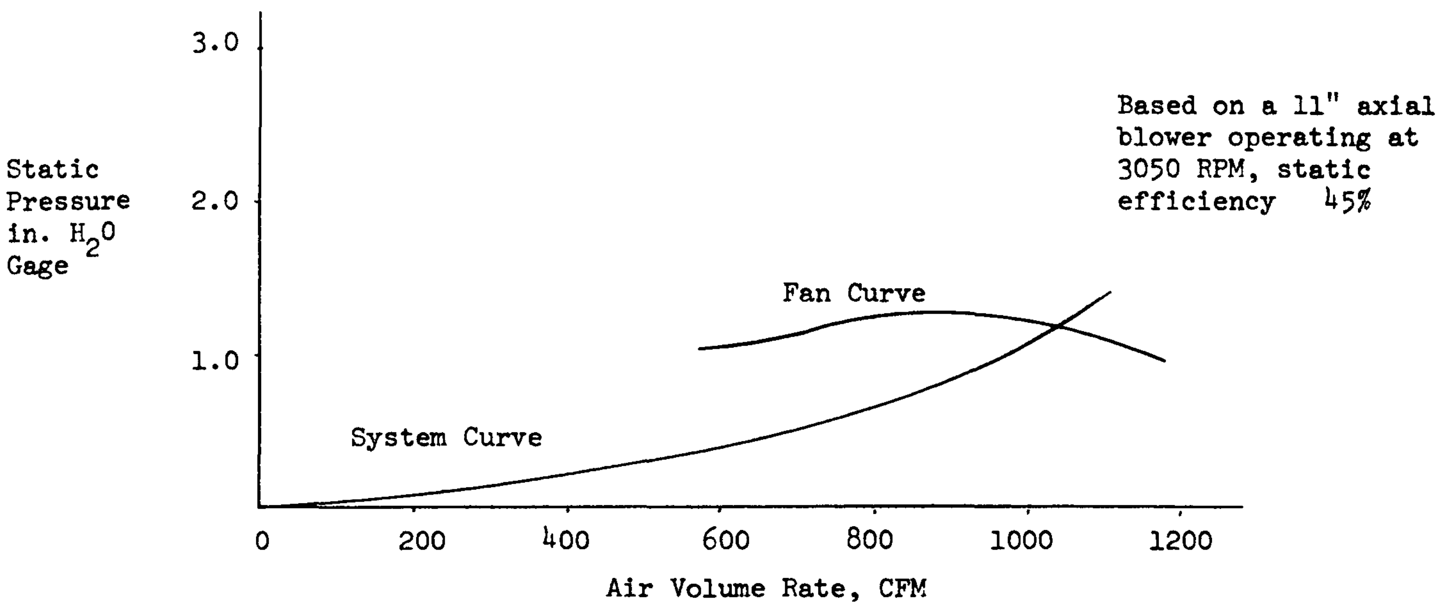
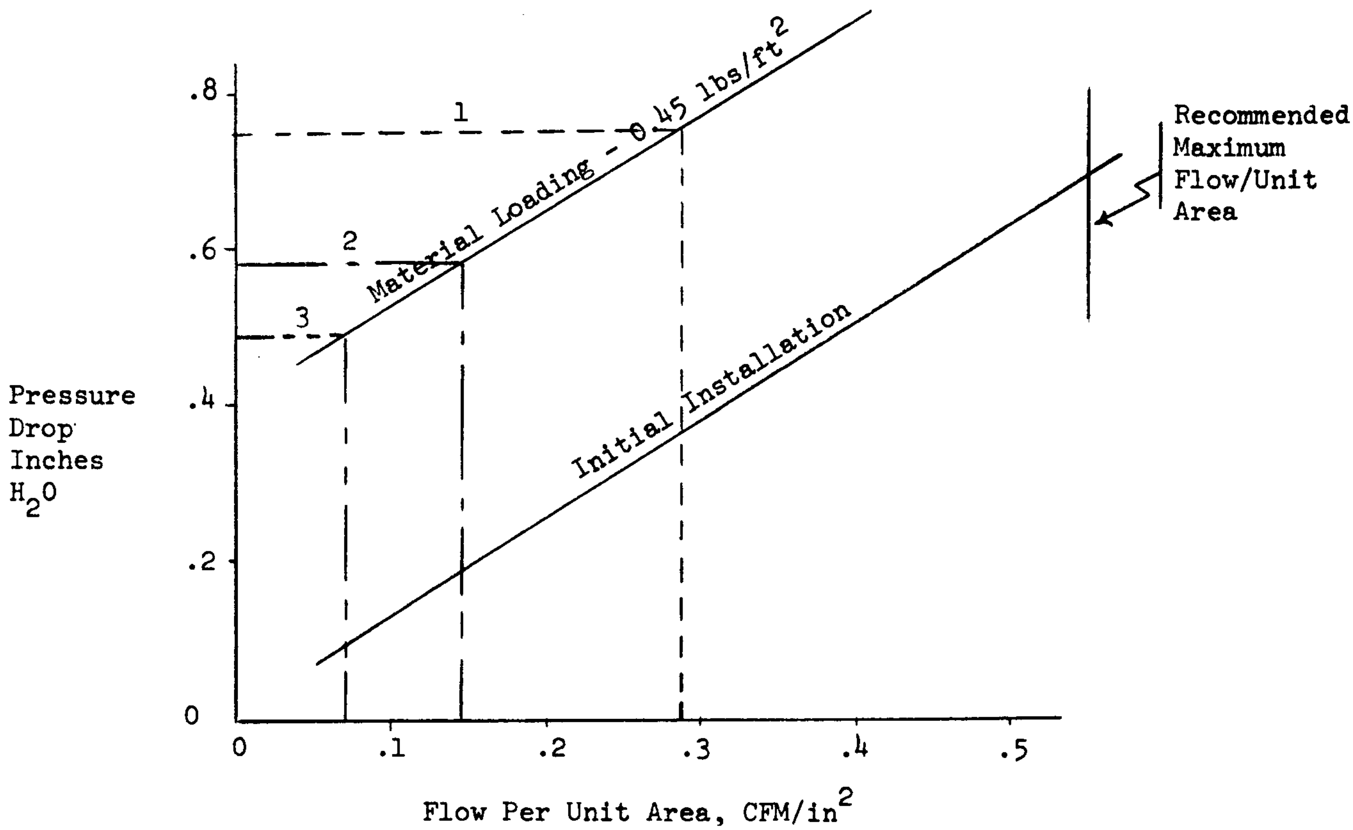


FIGURE 4-6 - SYSTEM FAN PERFORMANCE CURVES



1 Selection point represented in Module 1 pressure drop of 1.8 inches water gage

2 Represents doubling of surface area over 1

3 Represents tripling of surface area over 1

FIGURE 4-7 BACTERIAL FILTER PRESSURE AS A FUNCTION OF VOLUME FLOW

Figure 4-8 shows the test arrangement for the two ceiling mounted diffusers. The air velocity in the isothermal test set-up was measured by using a portable hot wire anemometer which had an accuracy of approximately $\pm$ 10%. Ratings for ceiling-mounted diffusers are in terms of minimum and maximum radius of diffusion. Minimum radius of diffusion is defined as the distance from the center line of the diffuser where the average air velocity is between 25 and 50 FPM. Maximum radius of diffusion defines the distance from the center line of the diffuser where the average air velocity is between 20 and 35 FPM. For the wall mounted diffusers these terms are called minimum and maximum throw.

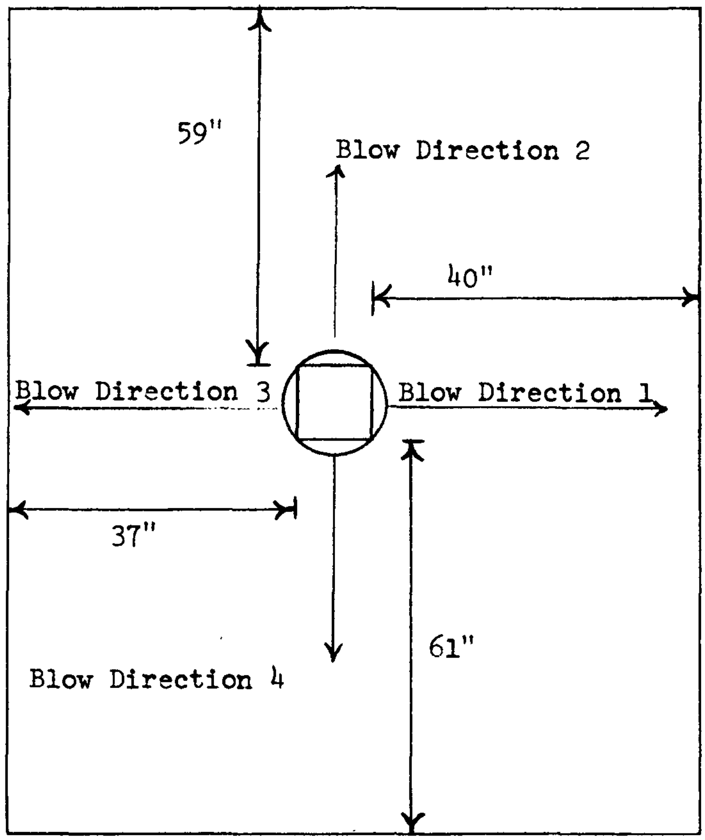
Modular Cored Unit with Perforated Plate

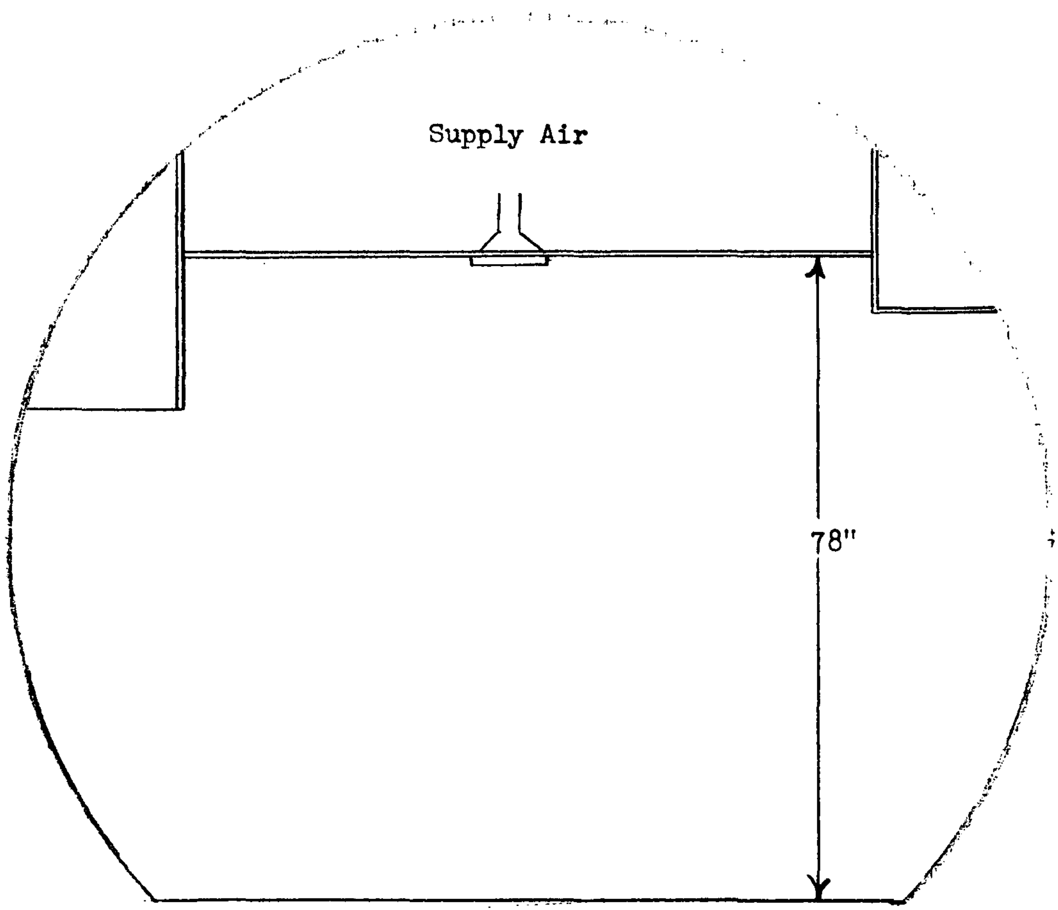
Figures 4-9, 4-10 and 4-11 present test results from this diffuser in three different configurations. The three configurations tested consisted of four-way blow, two-way blow, and single-direction blow. The diffuser could be adjusted to any of the three configurations by relocating the removable cores. Figure 4-9, 4-10, and 4-11 show the air velocity at the ceiling and six inches below. The measured air velocity at ceiling height showed a rapid decrease to reasonable levels as the distance from the diffuser increased. An area below the diffuser extending approximately two feet down and one foot in diameter was found to have velocities at or below the 20 FPM level. Overall velocities within the test area were found to be between 10-30 FPM except in the area 6" below the ceiling.

Circular High Induction Unit

Figure 4-12 shows the performance of the high induction diffuser (i.e., equal parts primary air and test area air) when operating at both 50 and 80 CFM. Rapid reduction in ceiling level air velocity occurred as the distance from the diffuser increased. A low velocity area also occurred below the high induction unit as with the modular unit previously described. Air velocities in the test areas ranged above 20 FPM as shown on Figure 4-12 with the exception of the ceiling area and the 6" below ceiling area. Lower velocities occurred in DIR. I than in DIR. II due to a sag in the temporary ceiling which created some minor turbulences.

FIGURE 4-8 - MODULAR AND HIGH INDUCTION DIFFUSER TEST SET UP





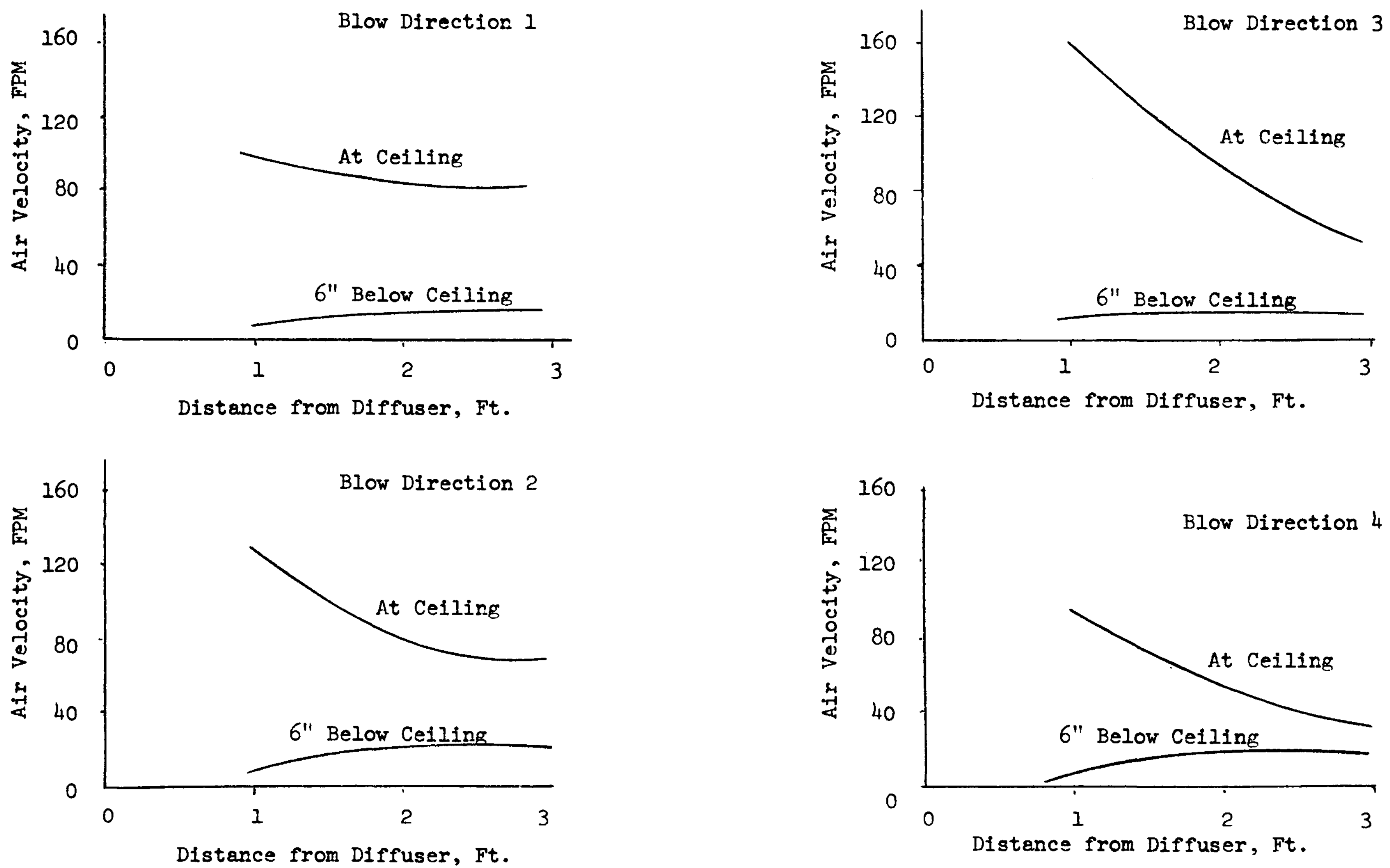


FIGURE 4-9 MODULAR DIFFUSER WITH FOUR WAY BLOW

NOTE: Velocity at ceiling and 6" below is 20-25 FPM for blow direction 1 and 3

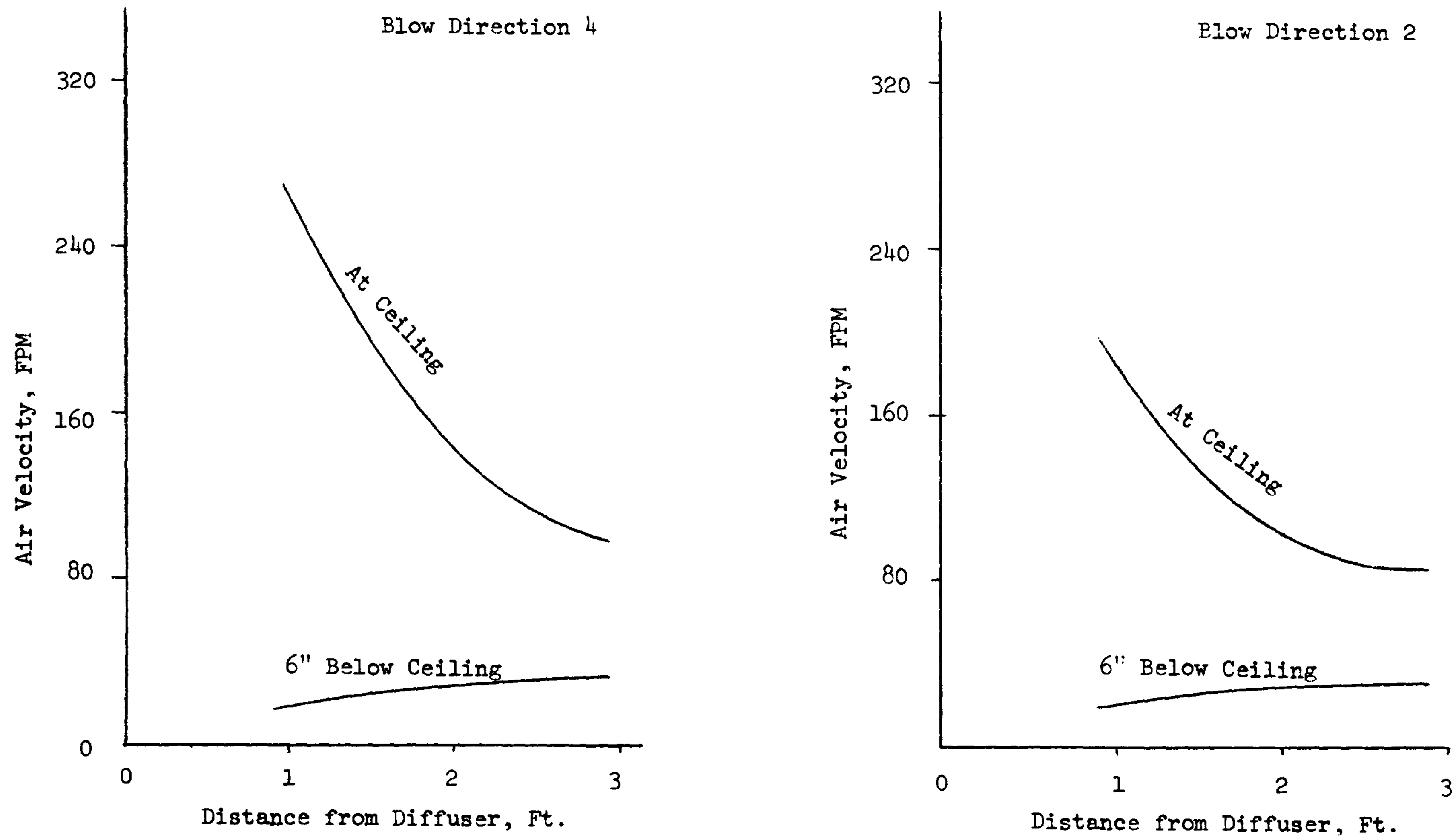


FIGURE 4-10 MODULAR DIFFUSER WITH TWO WAY BLOW

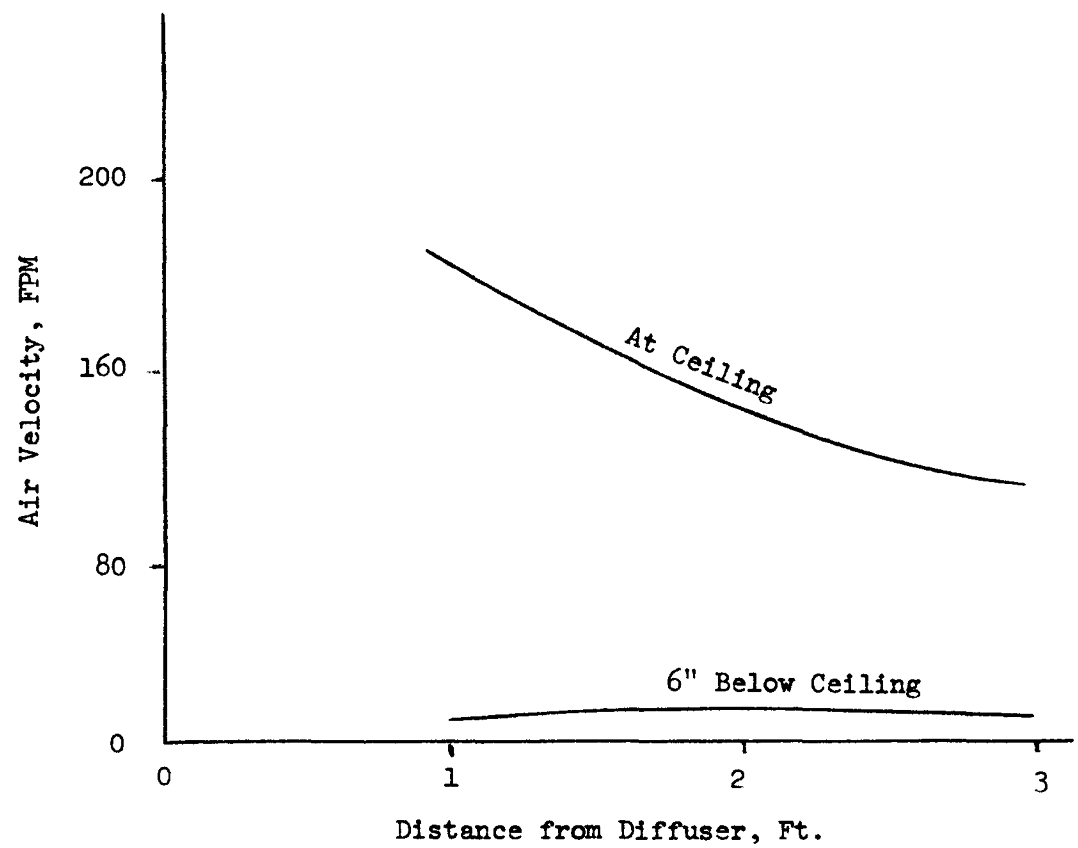


FIGURE 4-11 MODULAR DIFFUSER WITH SINGLE DIRECTION BLOW

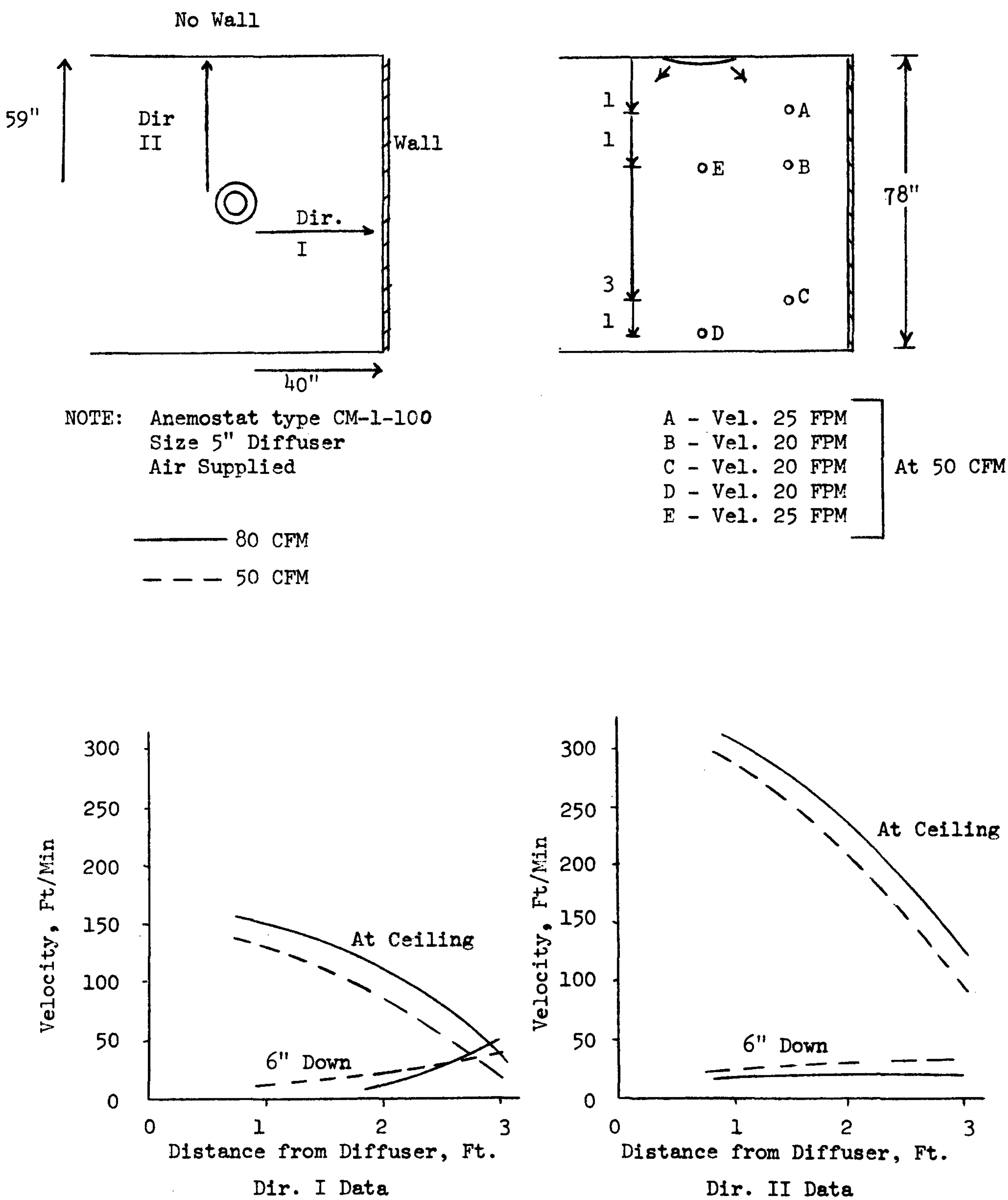


FIGURE 4-12 HIGH INDUCTION CIRCULAR DIFFUSER TEST ARRANGEMENT AND PERFORMANCE DATA

Wall Mounted Slot Diffuser

Figure 4-13 shows the test arrangement and performance of the wall mounted diffuser. High air velocity, as with the two previous diffuser types, existed only at the ceiling. Excessive velocity even at the ceiling was reduced to an acceptable level within 5 feet. Air velocity at other locations within the test area were in the acceptable region.

Test Findings

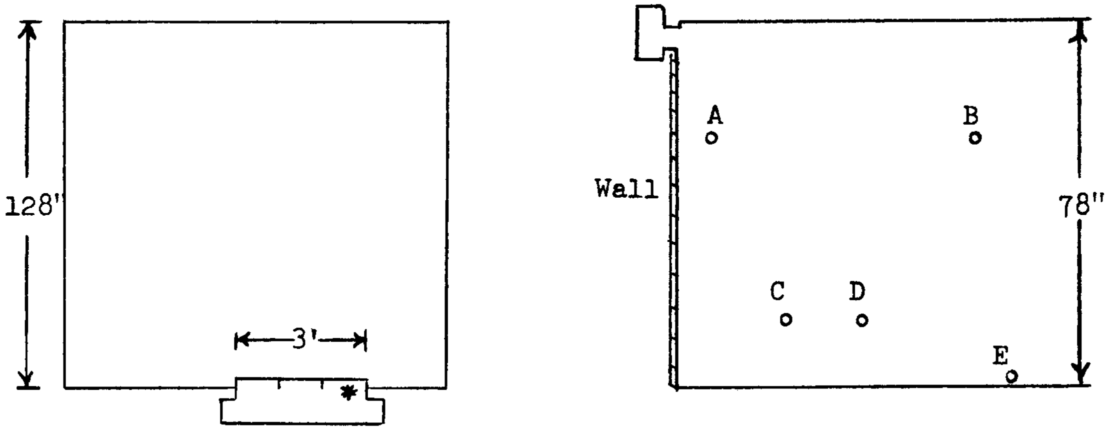
The preliminary test showed that air velocities considerably higher and lower than the 25 to 50 FPM average existed at specific location within the test area. However, the high and low velocity region was at the ceiling and 6" below ceiling where deviations from the comfort range of 20 to 50 FPM are not of great importance. Air velocities within the remaining area are in general very acceptable for all three of the diffuser designs.

Acoustical Analysis

Accepted sound level criteria was not specified in the design constraints for the space station except as suggested in Reference 4-2. Therefore, detailed design on noise attenuation could not be formulated during the study. In order to relate the sound generated due to fans and atmosphere movement within the transport ducts some constraints were assumed for purpose of analysis. The assumptions listed below were developed from estimated acoustical requirements for good speech communication, experience during the 90-day test, and basic equipment test data.

1) Sound pressure level (SPL) of a typical fan used in the space station would not exceed that of the four (4) fan cluster used on the Skylab program. (See Figure 4-14) (Note: Reliable SPL data was not available from manufacturers.

2) Perfect isolation of machine vibration exists with no other source of sound other than fan noise and atmosphere noise within ducts.



NOTE: Anemostat Type Slad
2-Slot (36" Long)

Both upper and lower
slot open on 2' section

Flow 50 CFM/2 Ft. Section

* 1' section closed

(A) Vel - 19 FPM
(B) Vel - 25 FPM
(C) Vel - 25 FPM
(D) Vel - 28 FPM
(E) Vel - 33 FPM

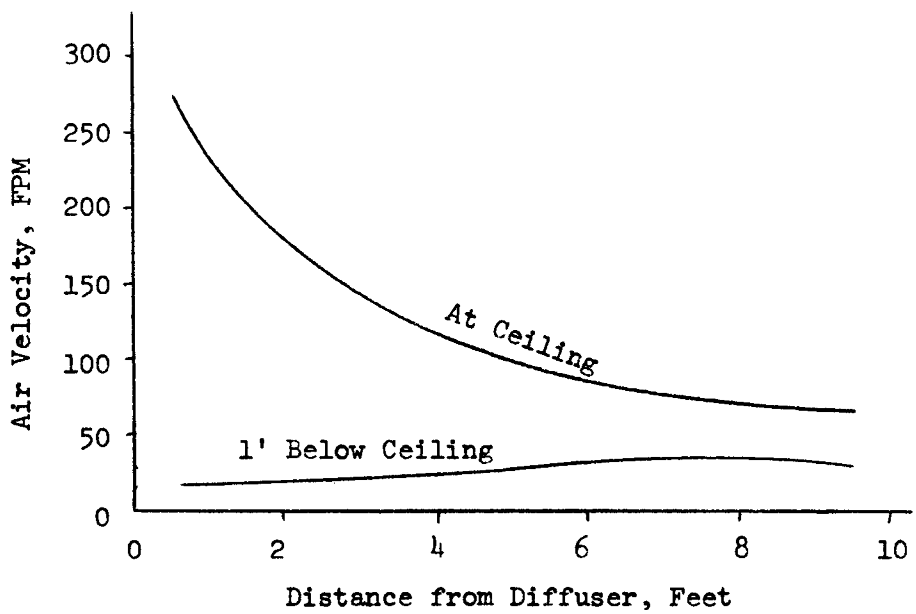


FIGURE 4-13 WALL MOUNTED SLOT DIFFUSER
TEST ARRANGEMENT AND PERFORMANCE DATA

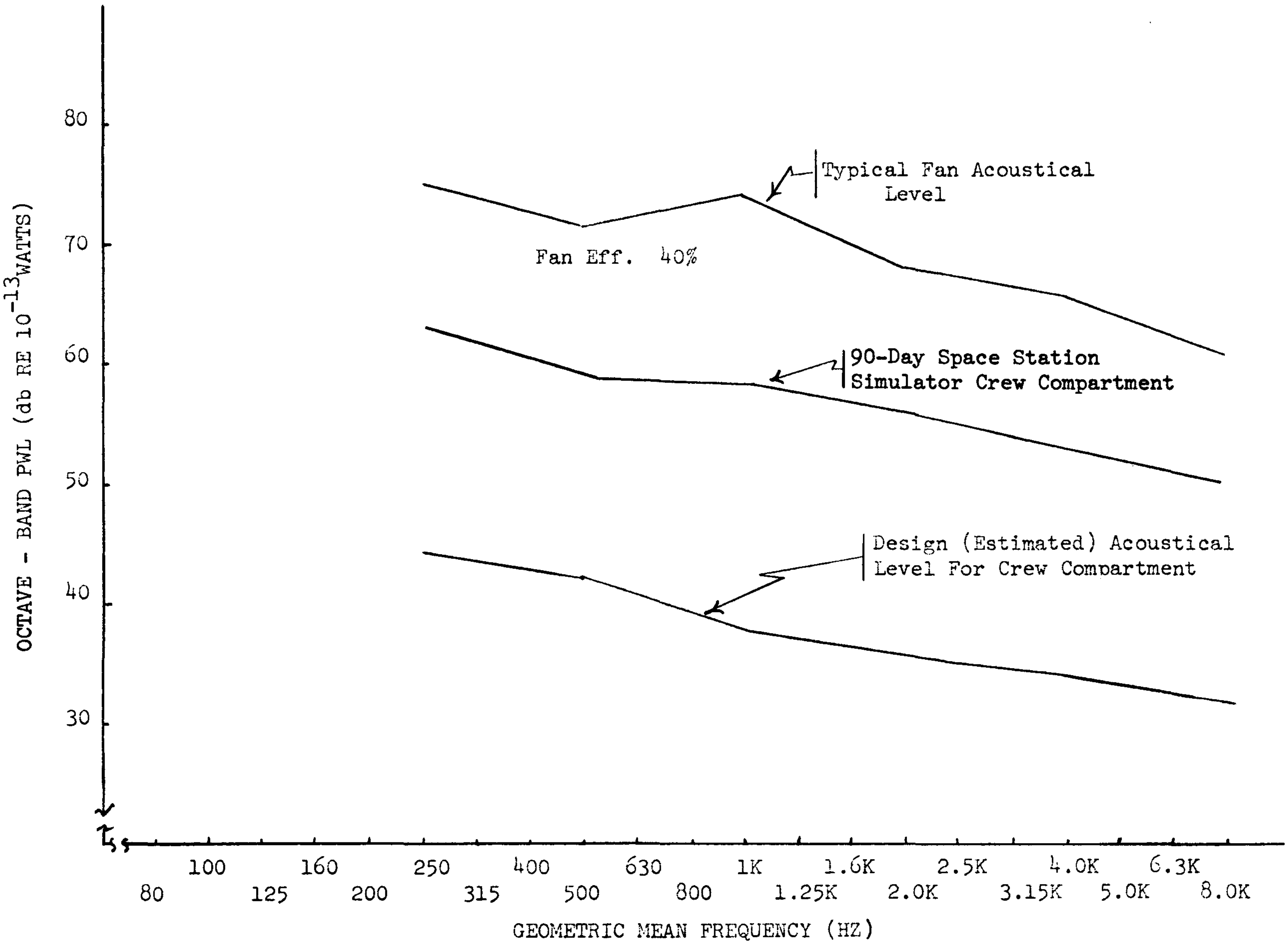


FIGURE 4-14 SOUND LEVEL VERSUS FREQUENCY

3) Design sound level would not be below that identified on Figure 4-14. (Note: Design level should be considered an estimate of acoustical requirements for good speech communication.)

The analysis was based on a typical crew compartment since excessive noise would probably be most objectional in that area.

Table 4-1 indicates the extent to which sound from a typical fan is attenuated as it moves through the distribution system to a crew compartment. Some portion of all the entering sound is lost in each segment of the distribution system. However, primary losses occur at the elbows which act as sound traps. The attenuation obtained from bare ducts is greater in the low frequency ranges than in the higher ranges. Bare duct attenuation consists basically of the transfer of sound energy to the duct walls, the reflection of sound energy at the openings (ex., diffusers and branch take-off), and the sound reflection due to turns or elbows. Air flow generated sound due to turbulences in elbows, vanes and take-off has also been calculated and is shown on Table 4-1. Its sound level over the frequency band is below that created by the fan and will be attenuated in the untreated duct system. Air flow generated sound at the low velocities, therefore, will not be a factor in the overall sound level of the crew compartment.

The added attenuation needed to achieve the estimated level for good speech communication can be had by installing duct lining before and after elbows (i.e., 18" at entering and exit of elbow) and locating sound traps on the return and supply side of the blower (Reference 4-3). Duct lining is most effective in the middle frequency range which is also the speech frequency range (600 - 4800 CPS). Duct lining usually offers a maximum attenuation in the middle frequency range with a minimum of weight and volume. Table 4-1 shows the reduction in db for duct lining over that for the duct system with no lining. Sound traps can be designed to accomplish the remaining needed attenuation. Figure 4-15 indicates the required attenuation which must be obtained from sound traps along with the achievable attenuation from a 12-inch long sound trap. The system trade-off studies included allowances for weight and volume requirements of duct lining and sound traps.

TABLE 4-1

SOUND ENERGY ATTENUATION WITHIN DISTRIBUTION SYSTEM SUPPLYING CREW COMPARTMENT

	BAND MID - FREQUENCY (CPS)					
	250	500	1000	2000	4000	8000
Typical blower SPL db (Re 10^{-13} watts)	75	70.5	73.5	67.5	65.5	60.5
Duct System Attenuation						
Vaned elbow Air outlet reflection Duct walls	22.4	19.6	17.6	18.6	18.6	17.6
SPL @ crew compartment outlet without acoustical attenuation	52.6	50.9	55.9	48.9	46.9	42.9
Estimated max. SPL required for good speech communication	44.0	42.0	38.0	36.0	34.0	32.0
Required attenuation	8.6	8.9	17.9	12.9	12.9	10.9
Air flow generated sound						
Air outlet Vaned elbows Duct turbulences	17.4	12.6	10.6	9.6	9.6	9.6
Required attenuation if duct lining ahead and after elbow is utilized.	5.0	5.9	11.9	6.9	4.9	-

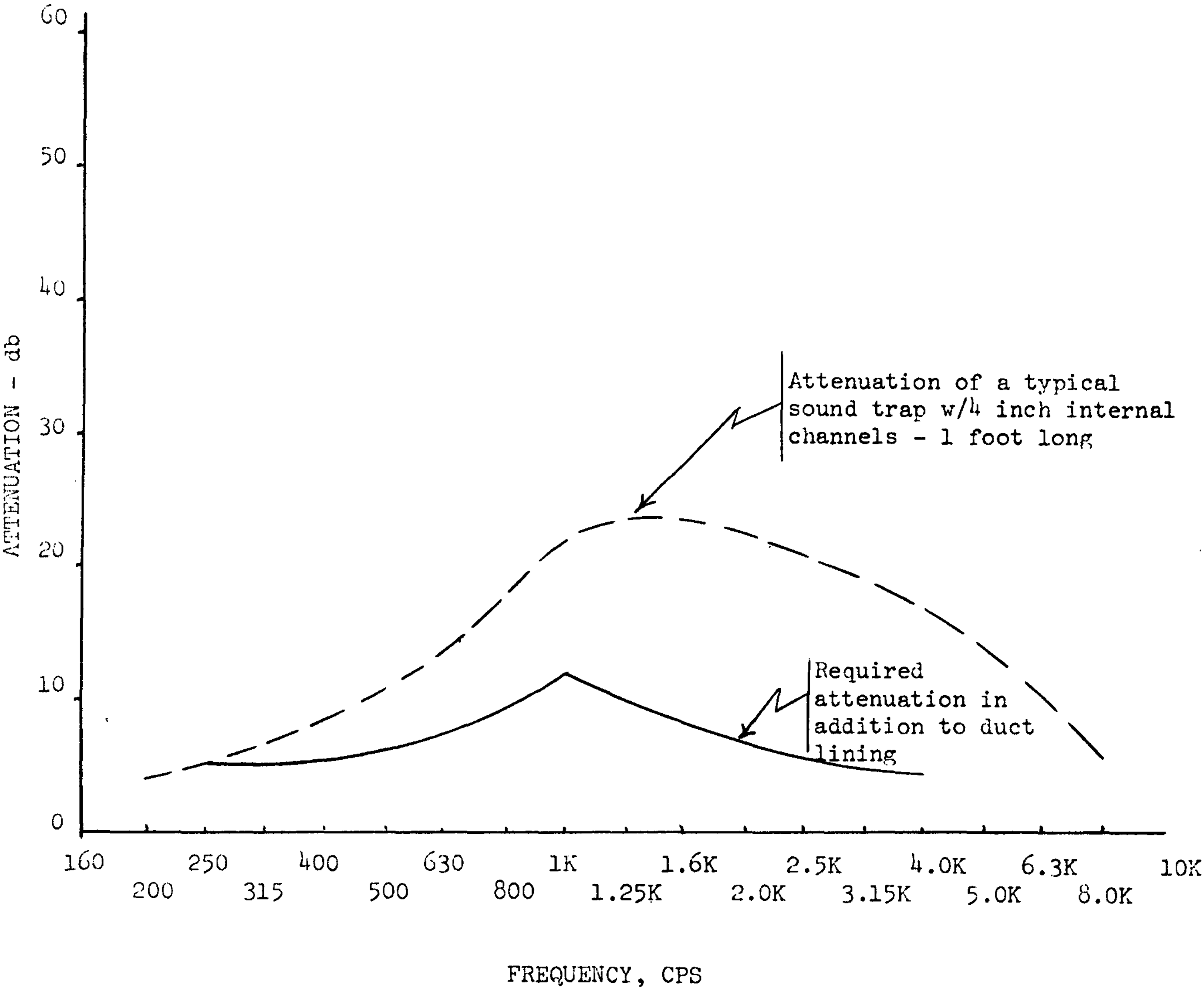


FIGURE 4-15 TYPICAL SOUND TRAP ATTENUATION

System Controls

A simplified automatic control technique resulted from the multiple zoning arrangement utilized for each module of the space station. The elimination of heat exchanger coolant fluid controls, made possible by use of modulating controls for mixing of cooled and bypassed atmosphere for each zone, minimized possible maintenance and improved system reliability.

Control Function

Each space station module is separated into eight (8) temperature conditioning zones for purposes of control. These eight (8) zones are comprised of crew compartments (six (6) zones), remaining area of deck 1 and 3 (one (1) zone), and deck 2 or 4 (one (1) zone). The two large zones (i.e., remaining area of deck 1 or 3 and deck 2 or 4) each have several heat detectors connected in series which by balancing or unbalancing a bridge network create signals causing accurate modulating of the face and bypass dampers located on the central thermal conditioning unit.

Several detectors in series are utilized to provide improved zone temperature control and enable more accurate sensing of the representative conditions. Figure 4-16 indicates the control schematic for the remaining area of deck 1 or 3 where two electronic heat detectors are utilized, each with 50% authority. The control schematic for deck 2 or 4 is shown on Figure 4-17. It utilizes four (4) electronic heat detectors each with 25% authority. One electronic heat detector is located in each of the three laboratories with the remaining electronic heat detector located at the return atmosphere intake.

Each crew compartment is treated as a separate zone which allows individual selection of temperature. Both conditioned and bypassed atmosphere is supplied to the crew compartment diffuser plenum which has dampers under control of the compartment heat detector. Figure 4-18 shows a typical crew compartment control schematic.

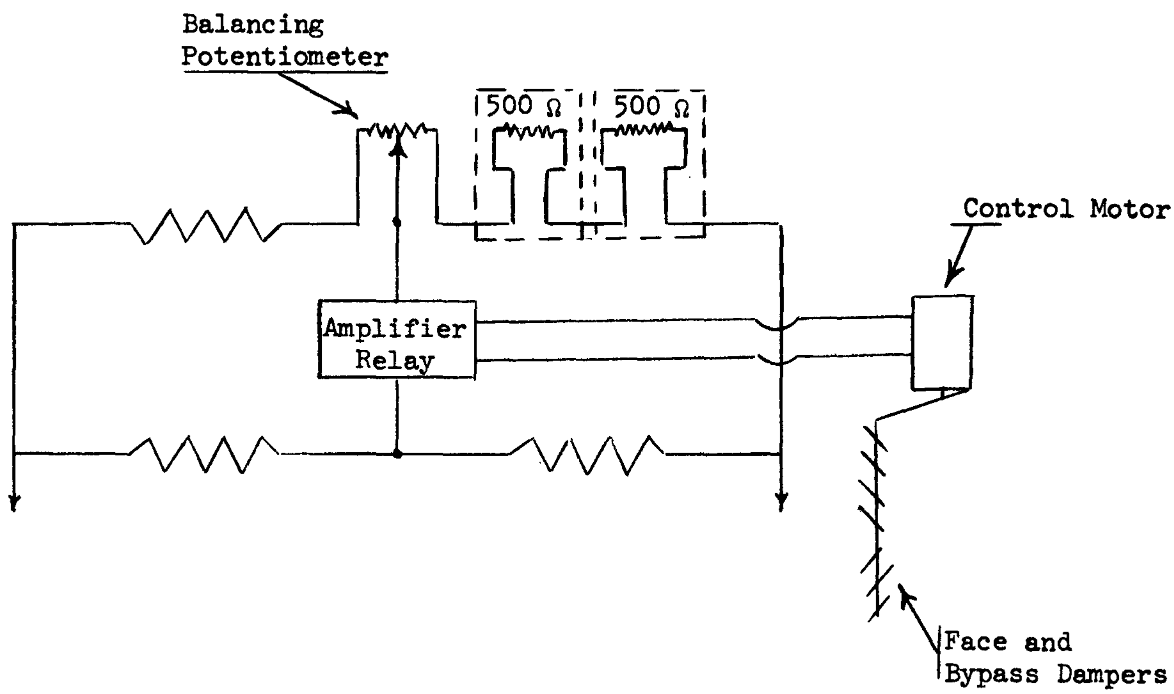


FIGURE 4-16 TYPICAL CONTROL SCHEMATIC FOR DECK 1 OR DECK 3 EXCLUDING CREW COMPARTMENT

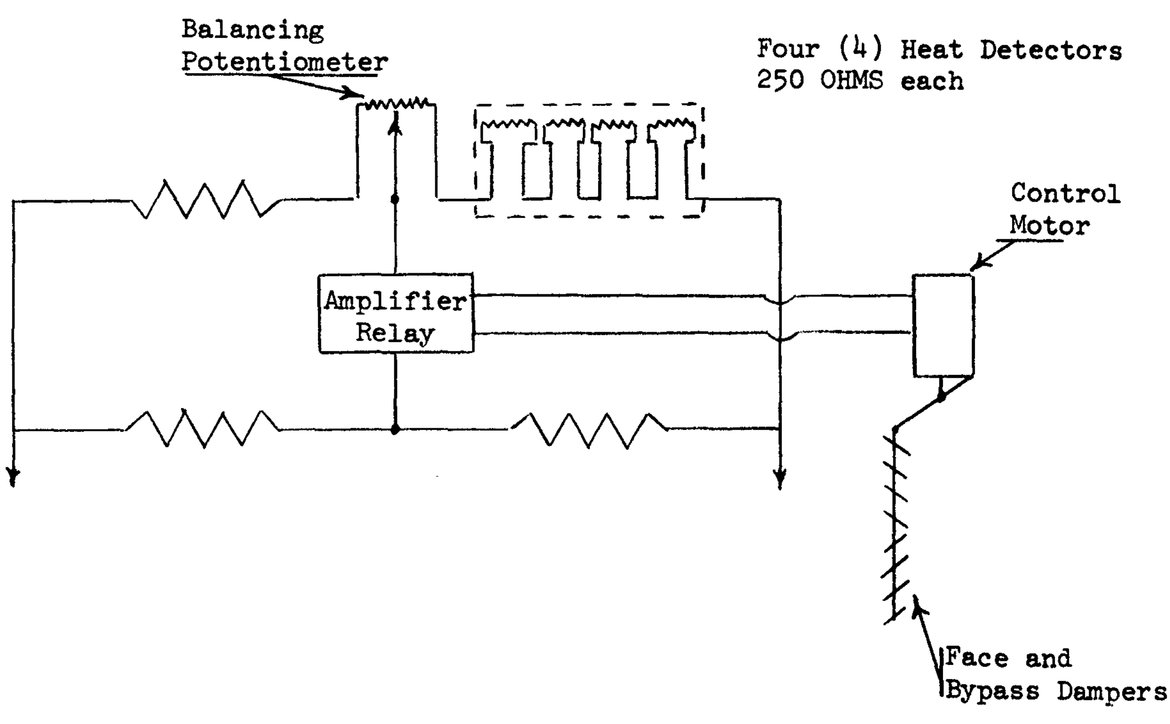


FIGURE 4-17 TYPICAL CONTROL SCHEMATIC FOR DECK 2 OR DECK 4

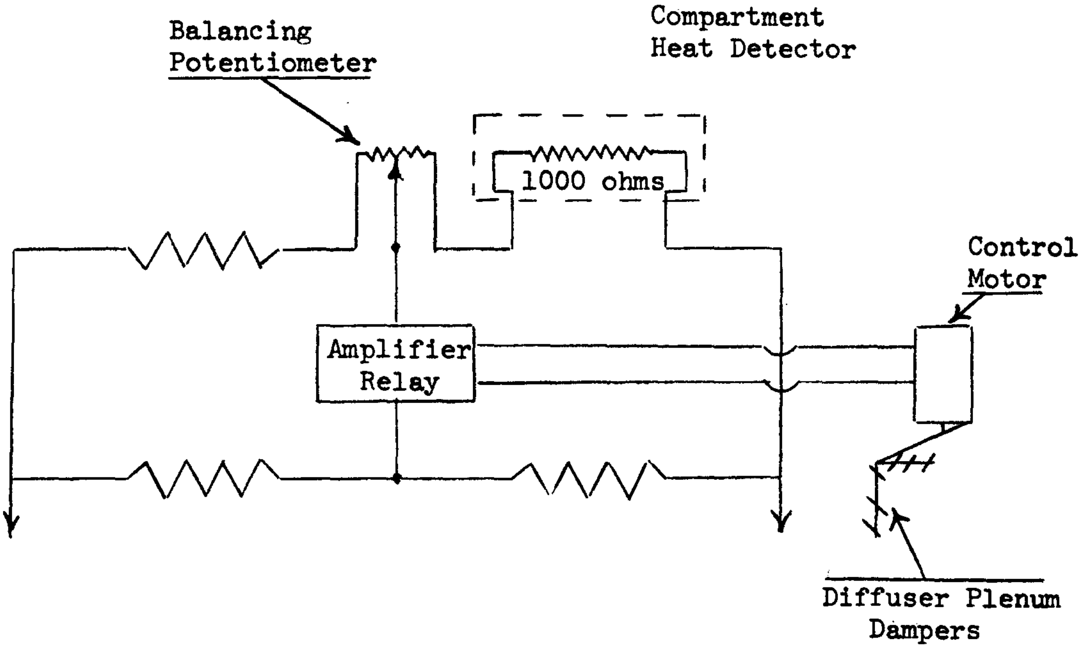


FIGURE 4-18 CREW COMPARTMENT MODULATING CONTROL SCHEMATIC

Types of Controls

Several types of controls exist which would provide proportional operation. However, only two types will meet the constraints imposed by the space station application. These constraints are: 1) Provide accurate measurement and rapid response to small changes in the control variable, (2) provide a means of adjustment in each zone to permit changes in the control variable, and 3) provide high reliability over long periods of time. The two types which meet the constraints are 1) modulating electric circuits and 2) modulating electronic circuits. Both types appear to some degree to meet the guidelines of adequate accuracy, rapid response, remote adjustability and good reliability. However, modulating electric circuits have the disadvantage of moving parts in the controller. Modulating electronic circuits do not have this disadvantage and appear well suited for the space station application. In addition, electronic controls operate on an error signal where the gain of the system determines the amount of error required to provide full output of the controller. High sensitivity is achieved by increasing the amplifier gain. The advantages of the modulating electronic over the modulating electric are as follows:

- Heat detectors provide rapid response due to low mass in addition to having no moving parts.
- Several heat detectors can be installed in series to provide averaging for large zones.
- High reliability solid state components can be utilized in the amplifier or relay part of the circuit.

Maintainability

System design has stressed high reliability and easy maintainability of all components. Component differences between the two modules were kept at a minimum to reduce the number of spares required and allow the greatest familiarity with the equipment. The components which may require occasional maintenance include the blowers and controls. On rare occasions the mixing dampers may require attention and filters changed as ΔP instrumentation indicates. Their maintainability is discussed as follows:

Blowers

Since the system pressure drop for the two modules are different the blower performance must vary. In order to achieve high reliability the blower would be designed for direct drive by use of a brushless motor. Module 1 and 2 blower pressure characteristics differ due to the increased system pressure drop resulting from bacteria filters. Between the two methods considered of achieving commonality it is felt that a blower design which uses identical housings and impellers but different motor sizes and speeds would provide the best reliability. The spare parts required would consist of two motors (one for each module) and a spare housing and impeller.

Controls

Each zone controller and its associated bridge network will be located in an accessable area within the zone. Any failure will only effect that zone. Controlled devices (i.e., motor operators) are located on the mixing dampers at the front of the central station unit or in the case of the crew compartment at the diffuser plenum dampers. Easy access to this area is provided. Commonality of components will exist as follows:

- All eight (8) motor operators are identical
- All bridge and amplifier relays are identical
- Controller (heat detectors) types are limited to three (3)

The ECLS compartment design, Figure 4-5, enhances maintainability by placing all items which will not require maintenance such as ducts and sound traps at the rear of the compartment, while the blower, heat exchanger, damper controls, etc., are placed at the front immediately facing the access doors.

EFFECTS OF ATMOSPHERE PRESSURE CHANGE

System design calculations were made based on a pressure of 14.7 PSIA within the Space Station and its inner tunnel. However, design allowances were made throughout the study to enable system operation at 10 PSIA while processing the same mass flow. At reduced pressure a higher volume flow results which affects the performance of the fans, diffusers and central station section of the thermal conditioning system. Performance of subcomponents such as controls are not effected by a change in pressure.

The characteristic changes which will occur in atmosphere transport losses, acoustic properties and diffuser performance are discussed below.

Atmospheric Flow Pressure Losses

In order for the mass flow to remain constant in a fixed system with a reduced pressure the volume flow must increase. This increase for a 10 PSIA pressure over that calculated for a 14.7 PSIA pressure is approximately 45% as shown in equation (11).

$$\text{Vol. Flow @ 10 PSIA} = \frac{\left[\dfrac{q_s}{\rho \cdot C_p \cdot \Delta t}\right] \text{@ 10 PSIA}}{\left[\dfrac{q_s}{\rho \cdot C_p \cdot \Delta t}\right] \text{@ 14.7 PSIA}} \cdot \text{Vol. Flow @ 14.7 PSIA} \qquad (11)$$

Increased pressure drop occurs as the volume flow increases due to higher duct velocities. This is calculated for 10 PSIA operation relative to 14.7 PSIA in straight runs of ducts by equation (12). A similar calculation can be made for elbows and branch takeoffs. All calculations show an increase in head loss which approximates 44%.

$$\text{Head Loss} = \frac{f \ {}^{L}/_{D} \ \dfrac{V_a^{\,2} \cdot \rho}{2g} \text{ @ 10 PSIA}}{f \ {}^{L}/_{D} \ \dfrac{V_a^{\,2} \cdot \rho}{2g} \text{ @ 14.7 PSIA}} \cdot \text{Head Loss @ 14.7 PSIA} \qquad (12)$$

Fan Characteristic Changes

Fan power and impeller speed must increase if the same fan is used for the 10 PSIA application as was used for 14.7 PSIA. Fan speed must increase by a factor of 1.5 and power by a factor of 2.25 (Reference 4-4).

Diffuser Performance

Pressure loss thru the diffuser though small is increased due to the higher velocities at 10 PSIA pressure. The throw or radius of diffusion is also increased. These changes are approximated as follows:

Pressure drop - Increases 40-50%

Throw or Radius of Diffusion - Increases 20-50%

[Note: Based on diffuser manufacturer's data (Reference 4-1).]

Acoustic Characteristics of the Chamber

In general, sound pressure level decreases with a decrease in atmosphere pressure for a fixed system (i.e., a system utilizing constant velocity with no change in blower speed). The decrease would be directly proportional to the change in mass density since the speed of sound remains essentially constant. However, in a system where a constant mass flow is required for heat removal, higher velocities in the ducts and higher fan speeds result which creates increased noise. Sound pressure level for air flow generated sound at the lower pressure will increase by approximately 10 db and blower noise by approximately 8 db. Based on this the crew compartment will have only a slight increase in sound pressure level at most.

Emergency and Out-of-Tolerance Operations

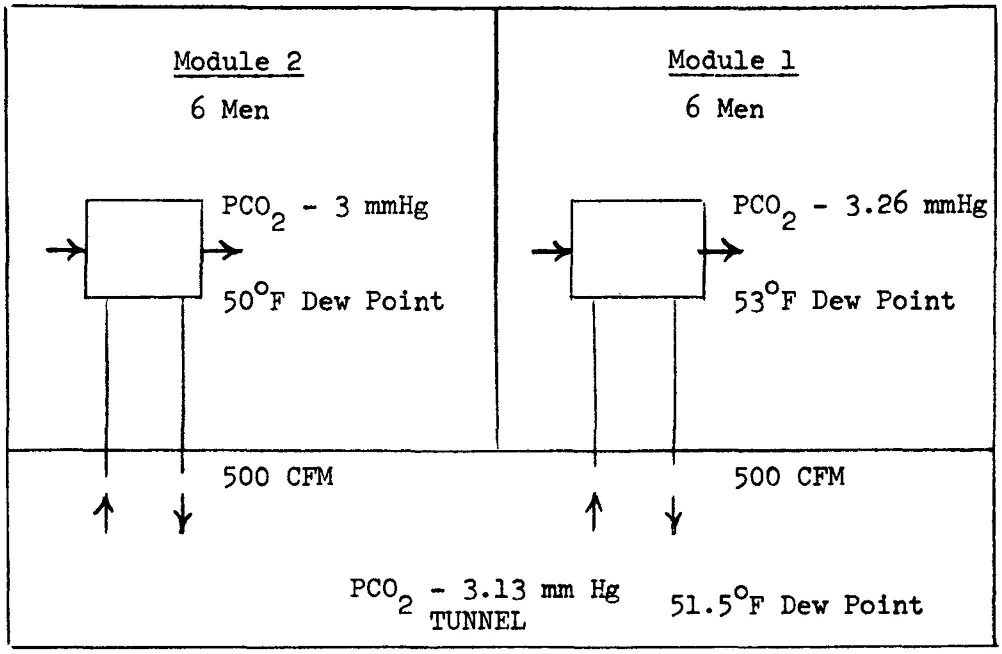
In the Baseline Space Station design, a small flow of conditioned atmosphere is continually supplied to the tunnel to prevent contaminant buildup and to remove the small amount of heat generated there. This conditioned atmosphere enters the ventilation assembly and is mixed with ventilation atmosphere and distributed in the tunnel. Normally, little equipment is operating in the tunnel and crew activity is limited to inter compartment passage and minor repair activities. Therefore only a limited amount of tunnel atmosphere conditioning is necessary. For emergency cases, (one water loop inoperative in one compartment or 12-men taking refuge in the tunnel), the following procedure is required.

A damper valve at the ventilation fan inlet is positioned to blow larger amounts of conditioned atmosphere into the tunnel from the humidity and temperature control assembly. This damper valve was not identified as a separate component in the Baseline design but requires a negligible amount of weight and no electrical power.

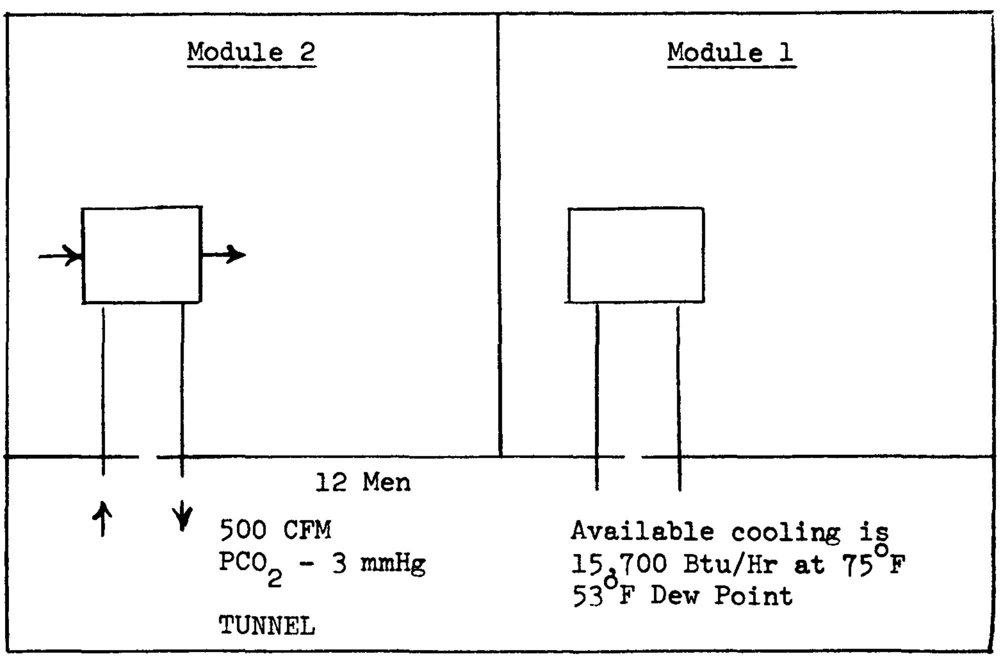
Figure 4-19 shows the expected atmosphere conditions during the emergency situations. Both ventilation assemblies operate during the inoperative water loop emergency. Conditioned atmosphere is blown into the tunnel by the ventilation assembly adjacent to the operating EC/LS and the tunnel atmosphere is interchanged with the disabled module atmosphere by the other ventilation assembly. When operating in this mode, the normal CO_2 level is exceeded by a small amount, 0.26 mm Hg, and humidity is well within acceptable limits. Adequate cooling will be available in the disabled module because of inoperative water loop will require shutdown of cold plated electrical equipment. Therefore, a reasonable environment is provided for six men sleeping in the compartment with an inoperative cooling loop. Additional cooling capacity is available in the compartment with the operating water loop by increasing the flow rate.

During emergency tunnel occupancy by all 12 crewmen, the ventilation assembly adjacent to the operating EC/LS is operated. Figure 4-19 also shows that the normal CO_2 level is only slightly exceeded, humidity is within normal limits. Available atmosphere cooling is 10,700 Btu/hr at $75^{\circ}F$ which should be more than adequate.

FIGURE 4-19 MODULE CONDITIONED AIR INTERCHANGE



EMERGENCY CONDITIONS FOR INOPERATIVE WATER LOOP



EMERGENCY CONDITIONS FOR 12 MAN LOADING IN TUNNEL
WITH 1 EC/LS OPERATING

REFERENCES

4-1 Anemostat Draftless Aspirating Air Diffusers, Selection Manual No. 60-1957, Anemostat Corporation of America, New York, New York. 1957.

4-2 Memorandum Between J. B. Sterett and Brooksbank at George C. Marshall Space Flight Center, Huntsville, Alabama, Dated June 20, 1969, I. D. No. S&E-ASTN-ADV-69-14.

4-3 Harris, Cyril M., Handbook of Noise Control, McGraw-Hill Book Co. Inc., New York, New York, 1957.

4-4 Jorgensen, Robert; Fan Engineering, 6th Edition, Buffalo Forge Company, Buffalo, New York, 1961.

SECTION 5.0
TESTING

TEST PLAN

This section discusses two test plans which have been outlined as a part of the study. One test plan will provide for full-scale mockup testing of the ventilation system design. The other test plan outlines a scaled-down test program utilizing only one deck of the mockup and substitutes analytical modeling of the remaining deck using the G-189 computer program. Correlation of any testing done would be made with pretest prediction developed from a math model.

Recommended 33-ft. Diameter Space Station Mockup Test

Table 5-1 outlines a test program utilizing the full-scale mockup as a test bed to validate the system design concept. Commercial components of the same design would be substituted for flight hardware in equipping the mockup. The test is designed to map the atmospheric movement rate, measure temperature gradients at various simulated loads, measure trace gas levels in dead volume area, and measure the sound pressure level in habitable areas.

Generalized Space Vehicle Ventilation Tests

Due to declining support for the 33-foot diameter space station concept, it is recommended that the follow-on test program be modified to a design verification test of several of the key concepts developed during the present study. The following test program can take advantage of the existing space station mockup as a test bed. The program may be carried out using only the first deck with only slight modifications and will not require unstacking the decks.

FIGURE 5-1 VENTILATION TEST PLAN OUTLINE FOR FULL SCALE MOCKUP

Section 1 INTRODUCTION

1.1 Program Objective
1.2 Program Organization
1.3 Program Schedule
1.4 Thermal Conditioning System Design for Space Station Mockup
1.5 Pre-Test Predictions

Section 2 TEST OPERATING PROTOCOL

2.1 Test Operating Staff
  2.1.1 Test Supervision
  2.1.2 Data Collection Engineer
  2.1.3 Technician
2.2 Test Supporting Staff
2.3 Safety Rules

Section 3 TEST EQUIPMENT AND SUPPORT FACILITIES

3.1 Space Station Mockup Preparation
  3.1.1 Unstack Decks
3.2 Component Evaluation and Procurement
  3.2.1 Performance
  3.2.2 Acoustical
3.3 Flight Design Thermal Conditioning System Installation
  3.3.1 Deck 1
    Subfloor Duct to simulate 13 ACCC
    Subfloor plenum and baffles to simulate 13 ACCB and 13 AR
    13 AC Ducting
    13 ACCC Ducting
    Diffusers, Dampers and Controls
  3.3.2 Deck 2
    Ducts to simulate 2 BC and 2 CC
    Ducts to simulate 2 AR including Bacteria Filters
    Diffusers, Dampers, and Controls
  3.3.3 Deck 3
  3.3.4 Deck 4
    Ducts to simulate 4 BC and 4 DC
    Ducts to simulate 4 R
    Diffusers, Dampers, and Controls
  3.3.5 Air supply unit installed in ECLS Box
    Heat exchanger and damper
    Blower
    Sound mufflers

3.4 Support Facilities
    3.4.1 Electrical Power
    3.4.2 Refrigeration System

Section 4 INSTRUMENTATION AND DATA MANAGEMENT

4.1 Instrumentation Selection and Procurement
    4.1.1 Air velocity measurement devices
    4.1.2 Temperature gradient measurement device
    4.1.3 Duct mass flow measurement device
    4.1.4 Acoustical (Sound Pressure Level)
    4.1.5 Gas Analysis Equipment
4.2 Instrumentation Calibration
4.3 Instrumentation Installation
4.4 Instrumentation Signal Conditioning
4.5 Data Collecting and Processing Equipment
4.6 Test Data Logs

Section 5 PRE-TEST PROCEDURE

5.1 Operational Checkout
5.2 NASA Readiness Inspection
5.3 Pre-Test Procedure Report

Section 6 TEST

6.1 Velocity Profiles
    6.1.1 Isothermal velocity mapping to simulate zero gravity
    6.1.2 Controlled temperature velocity mapping with simulated thermal loads
6.2 Thermal gradients
    6.2.1 Thermal mapping in conjunction with 6.1.2
6.3 Mixing
    6.3.1 Investigation of simulated contaminant leak distribution
    6.3.2 Trace gas introduction and monitoring to investigate dead volumes
6.4 Noise
    Sound power measurements during various modes of system operation
6.5 Subjective
    Occupation and subjective comfort evaluation of system during controlled temperature tests

Section 7 FINAL TEST REPORT

7.1 Summary
7.2 Test Results and Processed Data
7.3 Test Conclusions

DESIGN CONCEPTS AND TEST APPROACHES

High Wall Slot Diffuser - The use of high wall slot diffusers with a long throw shows promise of good circulation over a large area with minimum ducting. This may be confirmed in its design configuration recommended in options 13 AC and 13 BC.

Floor Slot Diffuser - Floor diffusers may be advantageous where subfloor ducting or plenums are attractive from weight and volume standpoints. By mocking up one or two crew compartments such as proposed in options 13ACCC and 13ACCB, both plenum and duct fed diffusers, as well as mixing and distribution characteristics, may be determined.

Bacteria Filters on Return Grilles and Negative Pressure Room - Design criteria call for biochemical laboratories and medical facilities being isolated to prevent the possible spread of bacteria. The design concept to be verified involves maintaining a room at a slightly negative pressure and passing the return air through a bacteria filter. This may be accomplished in the waste management area of the mockup.

Distribution in Room with Only Return Air - The primary air required for ventilation may be reduced by utilizing the movement of return air in areas with small thermal loads, or those where a temperature somewhat higher than the rest of the deck may be desirable. The distribution provided by this approach may be evaluated by testing option 13 FR in the mockup.

Negative Pressure ECLS Box and Return System - Mockup and test system as described in Section 4.0.

General Tests for Above Concepts - Velocity distributions with isothermal simulation of zero gravity. Temperature distribution with simulated thermal loads. Trace gas introduction and monitoring to investigate dead zones. Subjective comfort evaluations.

Data obtained from testing the first deck would be correlated with pretest analytical predictions in order to develop an accurate math model. Utilizing the model both transient and steady-state studies would be made for the complete space station.

Correlations of Test and Design Data

Correlation of design data with test data will be made at the completion of the test program on atmosphere velocity, temperature level versus heat dissipated, temperature gradient, humidity level, trace gas level, and noise level. Each area of the space station listed will be correlated with predictions made for that area. The correlated data can then be used to develop an accurate math model which will serve to evaluate changes in design or determine off design operating conditions.

The method of correlation would consist of comparing the reduced test data with the calculated data. Indicated differences would serve as a flag causing examination of the test condition and the assumptions used in the analytical model. If the analytical assumptions used in the analysis were not supported by the test data, they would be modified to agree with the test. By comparing each data point, the test data will serve to update the analytical model.

COSTS

Preliminary costing was made for both the full-scale mockup test and the scaled-down test program. The breakdown of time and materials furnished below should be used for rough estimating only prior to development of a detailed test plan and procedure document.

FULL-SCALE MOCKUP TEST [FOUR (4) DECKS]

	Cost	Manhours
Design (Layout & Specification)		900
Fabrication		1300
*Materials	40,000	
**Instrumentation & Data Processing	18,000	
Testing		300
TOTAL -	$58,000	2500

GENERALIZED TEST [SCALED DOWN - ONE (1) DECK]

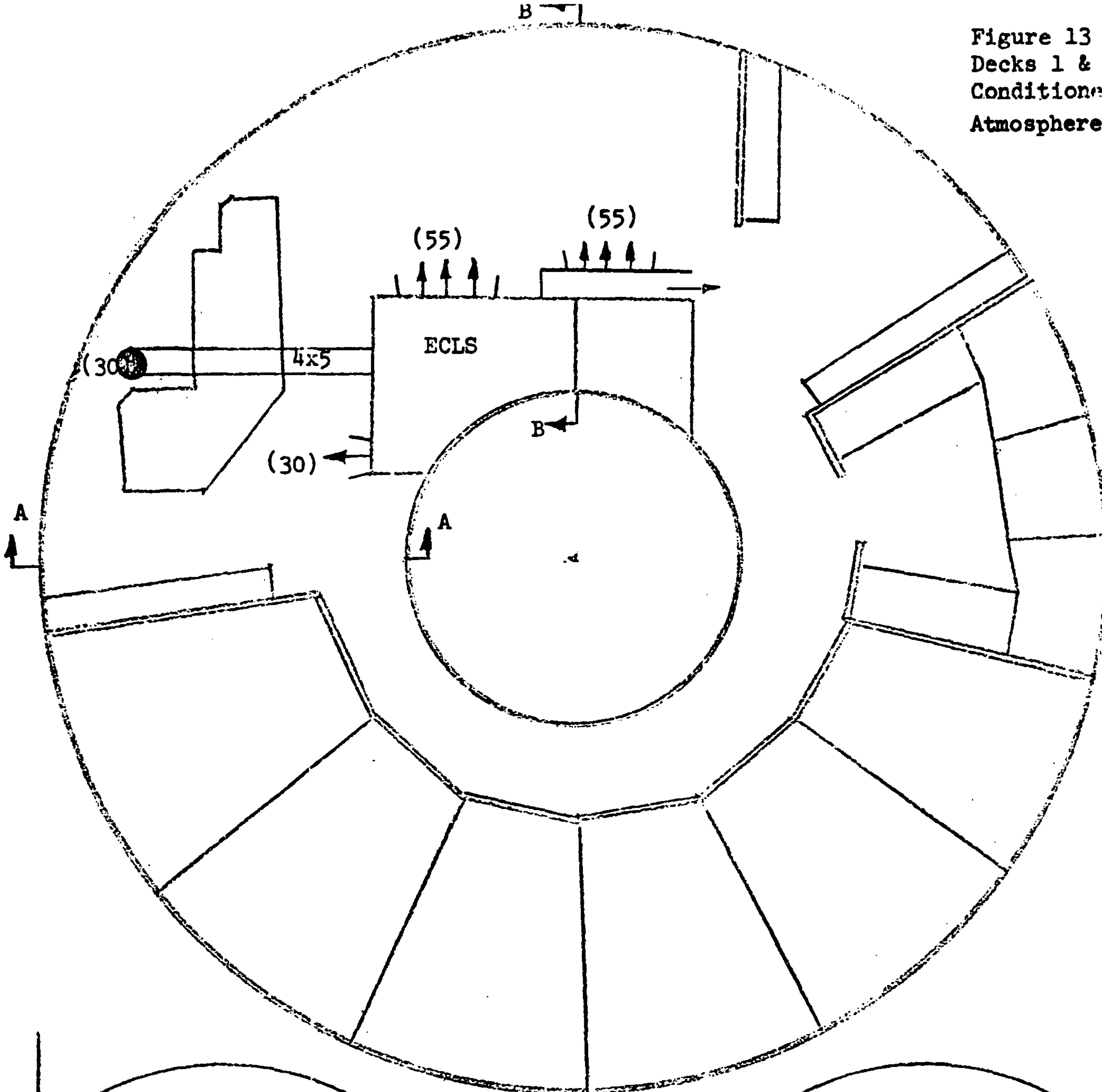
	Cost	Manhours
Design (Layout & Specification)		500
Fabrication		900
*Materials	18,000	
**Instrumentation & Data Processing	8,000	
Testing		200
TOTAL -	$26,000	1600

* Includes Blowers, Diffusers, Ducts, Filters, etc.
** Includes Hot Wire Anemometers, Thermocouples, Recorders, etc.

APPENDIX A

The configurations analyzed in making the trade-off studies are shown on the following figures. The trade-off studies are described in Section 3.0.

Figure 13 AC
Decks 1 & 3
Conditioned
Atmosphere



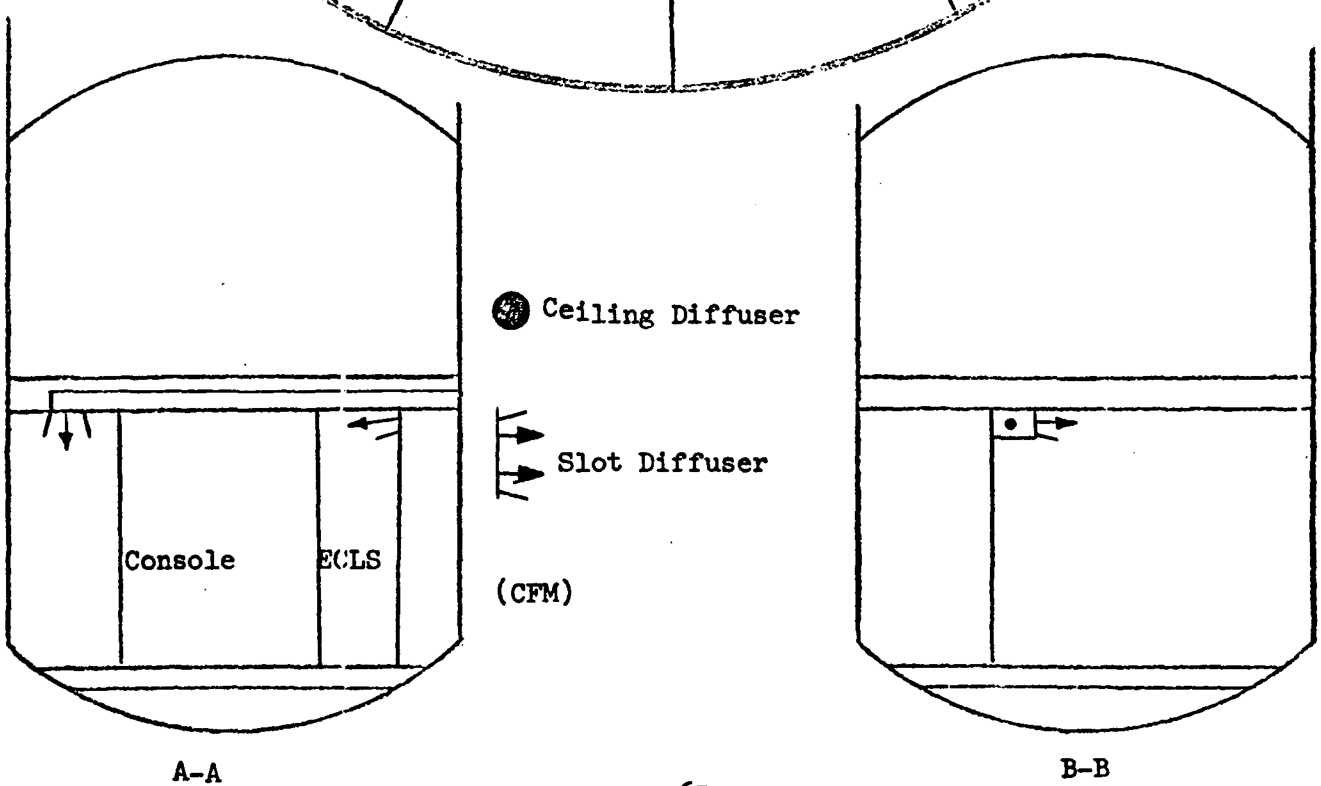


Figure 13 BC
Decks 1 & 3
Conditioned
Atmosphere

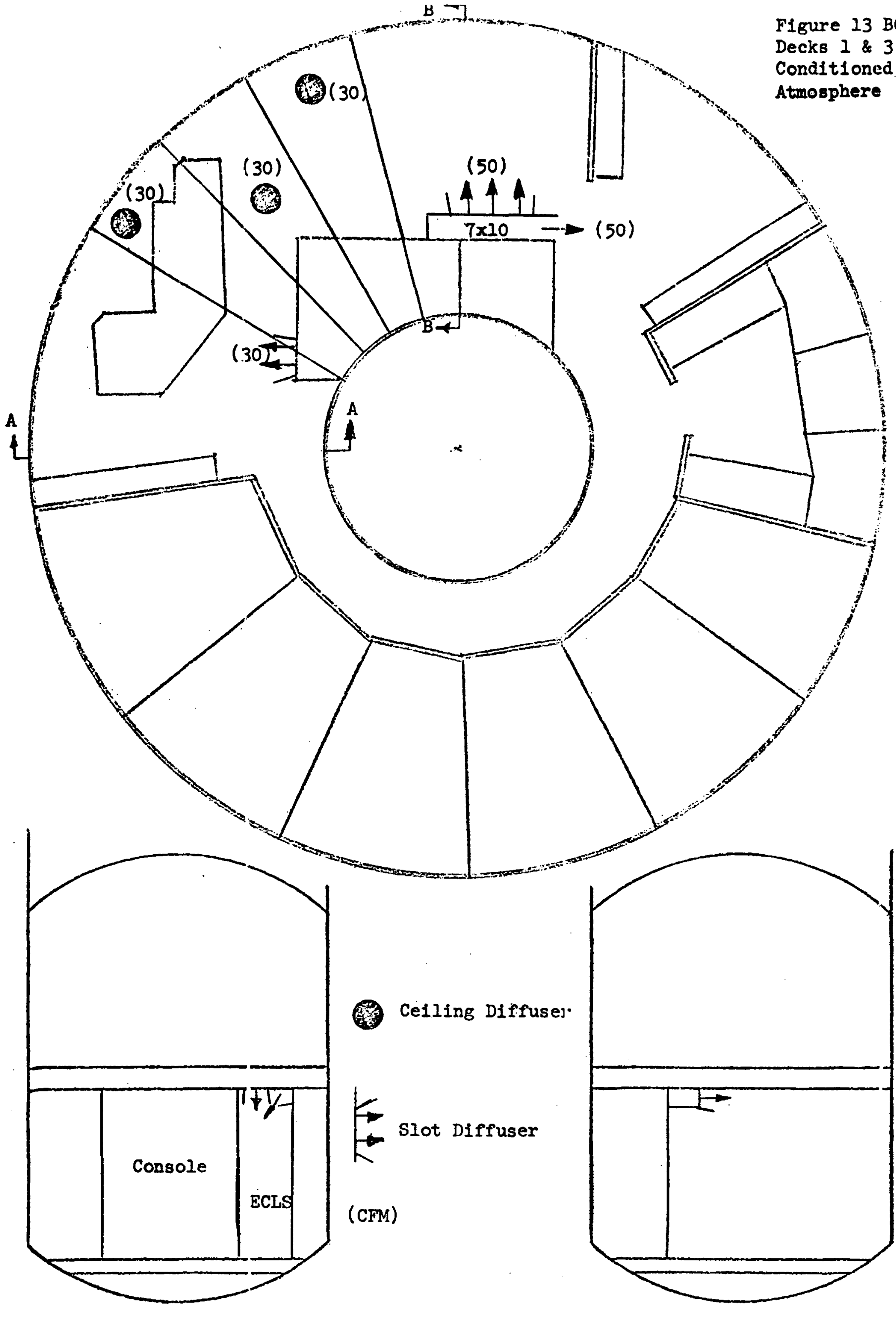


Figure 13 CC
Decks 1 & 3
Conditioned
Atmosphere

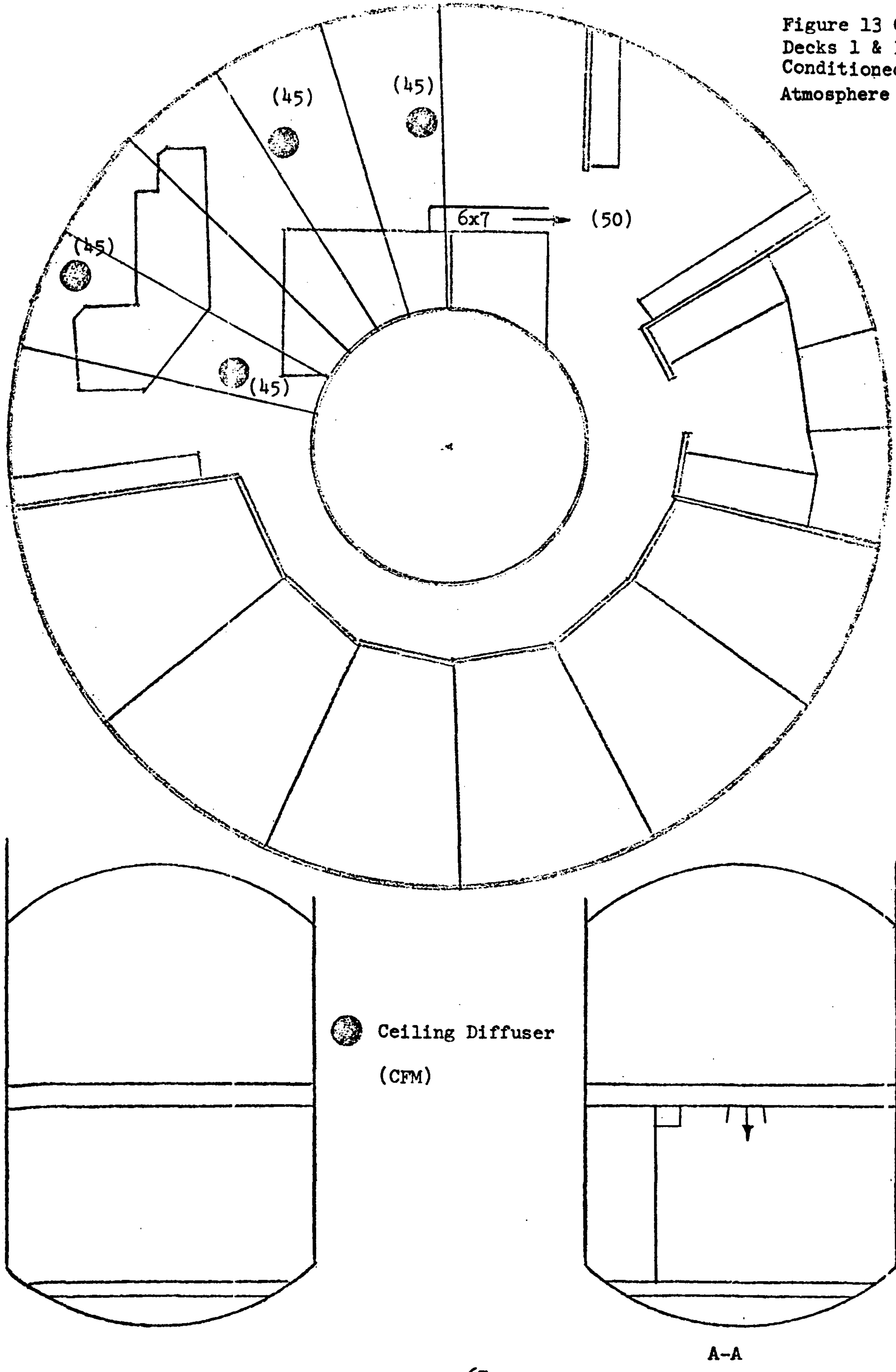


Figure 13 ACCC
Decks 1 and 3
Crew Compartment
Conditioned
Atmosphere

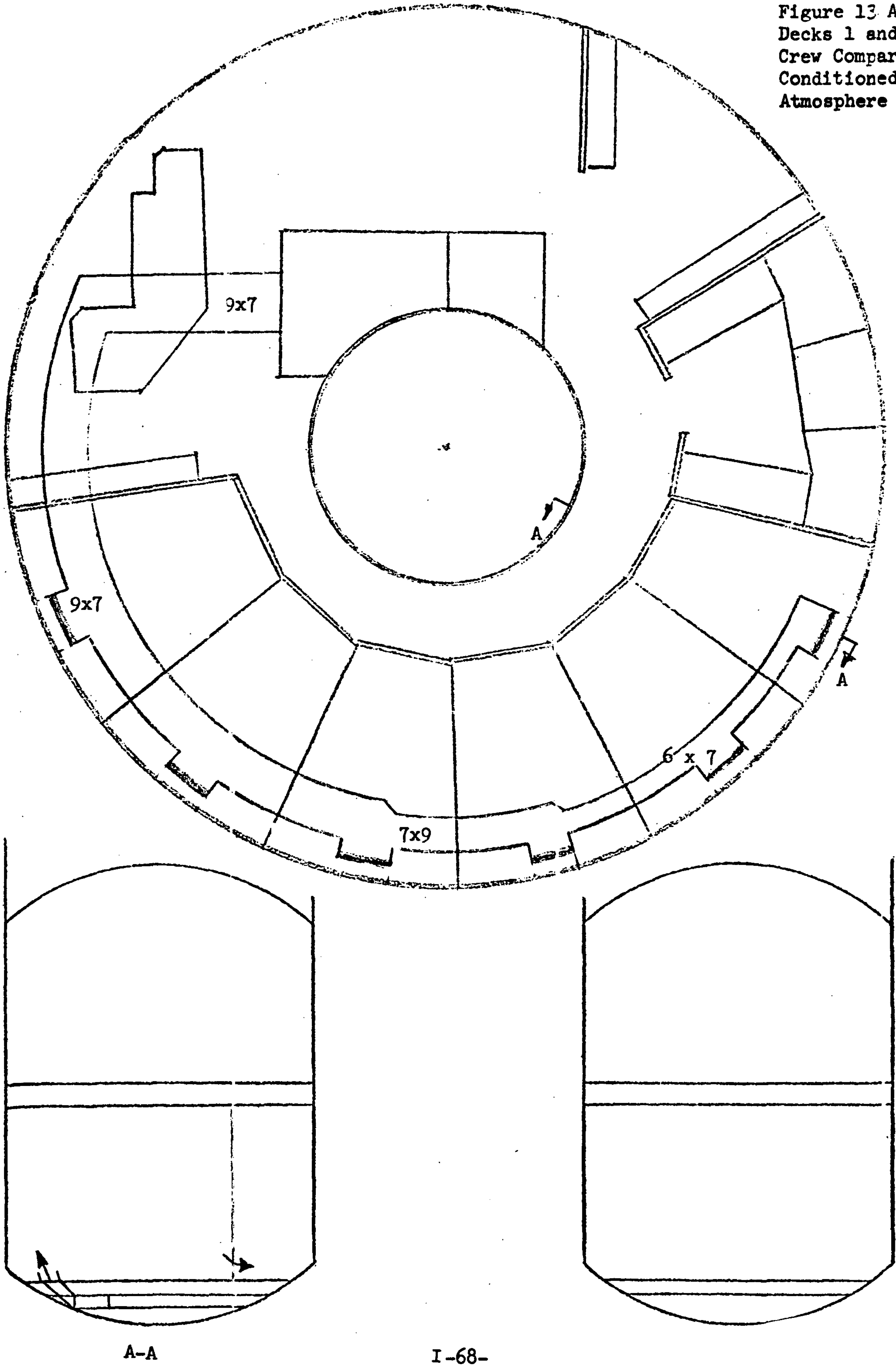


Figure 13 BCCC
Decks 1 & 3
Crew Compartment
Conditioned
Atmosphere

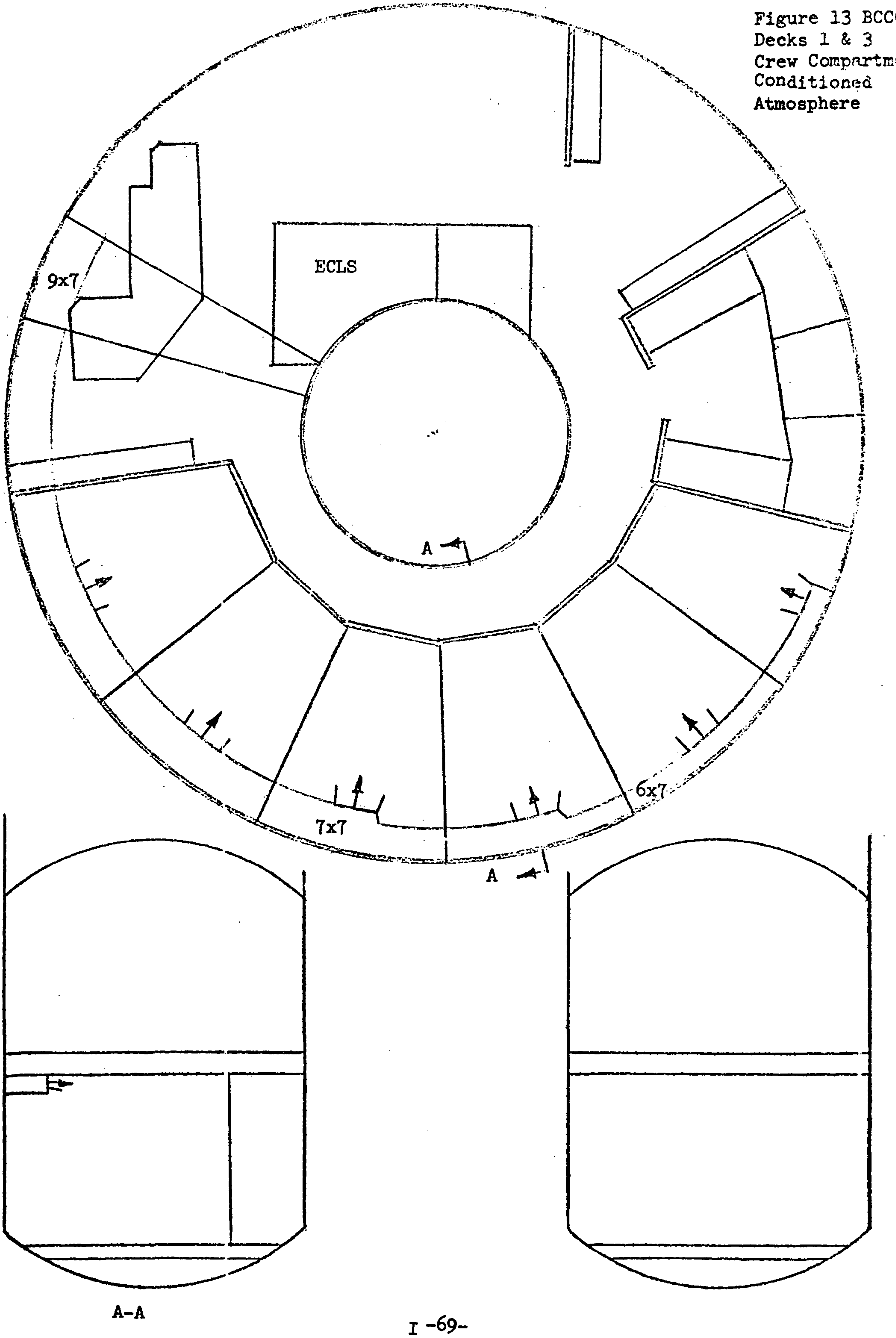


Figure 13 ACCB
Decks 1 & 3
Crew Compartment
Bypass Atmosphere
Pressurized Sub Floor
Plenum

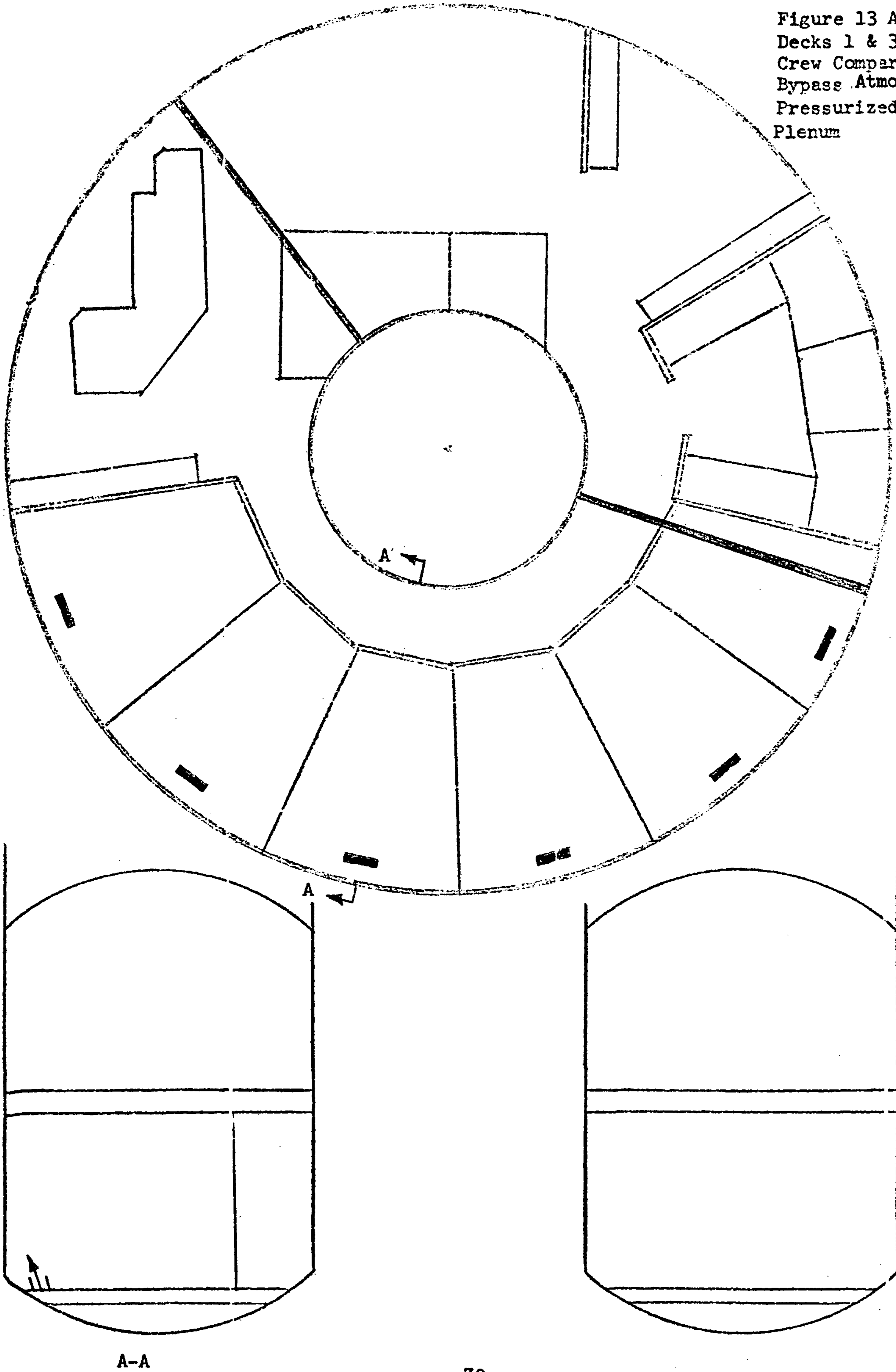


Figure 13 AR
Decks 1 & 3 Return
Sub Floor Plenum

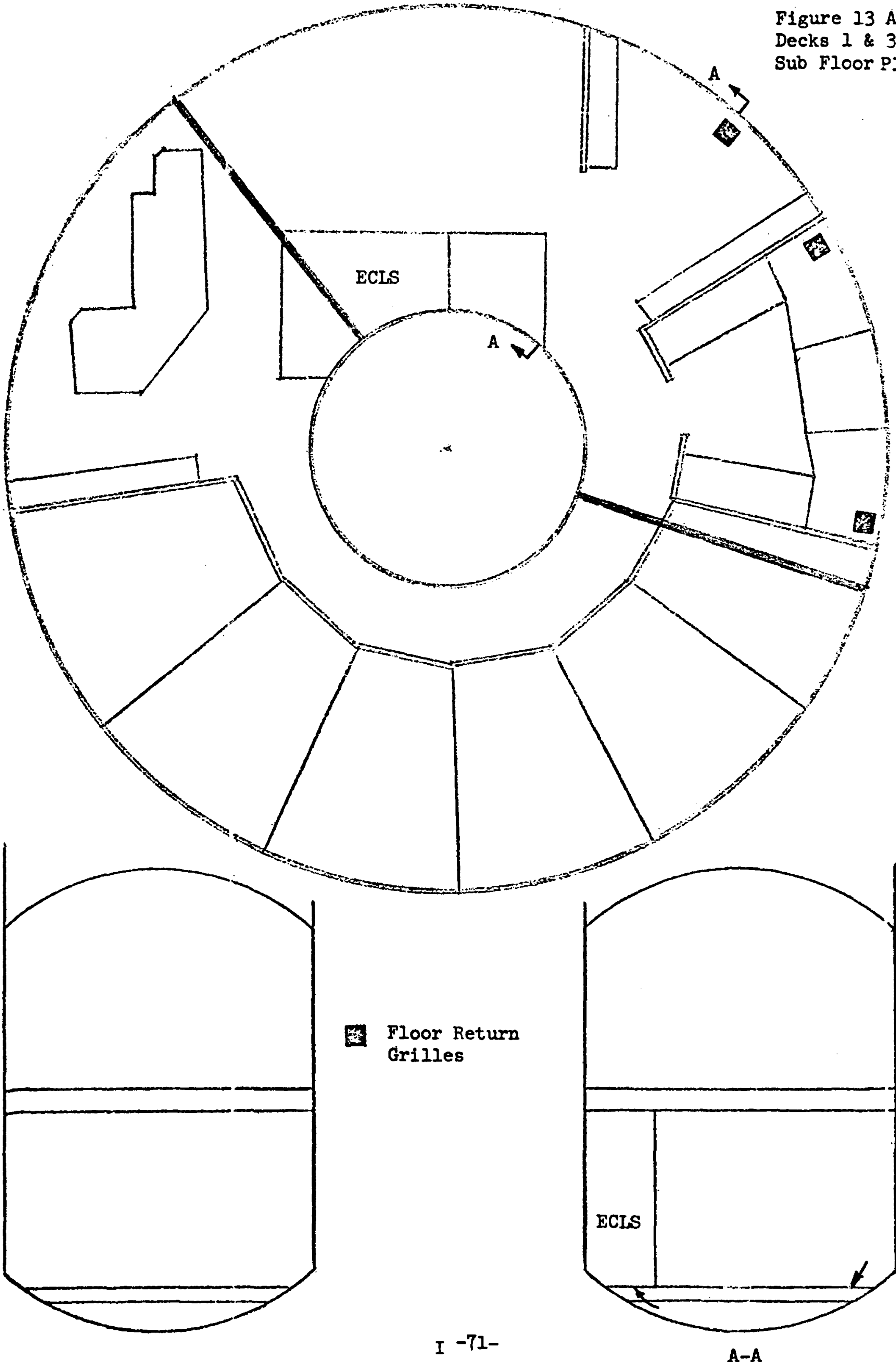


Figure 13 BR
Decks 1 & 3
Return

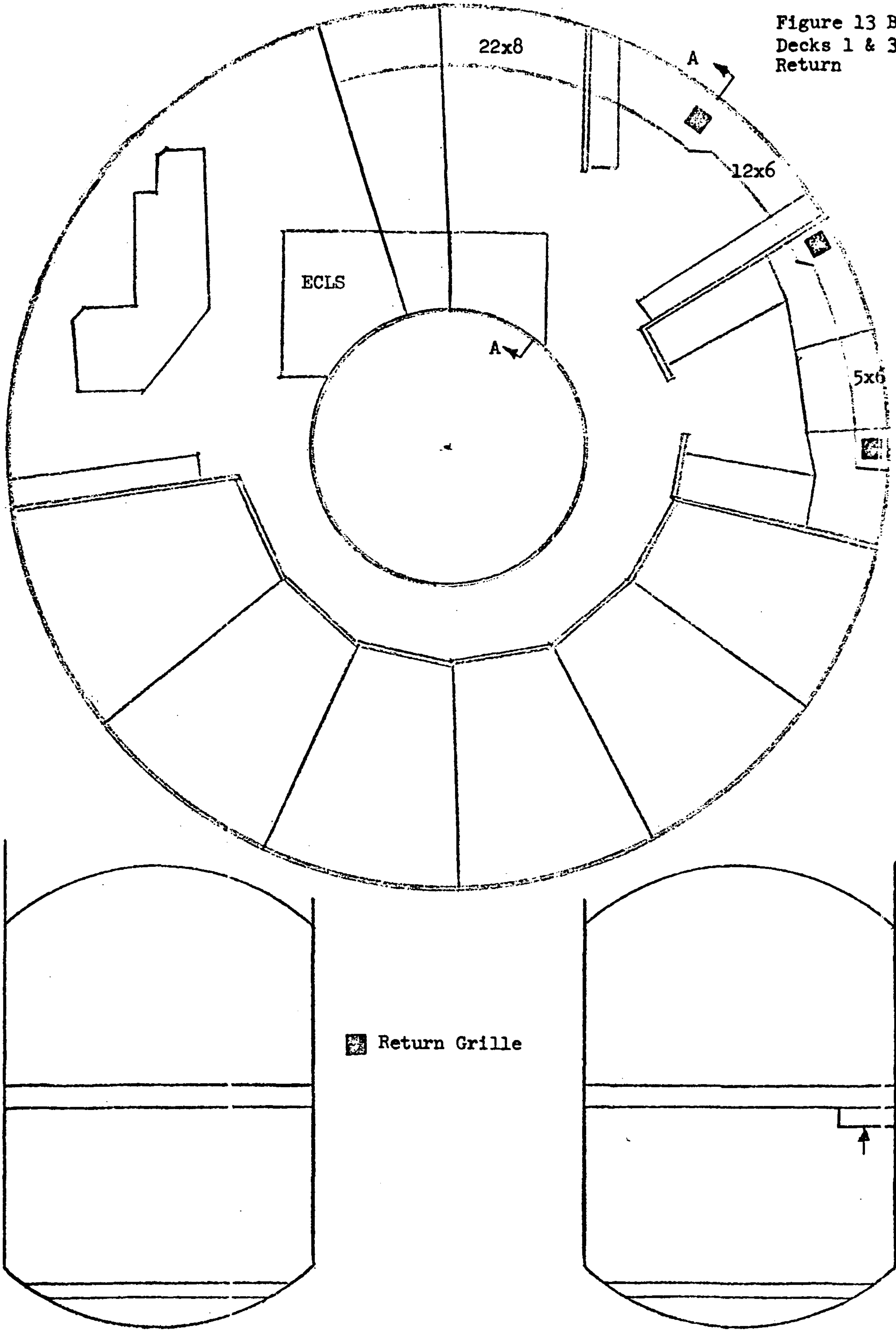


Figure 13 FR
Decks 1 and 3
Return
(Sub Floor Plenum,
Return from Deck 2)

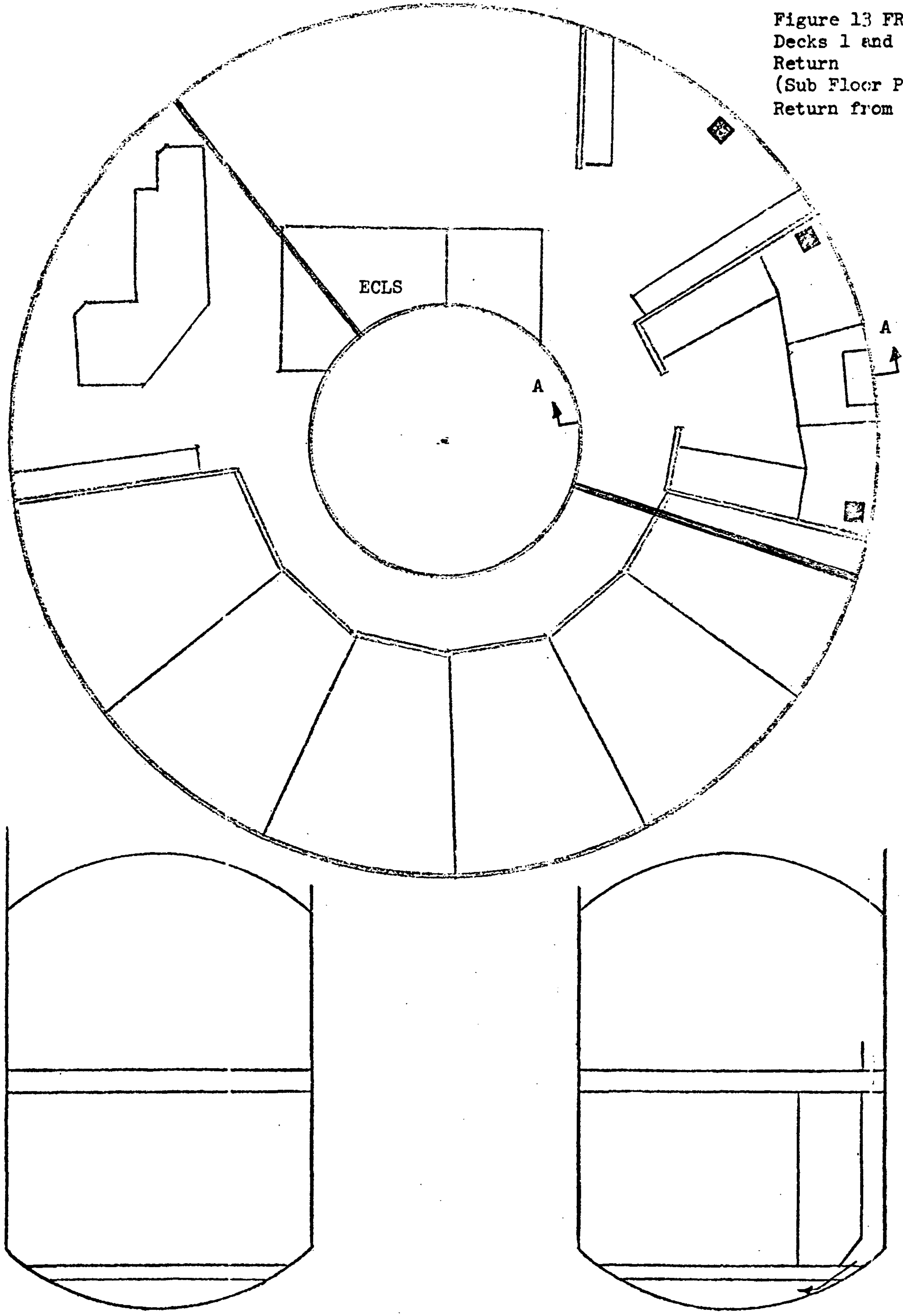
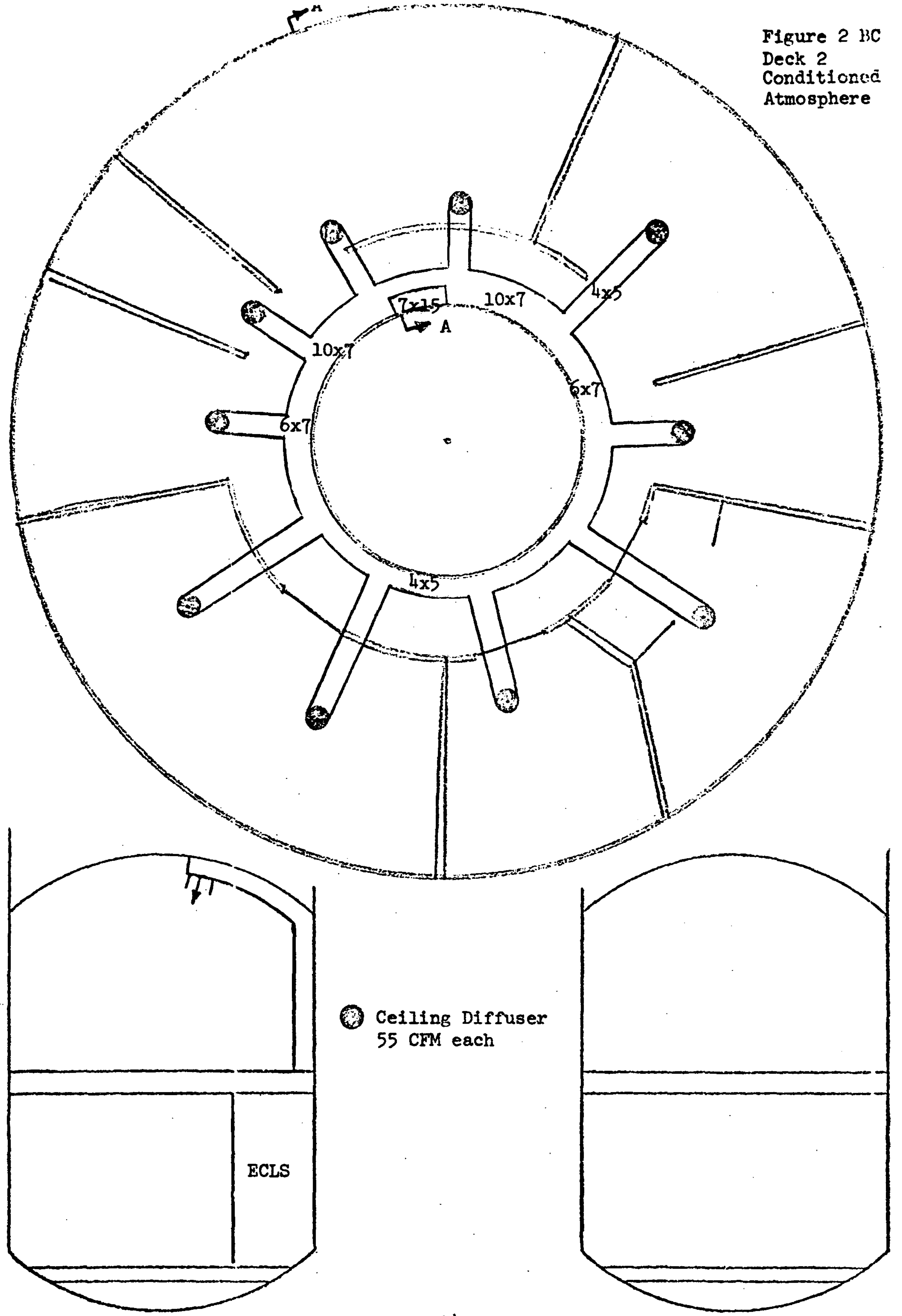


Figure 2 BC
Deck 2
Conditioned
Atmosphere



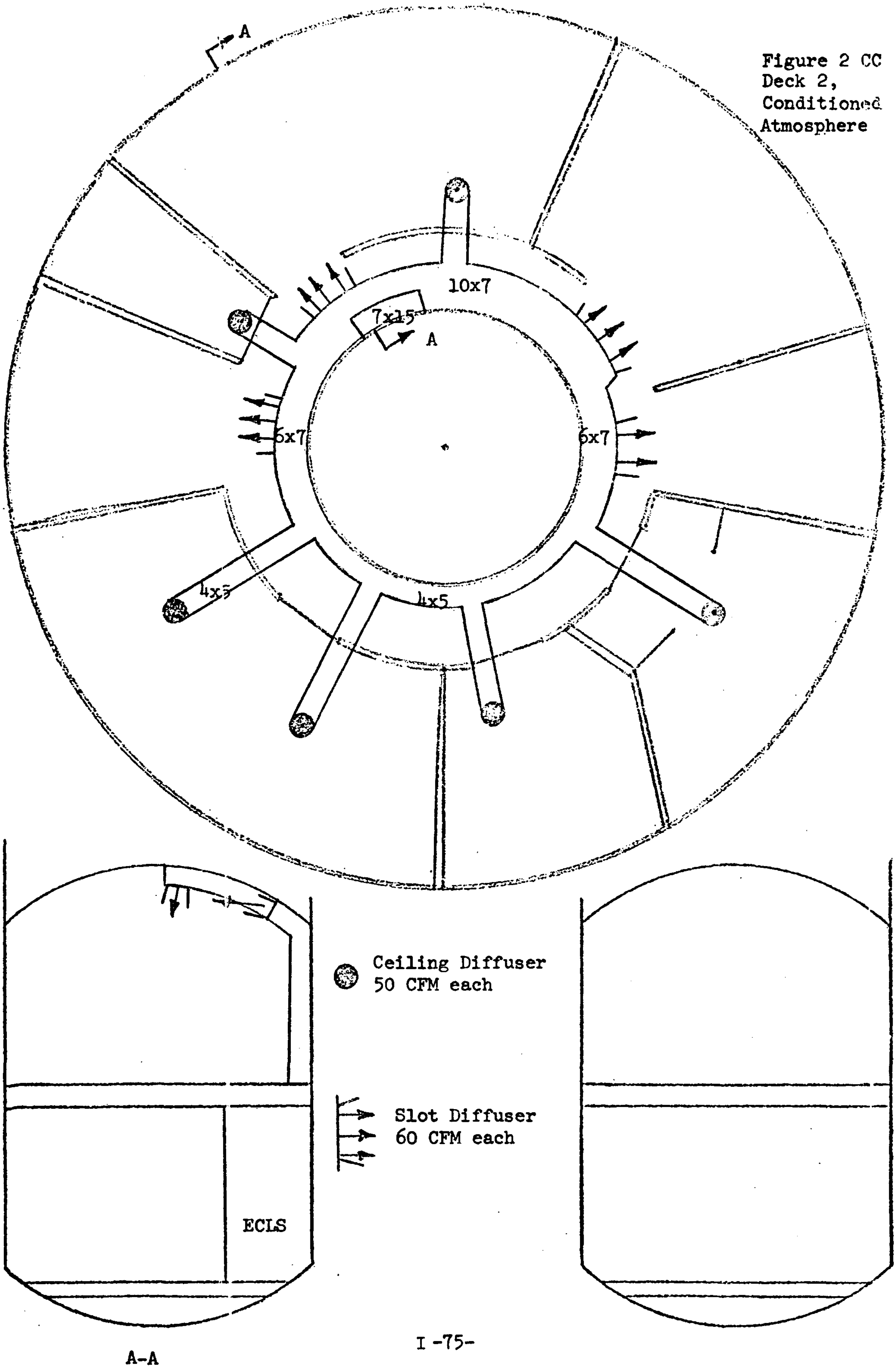


Figure 2 CC
Deck 2,
Conditioned
Atmosphere

Figure 2 AR
Deck 2 Return

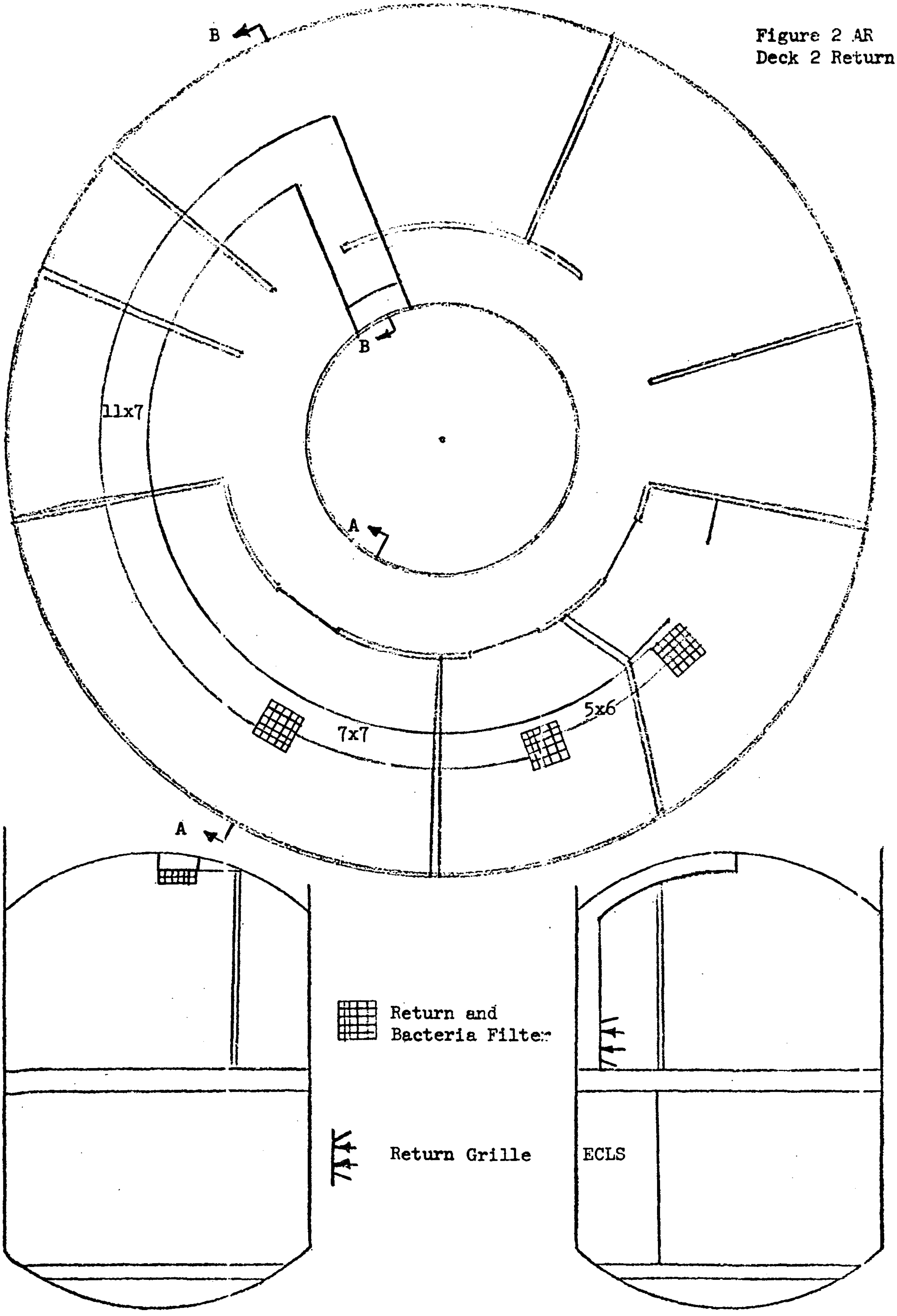
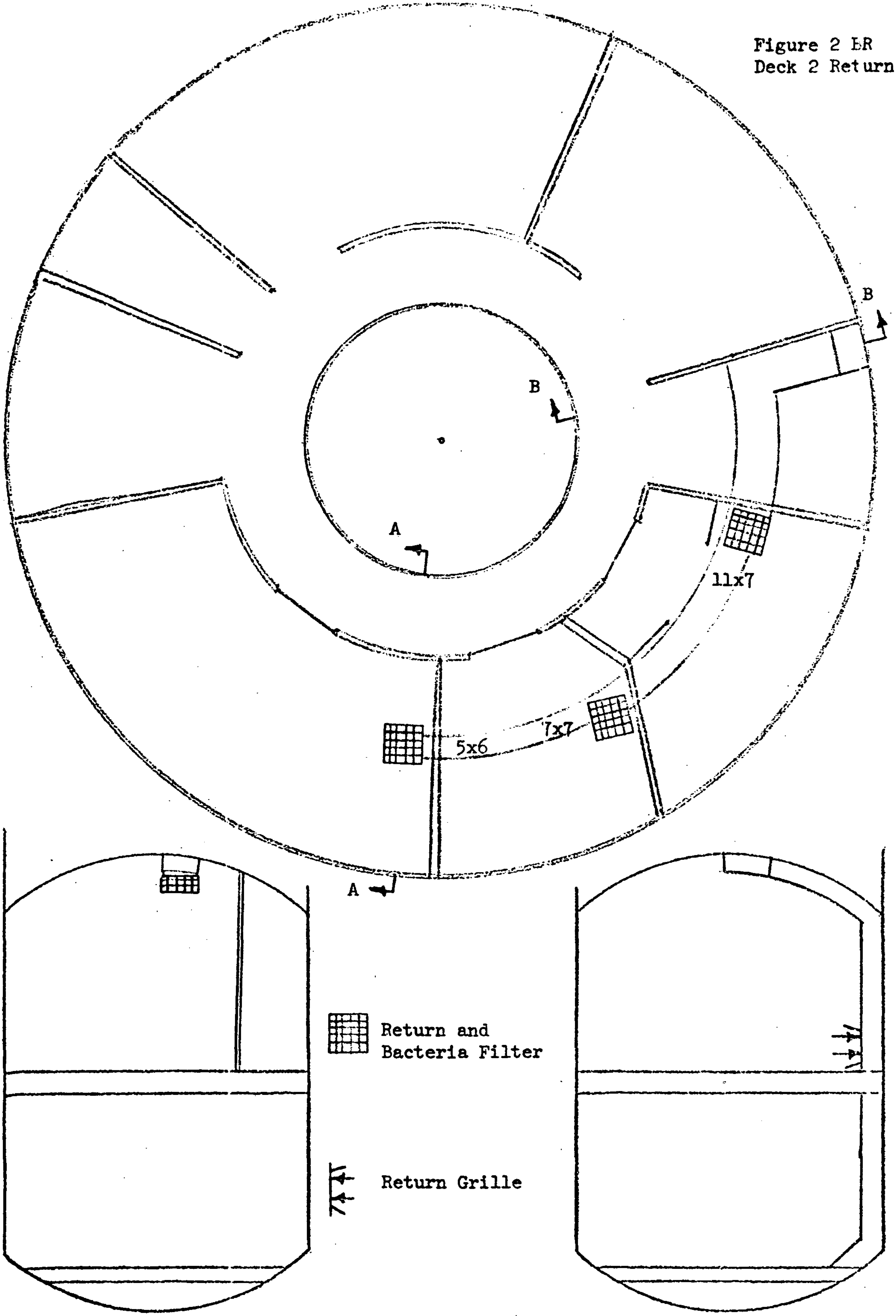


Figure 2 BR
Deck 2 Return

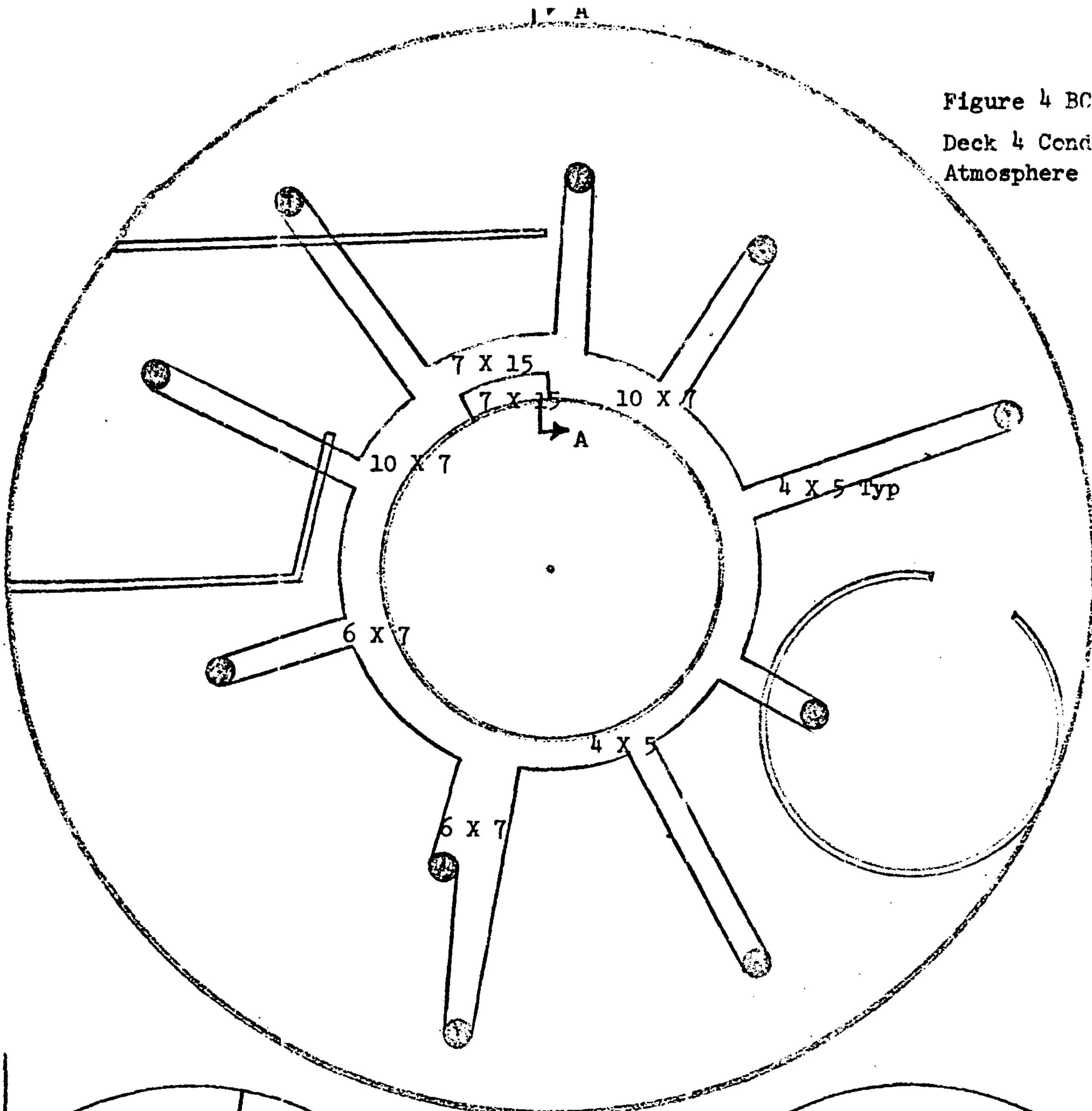


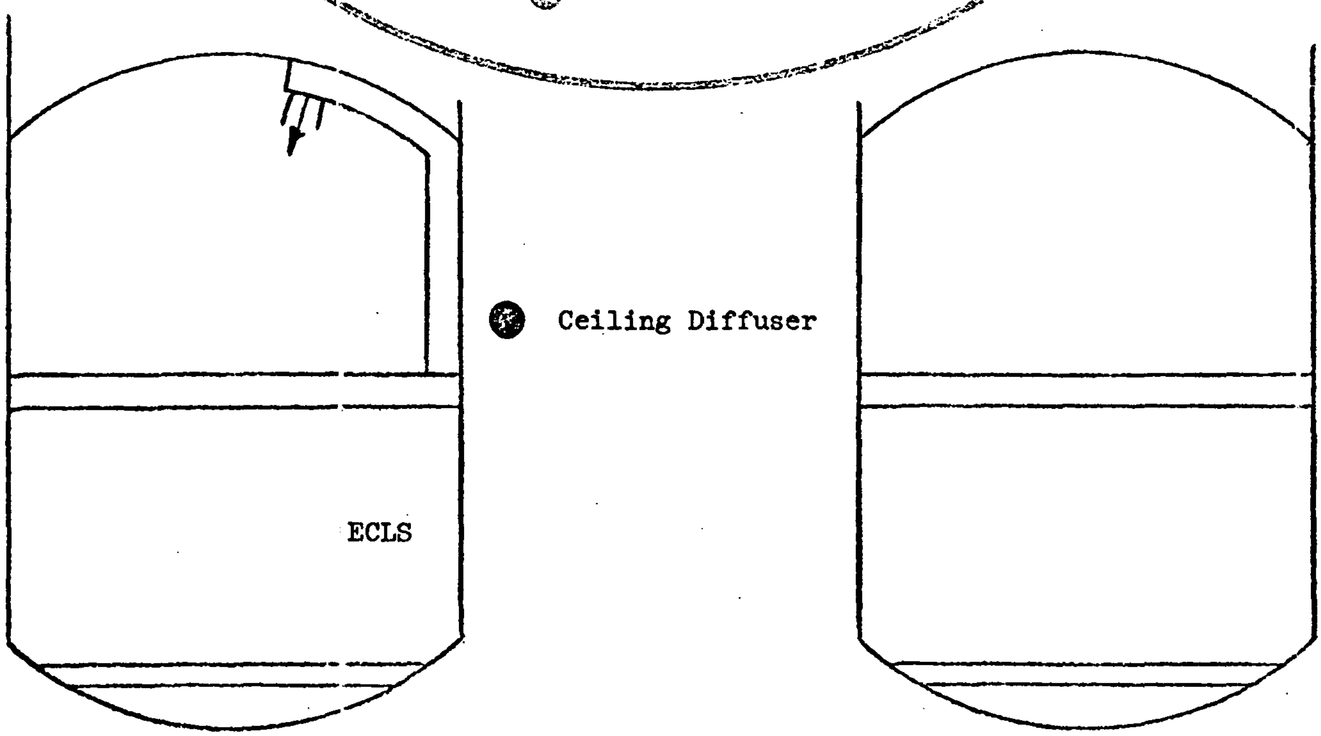
Return and Bacteria Filter

Return Grille

Figure 4 BC

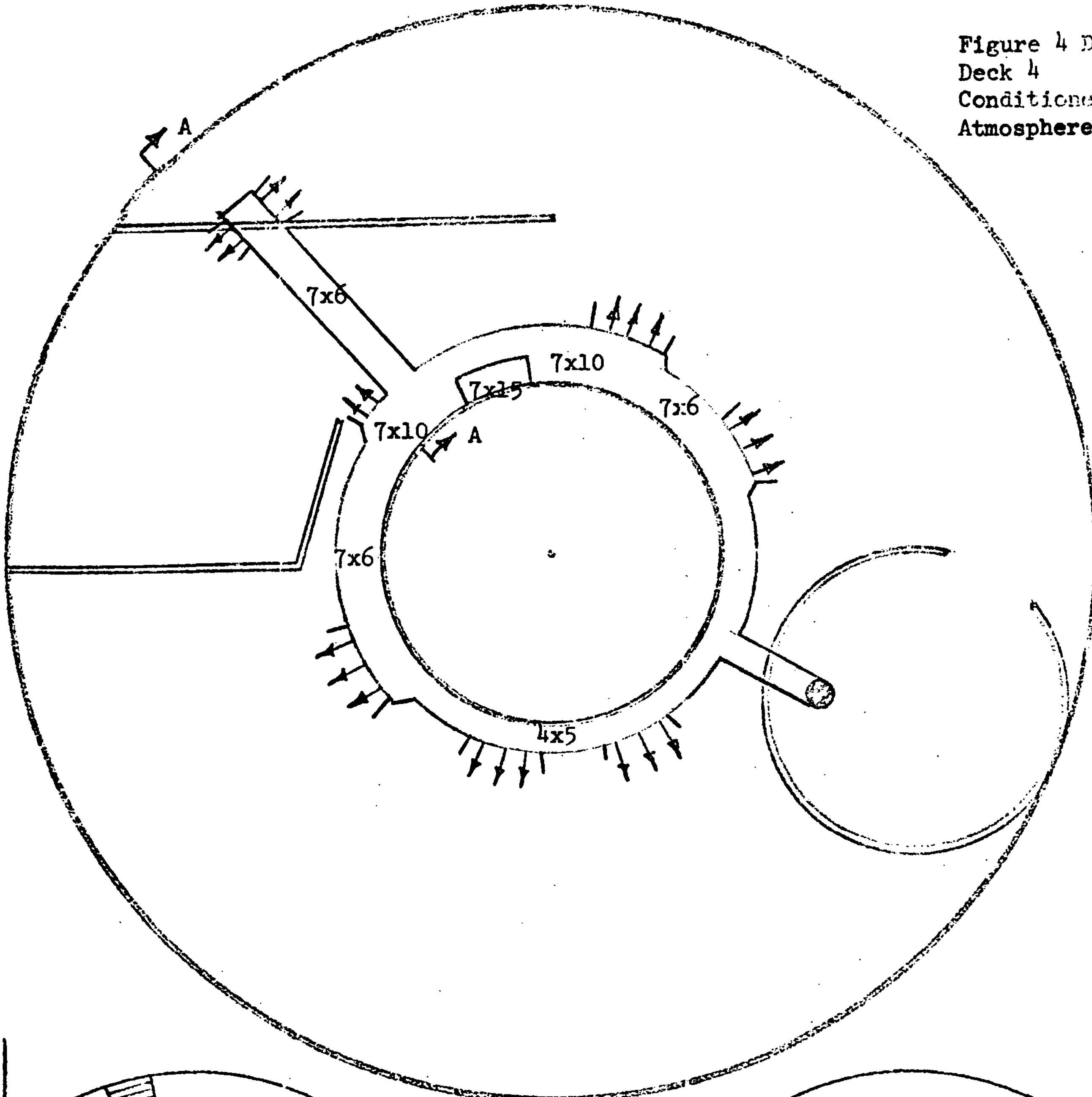
Deck 4 Conditioned Atmosphere

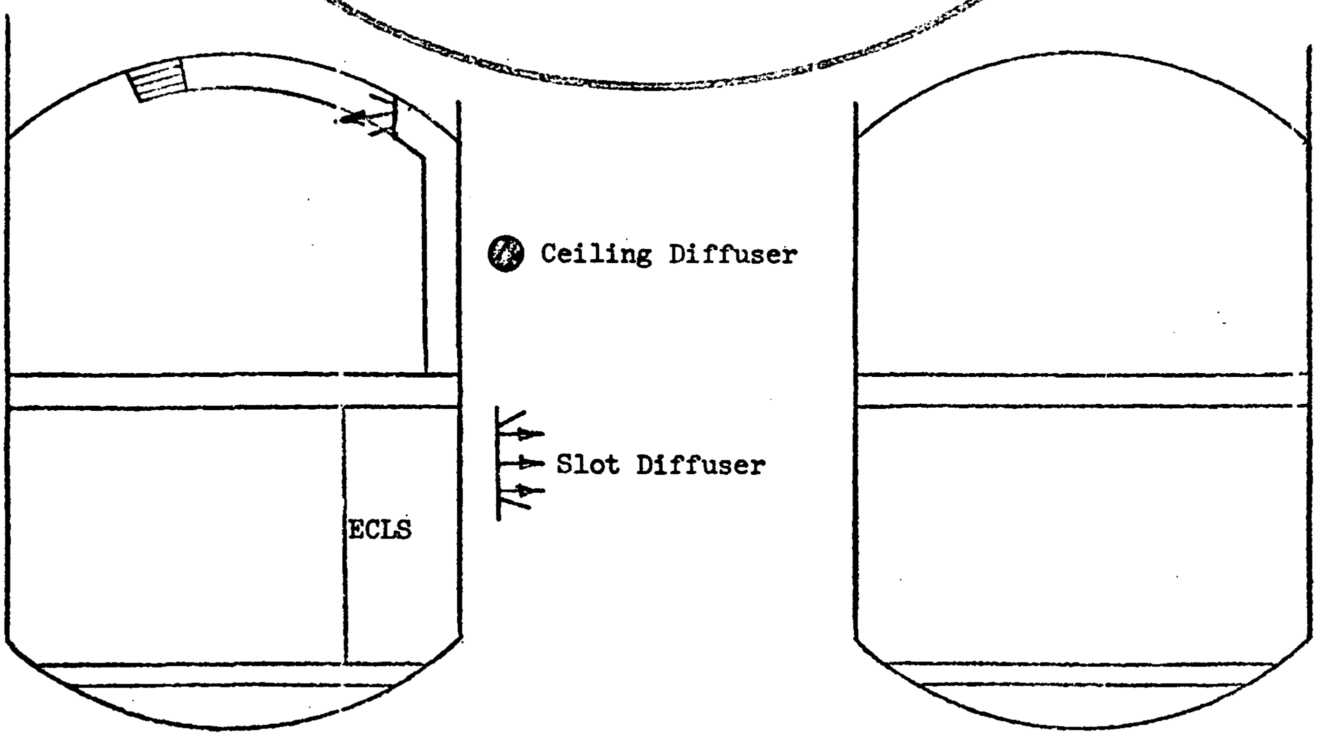




A-A

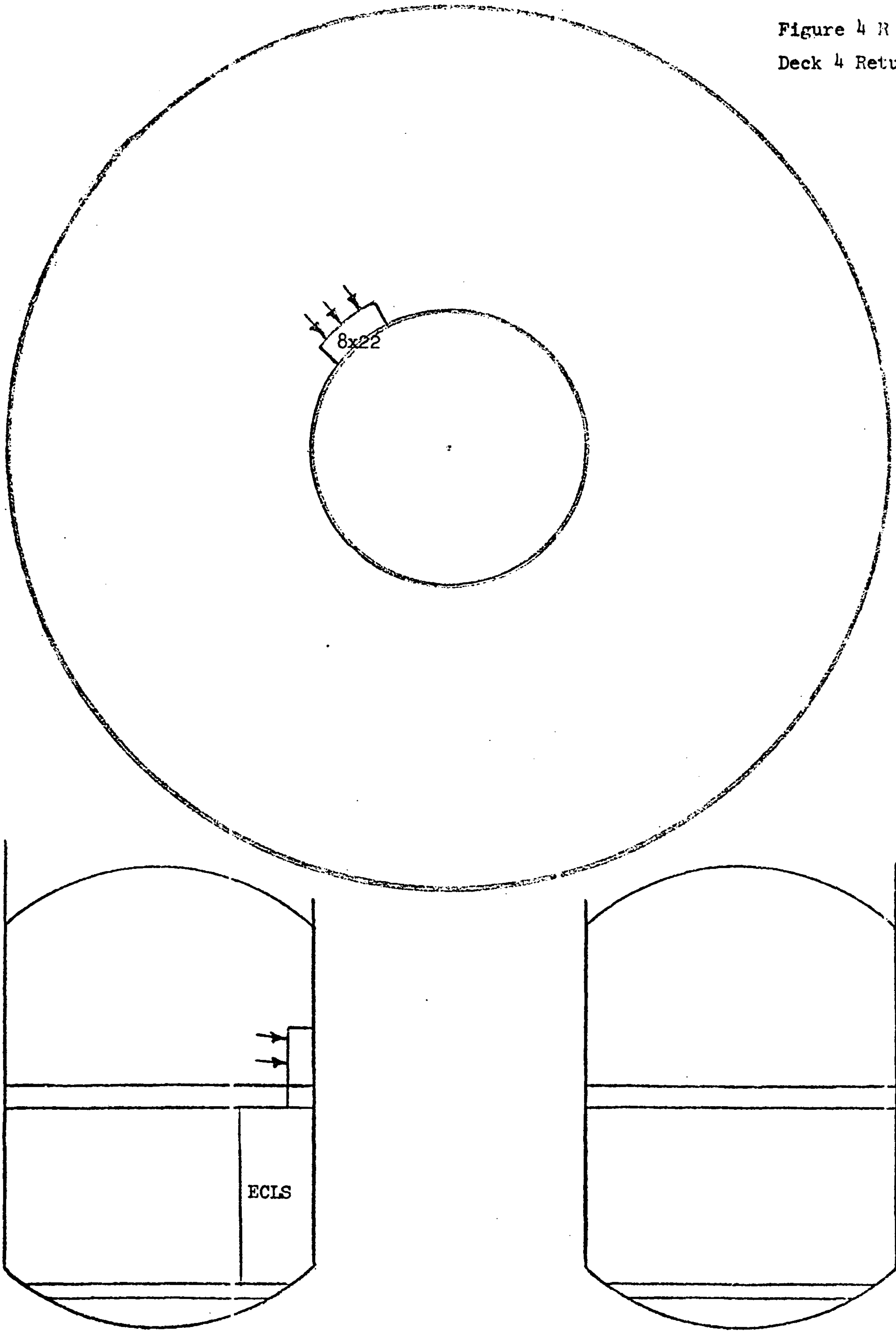
Figure 4 DC
Deck 4
Conditioned
Atmosphere





A-A

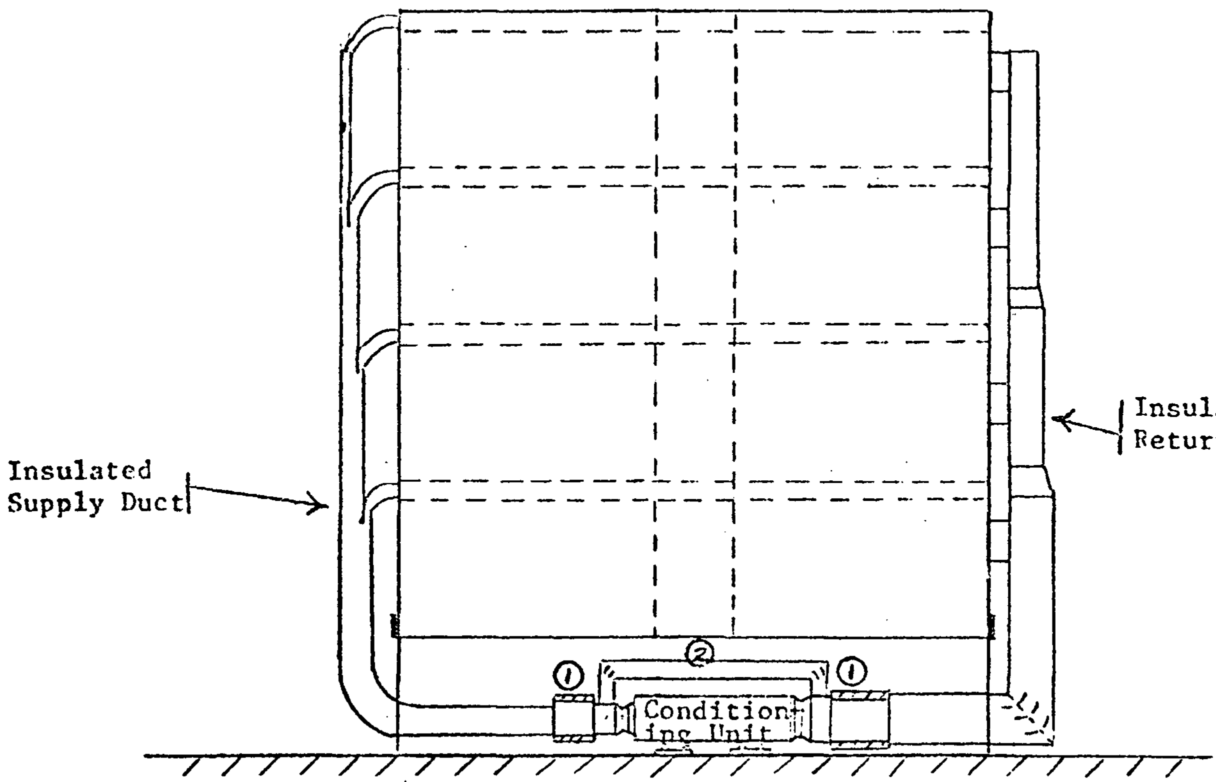
Figure 4 R
Deck 4 Return



APPENDIX B

TEMPORARY MOCKUP VENTILATION SYSTEM

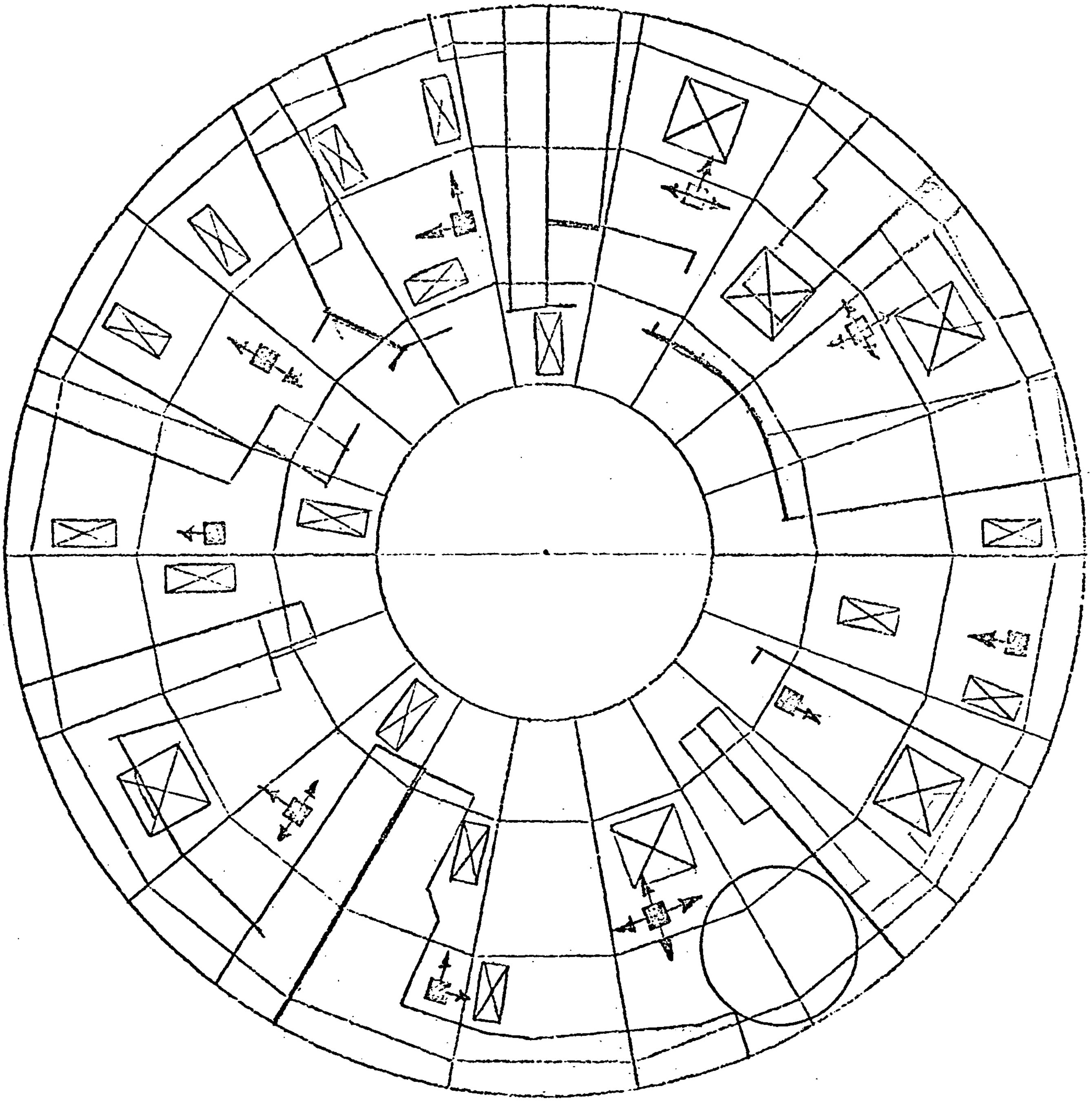
As part of the program to complete the construction of the MSFC Space Station Mockup by mid-December 1970, MDAC was requested to divert emphasis to assisting in the design of the mockup air conditioning system. MDAC was provided with mockup drawings which showed structural details including equipment and lighting locations. A design approach was agreed upon utilizing an existing heat pump, and making use of the volume between the mockup floors and ceilings as conditioned air plenums. The recommended air supply and return configuration is shown in Figure B-1. A diffuser was located by MDAC which has the capability of being adjusted to provide varying flows in any of four directions. The Anemostat model RMD-PT-4S diffuser (6" x 6") was recommended for use, and layouts showing recommended locations were prepared as shown in Figures B-2, B-3, and B-4. The use of 10 to 11 diffusers at 500 CFM per deck, provides substantially derated operation of the diffusers thus reducing draft problems in the low ceiling rooms, and eliminating diffuser noise. Some fan noise is anticipated, and inlet and outlet sound suppressors are recommended as shown in Figure B-1.

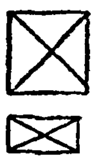


1 Acoustical trap

2 Bypass duct with volume damper for balancing unit output with mockup requirement

Figure B-1 - Exterior Duct and Equipment Layout for Space Station Mockup

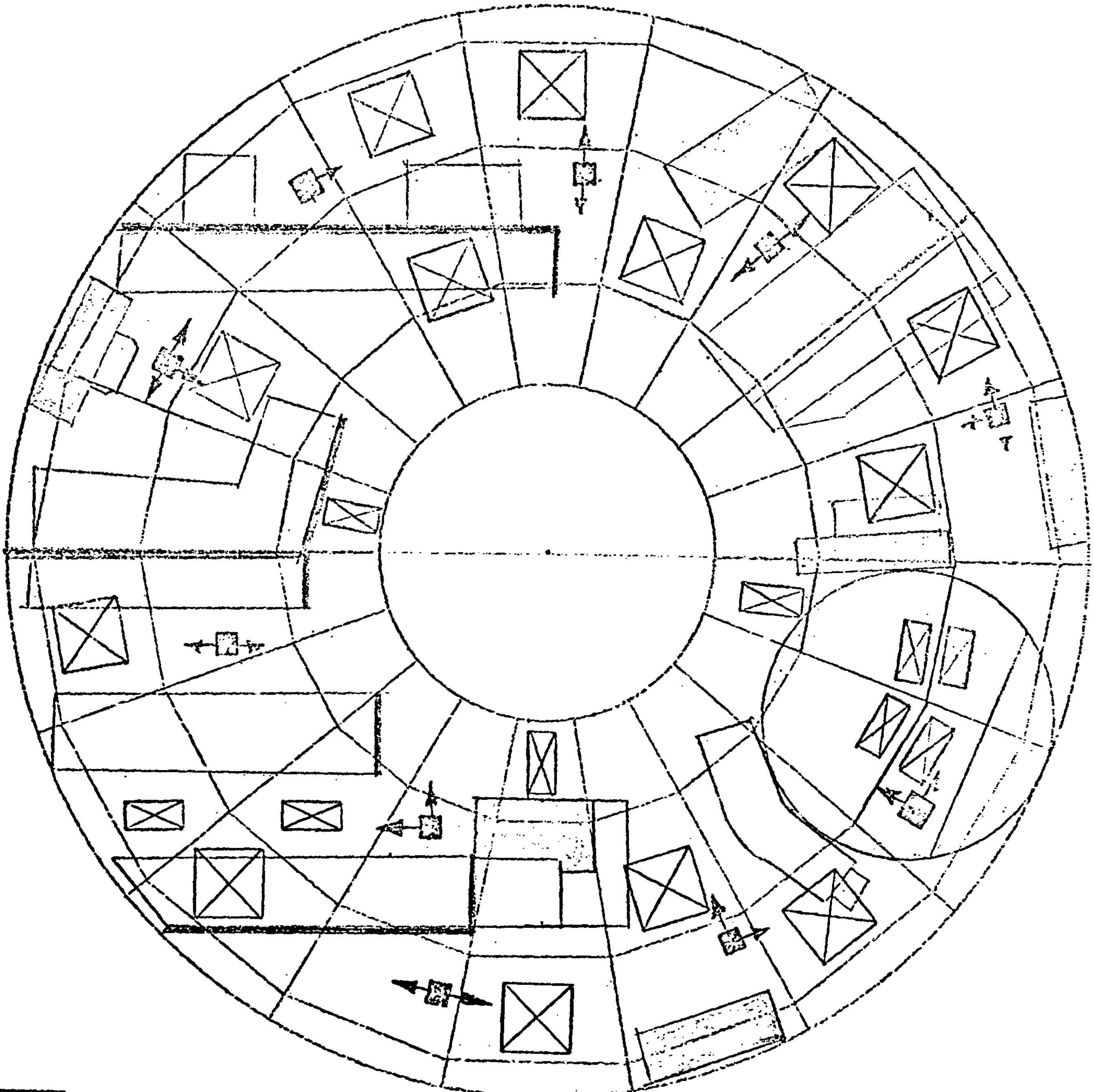




Flush Mounted Ceiling Lights

Anemostat RMD-PT-4S 6" x 6" Diffuser (10 required)
(Shaded areas ceiling high)

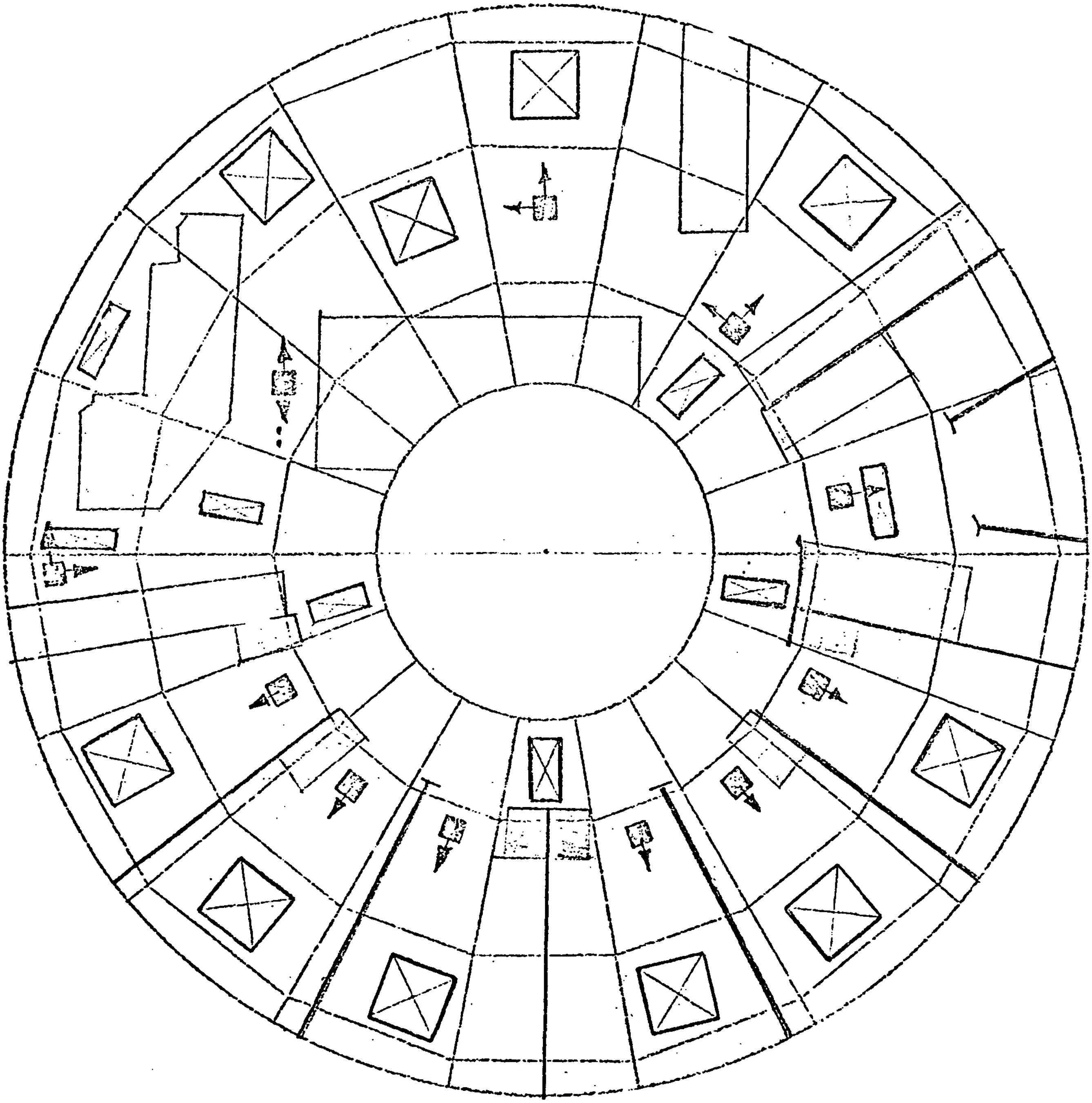
Figure B-2 - Deck 2 Layout

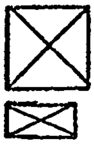


Flush Mounted Ceiling Lights

Anemostat RMD-PT-4S 6" x 6" Diffuser (10 required)
(Shaded areas ceiling high)

Figure B-3 - Deck 4 Layout





Flush Mounted Ceiling Lights

Anemostat RMD-PT-4S 6" x 6" Diffuser (11 required)
(Shaded areas ceiling high)

Figure B-4 - Decks 1 and 3 Layout

APPENDIX C

Penaltys were calculated on each configuration shown in Appendix A and tabulated in Table 3-1, 3-2 and 3-3 (see Section 3). In order to simplify penalty calculations aids were prepared such as Figure C-1 and Table C-1. Figure C-1 gives duct weight per unit length for various perimeters of insulated and uninsulated duct. Table C-1 tabulates the volume and weight per unit length for various sizes of insulated and uninsulated duct. The method of making a penalty calculation will be illustrated below based on configuration 1-1 for module 1 (see Table 3-3).

Configuration 1-1 incorporates Deck 1 design 13A (see Table 3-2) and Deck 2 design 2A (see Table 3-2).

See Appendix A For Layouts	Deck 1 design 13A is made up as follows: Supply layouts 13 AC, 13 ACCC, and 13 ACCB Return layout 13 AR Deck 2 design 2A is made up as follows: Supply layouts 2CC Return layout 2 BR

Penalty calculations shown in Table 3-1 were made as follows for each layout.

$$[\text{Duct Length x Vol.}/_{\text{Foot}} \text{ x Launch Vol. Penalty}] = \underset{(1)}{\text{Penalty}}$$

$$[\text{Duct Length x } \frac{\text{Weight}}{\text{Foot}} \text{ x Launch Weight Penalty}] = \underset{\text{Duct}}{\underset{(2)}{\text{Penalty}}}$$

$$[\text{Diffuser Wt. x Launch Weight Penalty}] = \underset{\text{(Diffuser)}}{\underset{(2)}{\text{Penalty}}}$$

FIGURE C-1 DUCT WEIGHT PER UNIT LENGTH VERSES PERIMETER OF DUCT

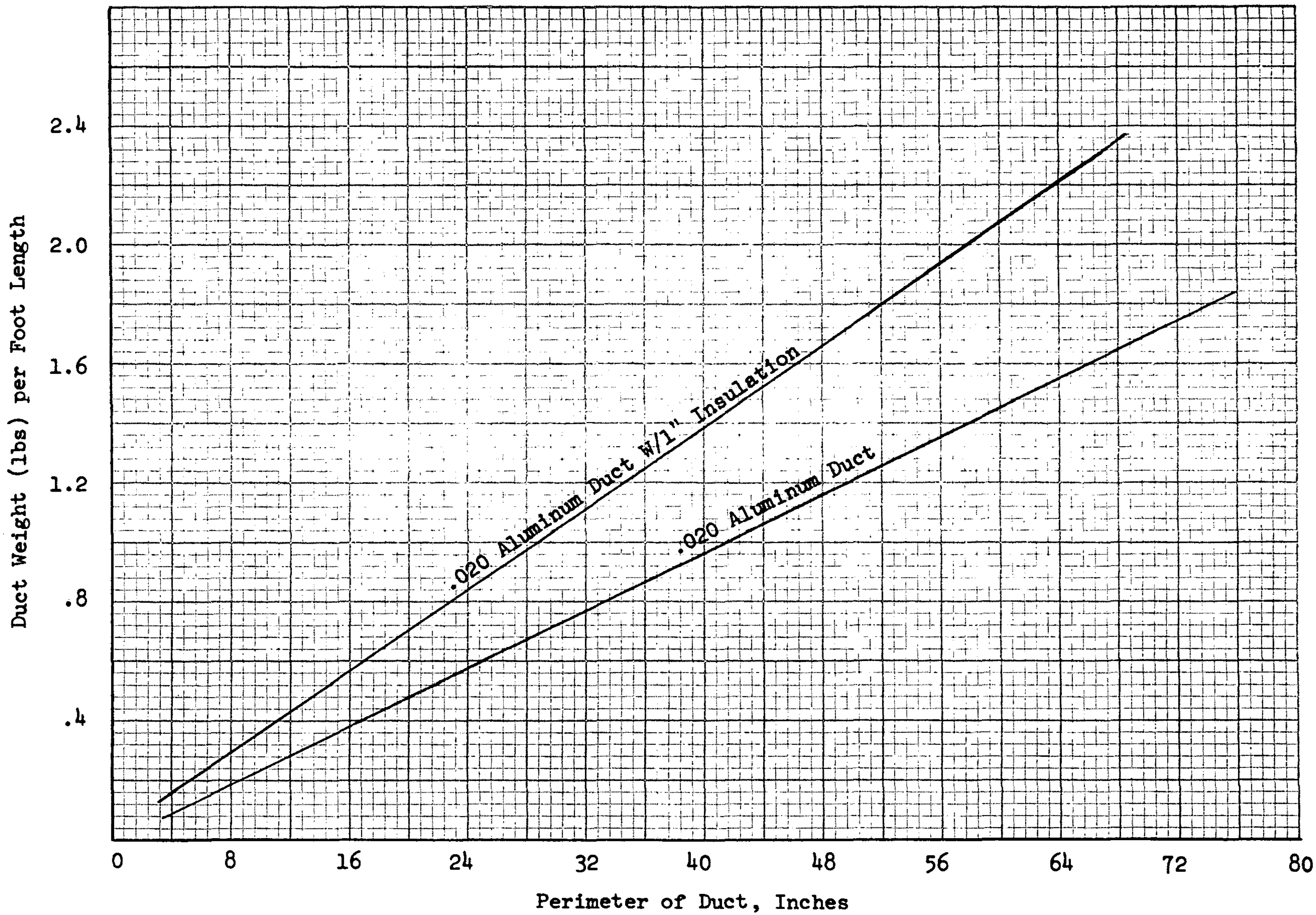


TABLE C-1 VOLUME AND WEIGHT FOR SELECTED DUCT SIZES

Size	Vol/Ft		Wt/Ft	
	Ins.		Ins.	
7 x 15	1.06	0.73	1.53	0.105
7 x 10	0.667	0.486	1.25	0.86
7 x 7	0.562	0.313	0.97	0.66
6 x 7	0.500	0.291	0.91	0.61
5 x 4	0.291	0.139	0.63	0.43
6 x 4	0.333	0.167	0.70	0.47
9 x 7	0.688	0.437	1.11	0.76
5 x 7	0.437	0.243	0.84	0.57
5 x 6	0.389	0.208	0.77	0.52
12 x 6		0.5		0.85
22 x 8		1.22		1.43
10 x 17		1.18		1.28
16 x 17		1.89		1.57
20 x 17		2.36		1.76

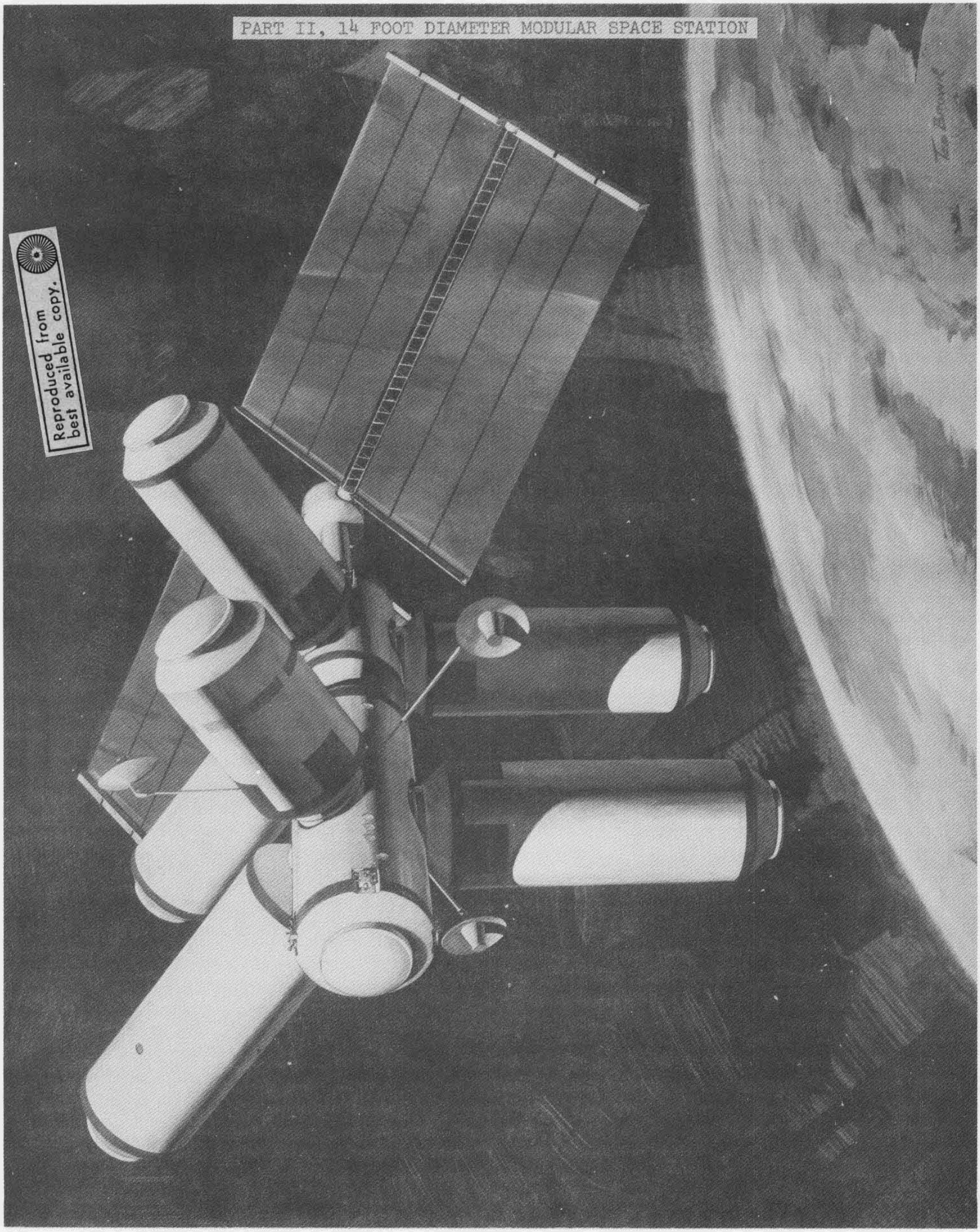
$$\begin{array}{l} \text{Total Vol.} \\ \text{and Weight} \\ \text{Penalty} \end{array} = \sum \quad \begin{array}{c} \text{Penalty;} \\ (1) \end{array} \quad \begin{array}{c} \text{Penalty,} \\ (2) \\ \text{Duct} \end{array} \quad \begin{array}{c} \text{Penalty} \\ (2) \\ \text{Diffuser} \end{array}$$

In computing the total volume and weight penalty for configuration 1-1 the above procedure would be followed for layout 13AC, 13ACCC, 13ACCB, 13AR, 2CC and 2BR.

The combination total volume and weight penalty would be shown on Table 3-2 where the maximum supply duct pressure is evaluated. Table 3-3 shows the total volume and weight penalty in addition to the fan power required based on Figure 3-2. The final calculation of total penalty is shown as follows:

$$\begin{array}{l} \text{Total Volume} \\ \text{and Weight} \\ \text{Penalty} \end{array} + \begin{array}{l} \text{Fan Power} \\ \text{Required} \end{array} \left(\frac{\text{Power Penalty}}{\text{Watt}}\right) = \begin{array}{l} \text{Total Penalty for a} \\ \text{specific module} \\ \text{configuration} \end{array}$$

PART II, 14 FOOT DIAMETER MODULAR SPACE STATION



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Section 1.0

INTRODUCTION AND SUMMARY

This part is an extension of Contract NAS8-26267 and is designed to investigate a ventilation system for the 14-foot diameter modular space station. The level of effort provided by the available funds did not allow the indepth study and analysis spent on the 33-foot diameter version covered in Part I. However, the scope of the study starts with the ventilation system design developed during Contract NAS8-25140 and expands the design variations in addition to determining trade-off penalties. The design and trade-off studies consider only the mass flow of primary air necessary to accomplish humidity control, CO_2 removal and trace contaminants control. Individual sensible heat removal units which will exist in each module to maintain the correct dry bulb temperature are not evaluated in this study.

The primary air ventilation system configured for the modular space station provides the greatest flexibility with the lowest weight, volume and power penalties. Each module has its own thermal conditioning unit to provide selectable sensible cooling for crew members in the area. The coolant loop and heat rejecting capability of each thermal conditioning unit is contained in the module it serves. This reduces transport ducting between modules and its associated penalties.

The design chosen is one where a constant volume of reconditioned primary air is available for CO_2, humidity and trace contaminant control. This minimizes the atmosphere reconditioning assembly (ARA) size and enables one efficient unit to serve the entire modular space station, including emergency control of the General Purpose Laboratory (GPL). The GPL has its own ARA for normal conditions, which is also sized and configured to serve the entire modular space station in a backup mode.

Transport ducting has been arranged in a series configuration rather than in a parallel configuration since the increased series ducting causes less penalty than the increased ARA size and air flow required for the parallel arrangement.

Recommendations for future investigations resulting from this study would encompass a more indepth analysis and evaluation of possible ventilation systems and their impact on the overall space station design. Specific recommendations include the following:

- Investigate possible ventilation distributions within each module by analytical and test techniques.
- Develop an analytical model to perform detailed trade-off studies at off-design conditions which include the individual thermal conditioning units.

Section 2.0

DESIGN REQUIREMENTS

The study was made on a 14-foot diameter modular space station configuration. Atmosphere conditioning for control of CO_2, humidity, and trace contaminants is accomplished using the central Atmosphere Reconditioning Assembly (ARA) located in a crew module. As a backup, the ARA located in the General Purpose Laboratory (GPL) can serve as the central reconditioner of the atmosphere in event of failure of the primary unit. All sensible cooling is accomplished in a separate unit within each module.

Table 2.1 shows the design requirements which were the basis of the performance and trade-off studies. Table 2.2 indicates additional off-design conditions which have been utilized in calculating performance and trade-off results.

TABLE 2.1 MODULAR SPACE STATION DESIGN REQUIREMENTS

Oxygen partial pressure	21.4 kN/m^2 (3.1 psia)
Total pressure	101 kN/m^2 (14.7 psia)
CO_2 partial pressure	Normal - 0.4 kN /m^2 (3 mm Hg) or less Emergency - 1.0 kN/m^2 (7.6 mm Hg) maximum for 7 days
CO_2 generation rate, peak/average	0.354/0.260 kg/hr (0.78/0.575 lb/hr) (6 men)
O_2 use rate, average	0.218 kg/hr (0.48 lb/hr) (6 men)
Trace contaminants	Same as Phase B SS Study
Free moisture in atmosphere	None allowed
Particulate filtration level	Class 100,000 clean room
Atmosphere heat load	Crew metabolic +20% of net electrical power output
Metabolic levels	Normal - 136 watts (465 Btu/hr) for 24 hr. Design - 2 men at 235 watts (800 Btu/hr) 4 men at 161 watts (550 Btu/hr)
Atmosphere temperature	18.4 to 23.9°C (65 to 85°F) selectable
Dewpoint temperature	7.2 to 15.6°C (45 to 60°F) with transients to 4.5°C (40°F) allowable
Mean radiant wall temperature	18.4 to 23.9°C (65 to 85°F)
Velocity in occupied regions	0.1 to 0.25 m/sec (20 to 50 ft/min)
Design latent load	
Crew	640 watts (2180 Btu/hr)
Crew equipment	385 watts (1313 Btu/hr)
Experiments	306 watts (1042 Btu/hr)

Table 2.2

LOCATION AND LEVEL OF MAN LOADING UTILIZED IN STUDY DESIGN CONDITIONS

I.D.	Location	No. Men	Loading
Case 1	Power Module	4	580 K Joule/hr (550 Btu/hr)
	Experiment Module (1)	2	840 K Joule/hr (800 Btu/hr)
Case 2	Crew Module	2	580 K Joule/Hr (550 Btu/hr)
	Experiment Module (1)	2	840 K Joule/hr (800 Btu/hr)
	Experiment Module (2)	2	580 K Joule/hr (550 Btu/hr)
Case 3	Crew Module	2	580 K Joule/hr (550 Btu/hr)
	Experiment Module (1)	2	840 K Joule/hr (800 Btu/hr)
	Experiment Module (5)	2	580 K Joule/hr (550 Btu/hr)

Average Condition

Case 4	Crew Module	4	2 @ 316 K Joule/hr (300 Btu/hr)
			2 @ 474 K Joule/hr (450 Btu/hr)
			Plus 0.57 Kg/hr (1.26 lb/hr) Equip. Moisture
	Experiment Module (1)	2	632 K Joule/hr (600 Btu/hr)

SECTION 3.0

SYSTEM DESIGN, ANALYSIS AND TRADEOFF

This section deals with the ventilation system component design and function. In addition, module CO_2 levels, dew point levels and transport duct trade-off results are given.

System Design

Primary components of the ventilation system are the Atmosphere Reconditioning Assembly, air temperature control assemblies, associated ducts and module diverter valves.

Atmosphere Reconditioning Assembly (ARA)

The atmosphere reconditioning assembly (ARA) basically performs three functions. These functions are: 1) humidity control, 2) CO_2 removal and 3) trace contaminant control.

Atmosphere humidity is controlled by two assemblies located in the Crew/Module and the GPL Module. The unit located in the Crew/Operations Module dehumidifies air in the Crew/Operations Module, Power/Subsystems Module and any attached modules. Under normal operation the GPL unit dehumidifies air only in the GPL Module.

Process gas for humidity control is drawn into the condenser and cooled to 10°C (50°F) by the cold circulating water on the liquid side of the condenser. This temperature is below the cabin dew point. Excess moisture is condensed from the process air, separated from the air stream by a face type wick separator and pumped to the water management assembly group for processing.

The humidity control assembly is designed to remove 1,330 watts (4,535 Btu/hr) of primarily latent load. This is comparable to the design point for the Space Station Prototype Program. Allowances are included for the crew at high metabolic loads in a warm 24°C (75°F) cabin, crew equipment such as showers and washers at 386 watts (1,313 Btu/hr) and 306 watts (1,042 Btu/hr) from experiments.

CO_2 removal is accomplished in the ARA by a molecular sieve. One ARA with a molecular sieve is located in the Crew/Operations Module and one is located in the GPL Module. Each is capable of removing 0.354 kg/hr (0.78 lb/hr) of CO_2 which corresponds to 2 men at 235 watts (800 Btu/hr) and 4 men at 160 watts (550 Btu/hr). The units are completely independent from one another; each unit is serviced by different process heat and coolant water loops. This arrangement reduces the possiblity of losing both CO_2 removal assemblies at one time.

Atmosphere laden with CO_2 is drawn from downstream of the humidity control assembly by the process flow fan and passed through a liquid-cooled, adsorbing desiccant bed where the stream is dried to a dewpoint of approximately -65°C (-85°F). The air continues through a liquid-cooled, adsorbing molecular sieve canister, where CO_2 is removed by adsorption on zeolite. Effluent air returns to the cabin through the desorbing desiccant canister where desorption of the contained water rehumidifies the air and regenerates the desiccant bed.

Control of the CO_2 removal unit is under direction of a demand control. It senses the partial pressure of CO_2 in each module through sensors located in the ARA. After the molecular sieve timed cycle is completed, the process is repeated. An overboard dump line is provided to desorb the molecular sieve canister to space if desired. Electrical heaters are provided in both the silica gel and molecular sieve beds because periodic bakeout may be required.

A dew point sensor provides information as to the amount of water vapor in the gas stream during startup of the CO_2 concentrator after long-term shutdown. When the gas stream is adequately dry, the bypass valve is closed and the flow is directed through a molecular sieve bed for CO_2 removal.

Trace contaminants are controlled by the trace contaminants and odor control portion of each ARA. Process gas from the condenser outlet is passed through the nonregenerable charcoal cannister where heavy molecular weight contaminants, such as hydrocarbons, are removed. The fan provides the high flow [(2.54 m^3/min (90 cfm)] for the charcoal canister and a lower flow [0.156 m^3/min (5.5 cfm)] for the catalytic oxidizer. Carbon dioxide, hydrogen, and methane are oxidized in the catalytic oxidizer to produce water and other products which can be removed by other EC/LS equipment.

The trace contaminant canister contains copper sulfate beads to remove ammonia and lithium carbonate sorbent to remove acid gasses in addition to nonregenerable charcoal. Removal of these products prevents poisoning of the catalyst bed. An on-off heater control maintains catalytic bed temperature at the design temperature of 371°C (700°F).

Air Temperature Control Assemblies (ATCA)

A separate ATCA is provided in each module which removes the sensible heat load and maintains the selectable temperature at 18.4 to 29.4°C (65 to 85°F). Cabin air is passed through a liquid-to-air heat exchanger where the air is cooled by the circulating cooling water. The cabin temperature is controlled by the temperature control valve which bypasses cooling water based on a signal from the electronic temperature selector and control. Input to the controller originates from the temperature sensors located in the process gas duct.

A minimum circulating water temperature of 14.5°C (58°F) is provided at the cabin heat exchanger inlet to avoid inadvertent moisture condensation in the process gas. The temperature control valve bypasses sufficient warm circulating water through the regenerative heat exchanger to maintain the condenser surface temperature above 15.5°C (60°F).

The air temperature control assemblies have sufficient cooling capacity to remove crew thermal loads, EC/LS calculated sensible loads, and equipment sensible loads.

Electrical loads are liquid cooled in all possible locations since liquid cooling represents a smaller penalty than air cooling. It is estimated that 80% of all electrical heat loads other than EC/LS loads can be removed by liquid cooling.

Special ventilation is required in the crew quarters because no atmosphere mixing can occur with the doors closed. The crew quarters located in the crew module will require high ventilation flow but low conditioning flow since the heat load is small. The crew quarters temperature will be no higher than the average deck temperature since the crew will be at a low metabolic rate in that area. Crew quarters temperature may approach the minimum supply air temperature of 15.5°C (60°F) due to long periods at low heat loads. Supply air therefore cannot be directly added to the crew quarters. To maintain the proper crew quarters temperature, air is drawn from the main deck area with a fan and distributed to the crew quarters by ducting and diffusers. Each unit supplies 14.1 m^3/min (500 cfm) to three crew quarters, which is sufficient flow to provide normal crew cooling with a 1.8°C (2°F) temperature rise in the gas stream. This flow rate is also sufficient to prevent appreciable buildup of crew metabolic products in the crew quarters. The reconditioned atmosphere from the ARA is expelled into the main distribution system which distributes the air throughout the Space Station. The air returns are located in the hygiene and galley areas so that the air movement towards those areas will prevent odors from escaping to the remainder of the station.

System Analysis

Calculations were made to determine CO_2 level and dew point in each module at various manned loading levels. A series flow arrangement shown in Figure 3.1 for purified air from the Crew/Operations Module ARA is of particular significance. Values shown for dew point temperature and CO_2 partial pressure represent design point conditions for humidity control and CO_2 removal. The design point condition taken from Table 1.1 for atmosphere distribution is based on 2 crewmen located in an attached module working at 234 watts (800 Btu/hr). Equipment humidity loads assumed in the attached module are 360 watts (1,042 Btu/hr) and in the Crew Operations Module are 386 watts (1,313 Btu/hr). Purified air is delivered to the modules in a series arrangement. This approach, as will be shown later, was found to minimize the total air which must be processed and delivered. It also minimizes the required capacity of atmosphere purification equipment because the series arrangement results in a higher concentration of H_2O vapor and CO_2 entering the atmosphere purification equipment.

The design point for atmosphere distribution assumes two men at high metabolic load in an attached module, however, a greater number of crewmen can be accommodated in one attached module if they are working at lower levels. Sufficient flow to the Power/Subsystems Module and the attached modules exists so that the entire crew can be in those areas working at their average metabolic rates without exceeding design atmosphere conditions. The values given assume steady-state conditions. However, it would take time for CO_2 and water vapor to build up to the maximum allowable level under higher crew and equipment loads.

Additional cases have been calculated using off-design conditions shown in Table 2-1. Figures 3.1 thru 3.5 show results of these calculations when a series flow arrangement is utilized. Figures 3.6 thru 3.10 show the same conditions when a parallel flow arrangement is utilized. It can be noted

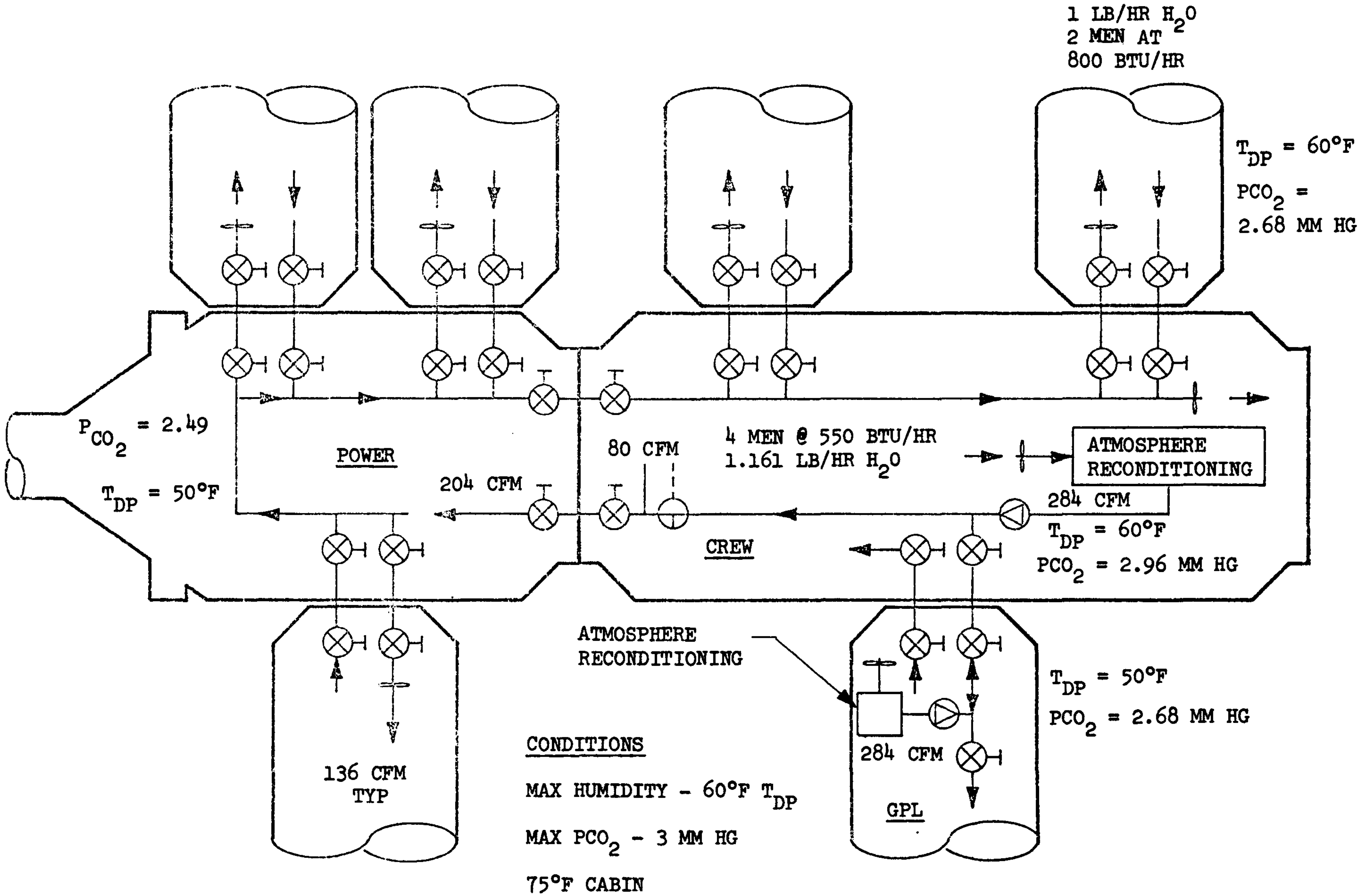

FIGURE 3.1 SERIES FLOW DESIGN CONDITIONS

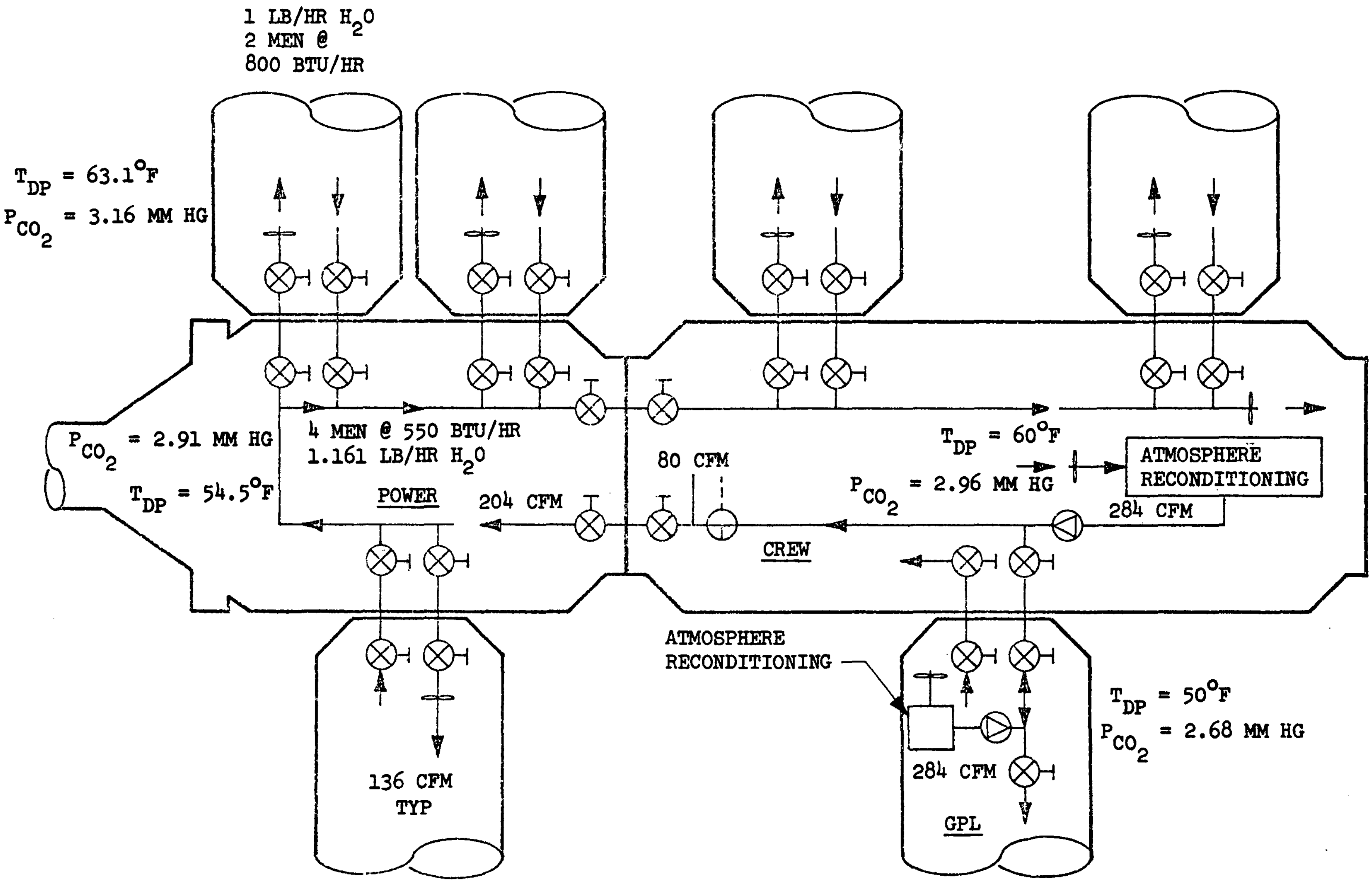

FIGURE 3.2 SERIES FLOW CASE 1 CONDITIONS

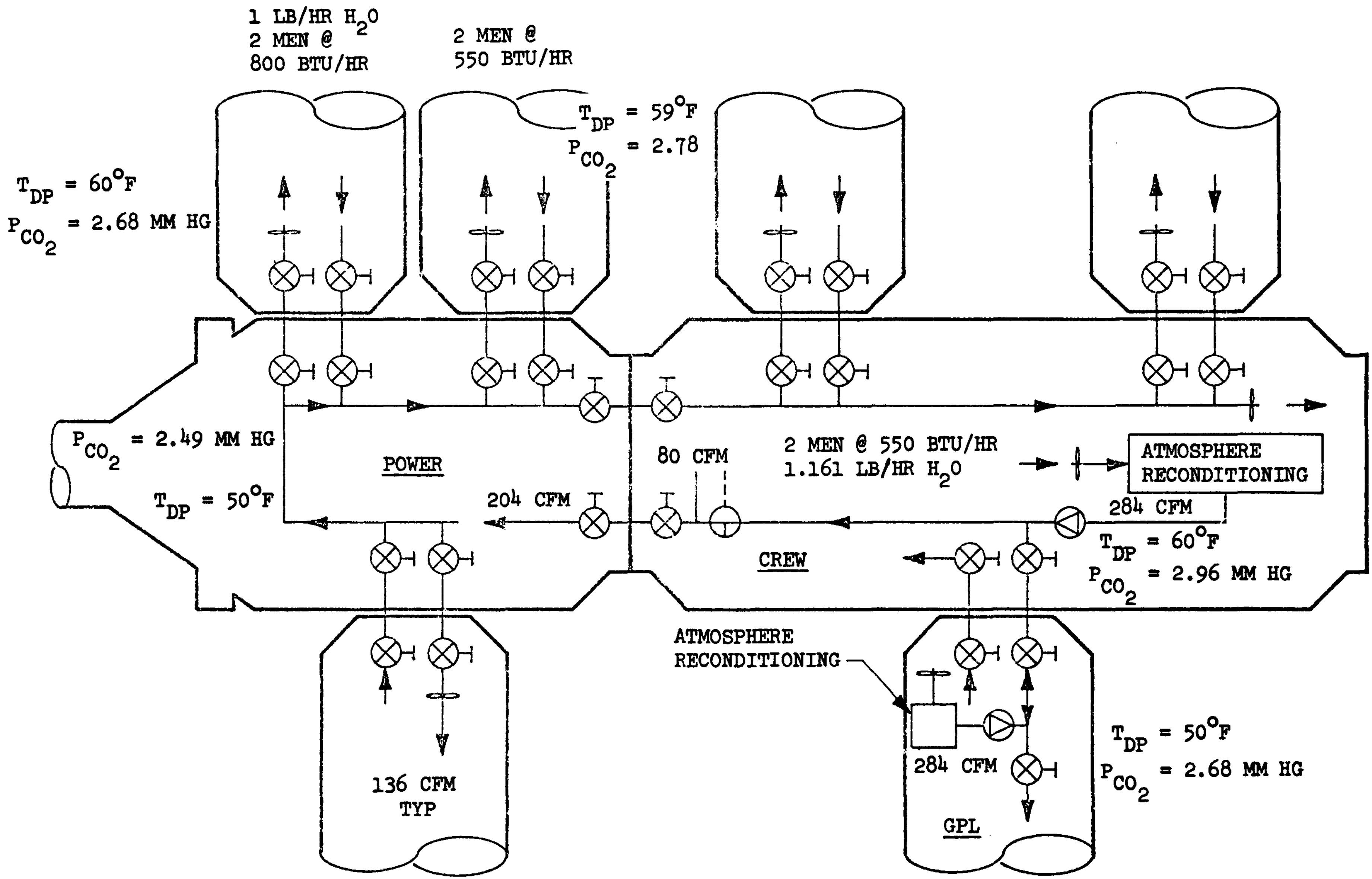

FIGURE 3.3 SERIES FLOW CASE 2 CONDITIONS

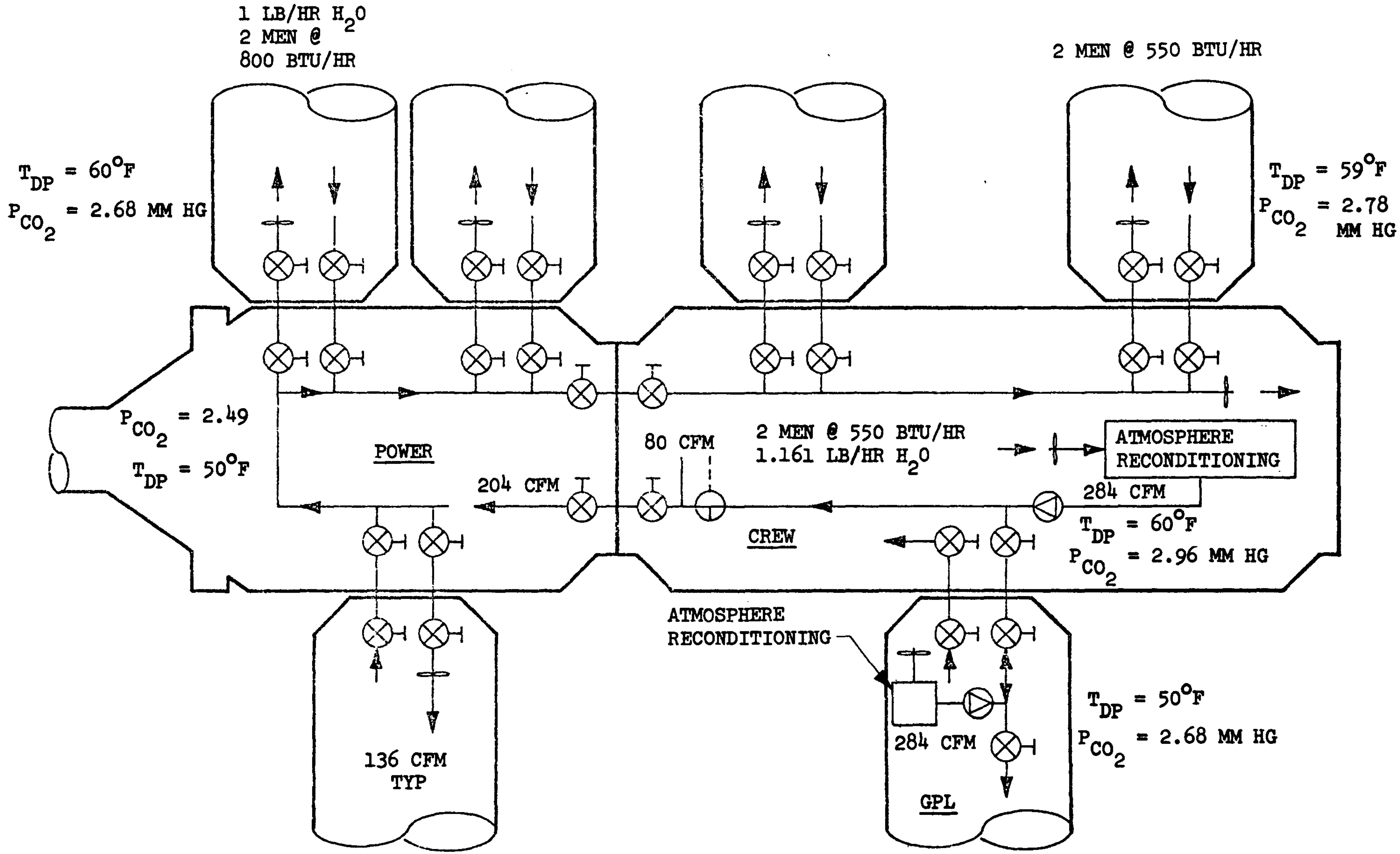

FIGURE 3.4 SERIES FLOW CASE 3 CONDITIONS

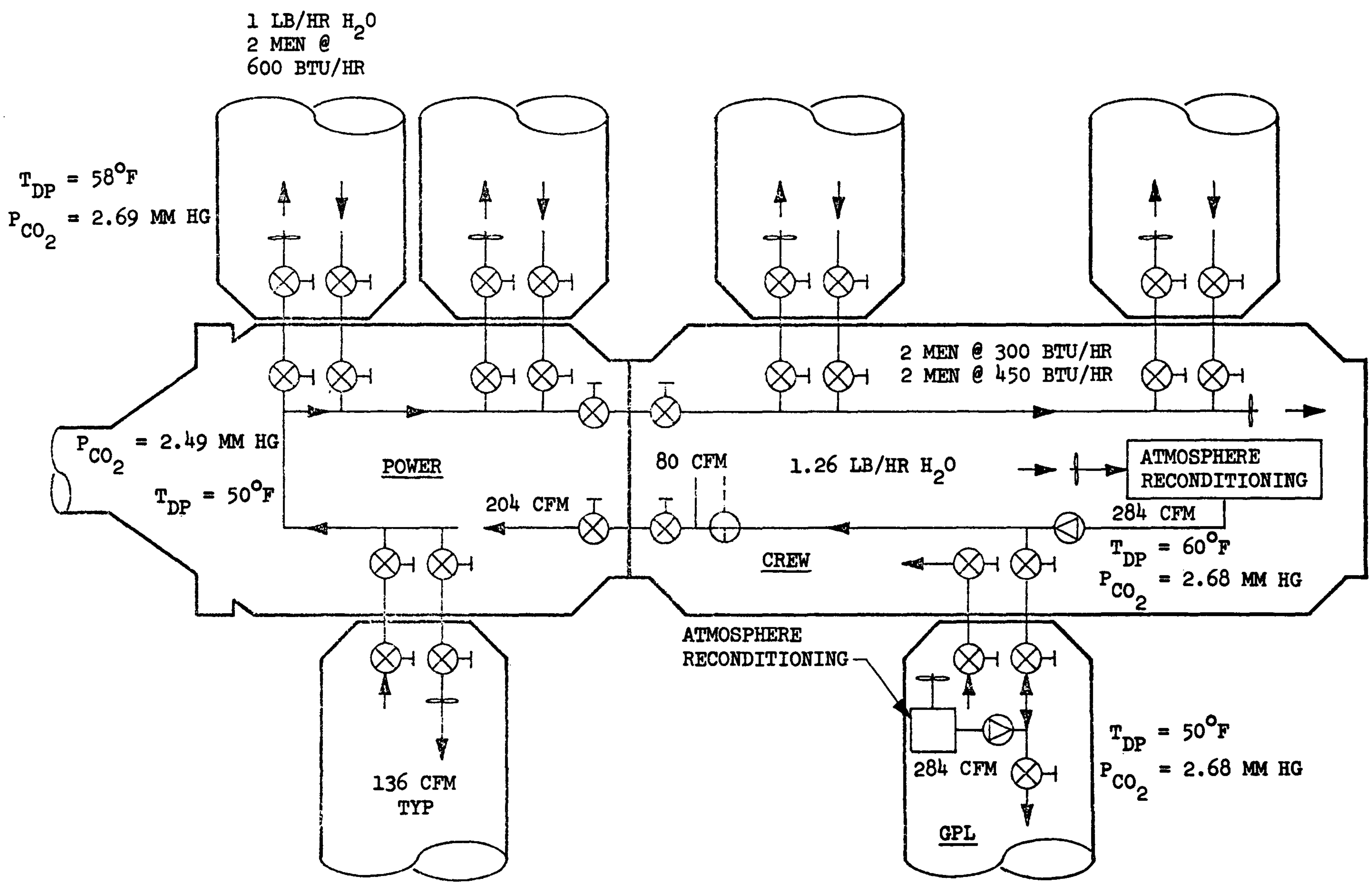

FIGURE 3.5 SERIES FLOW CASE 4 AVERAGE CONDITIONS

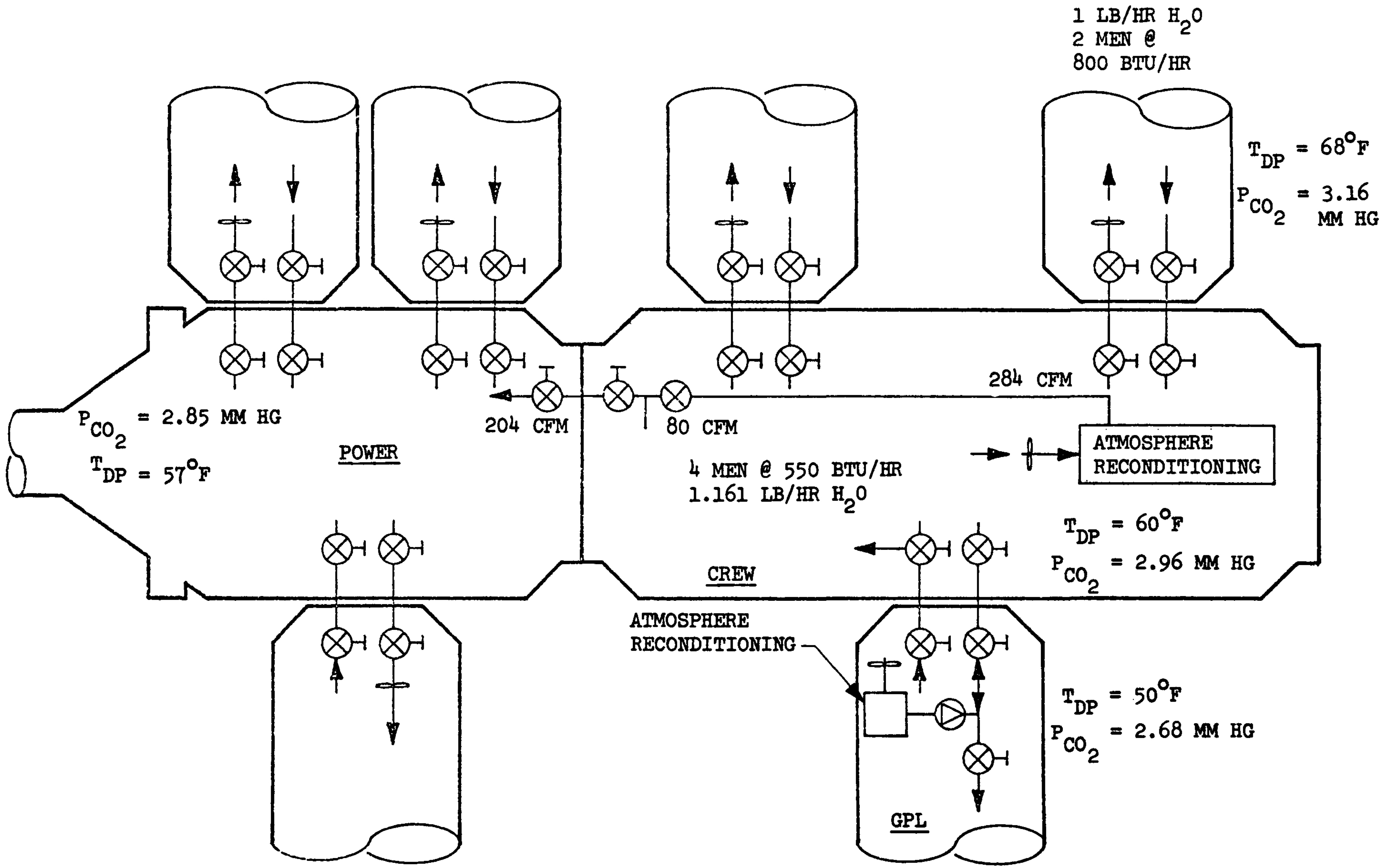

FIGURE 3 .6 PARALLEL FLOW DESIGN CONDITIONS

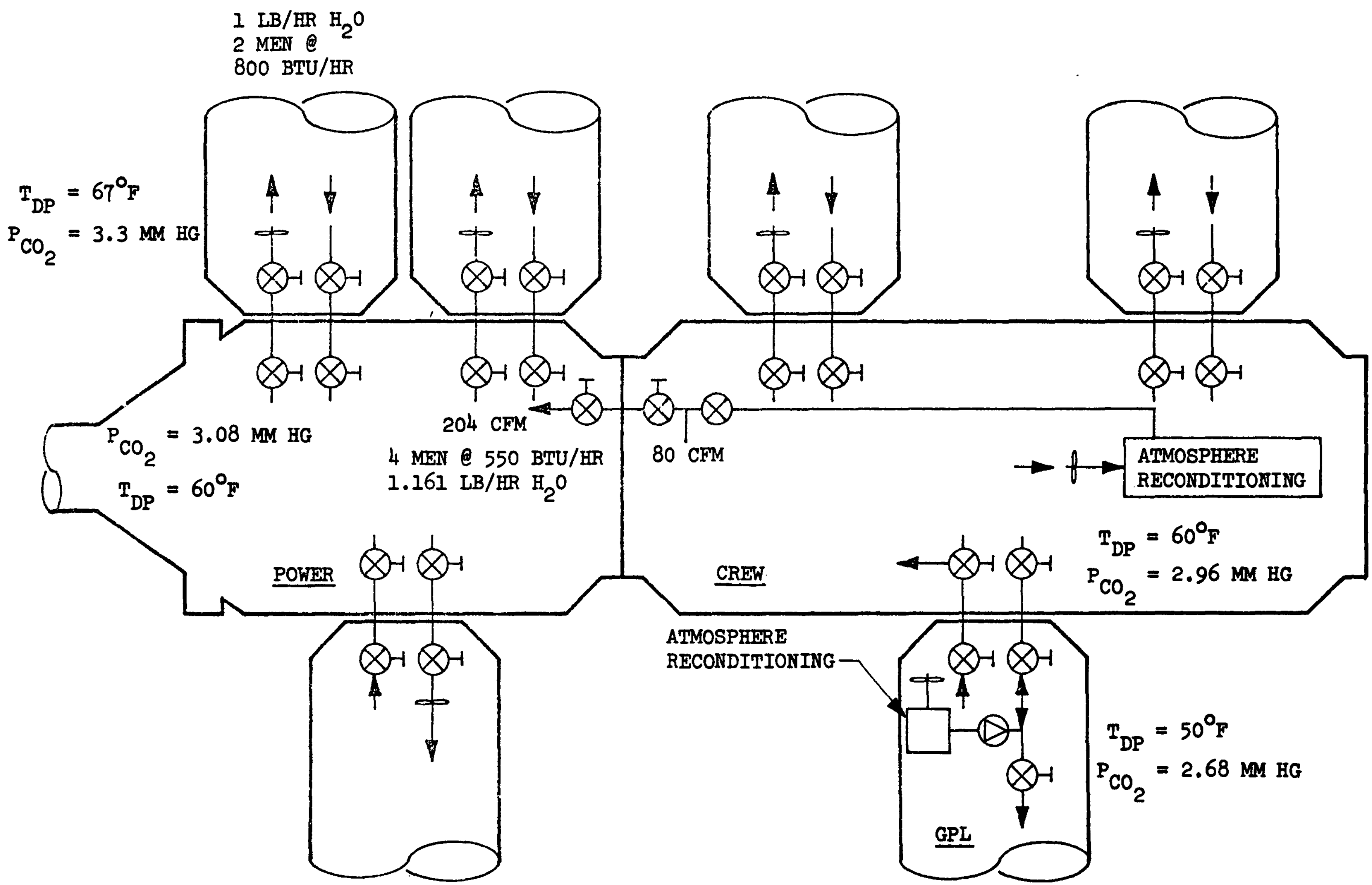

FIGURE 3.7 PARALLEL FLOW CASE 1 CONDITIONS

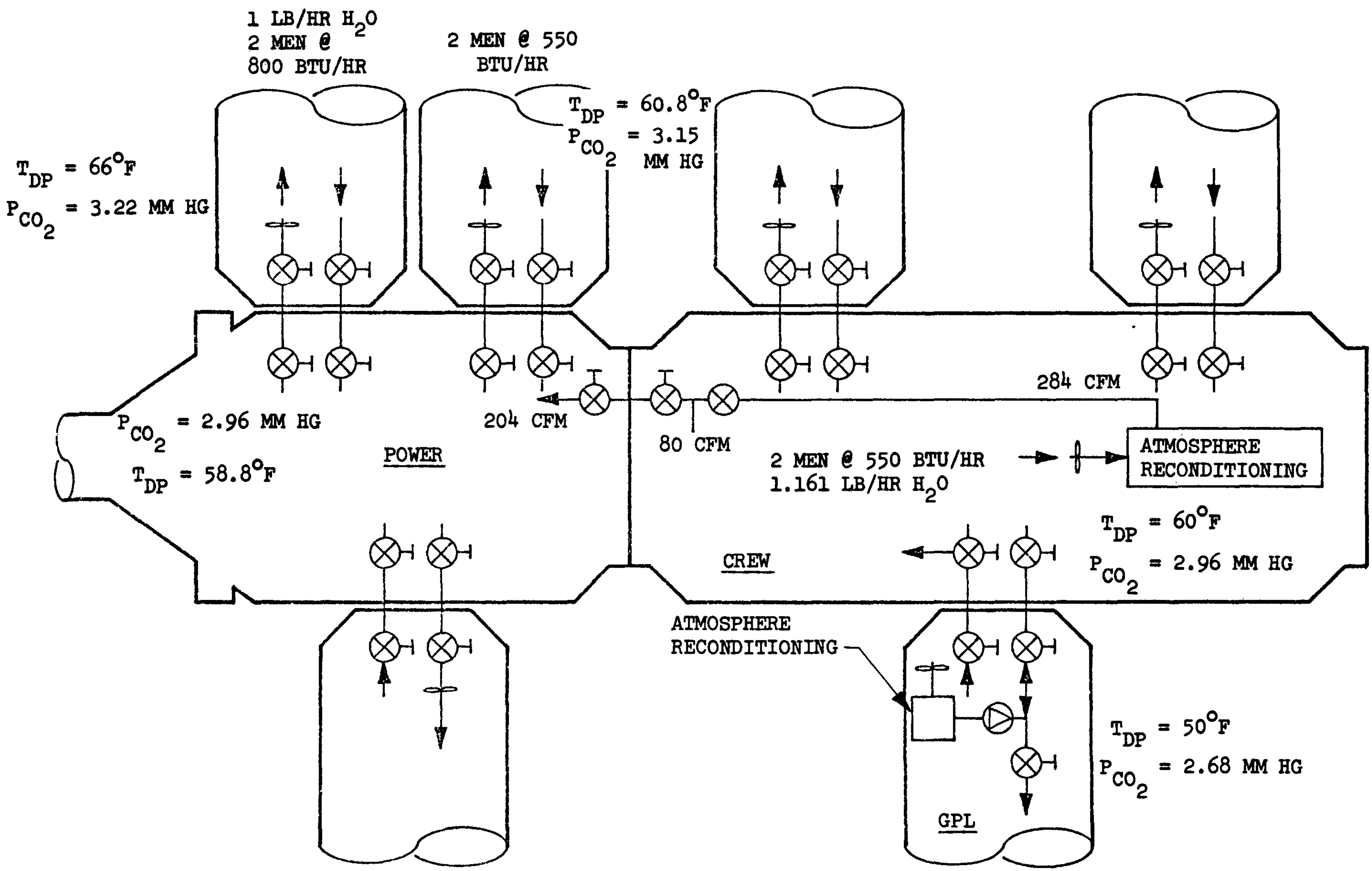

FIGURE 3.8 PARALLEL FLOW CASE 2 CONDITIONS

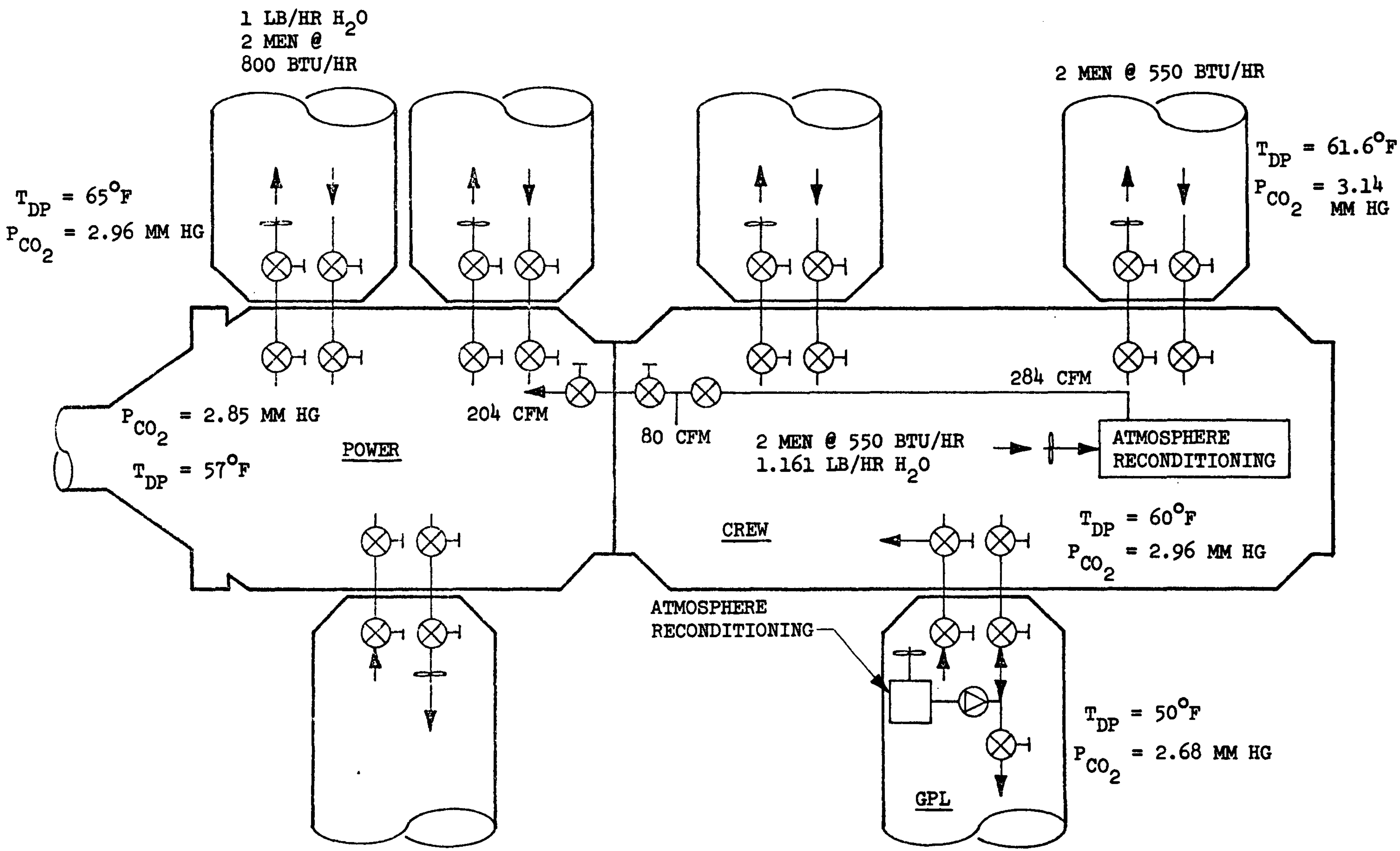

FIGURE 3.9 PARALLEL FLOW CASE 3 CONDITIONS

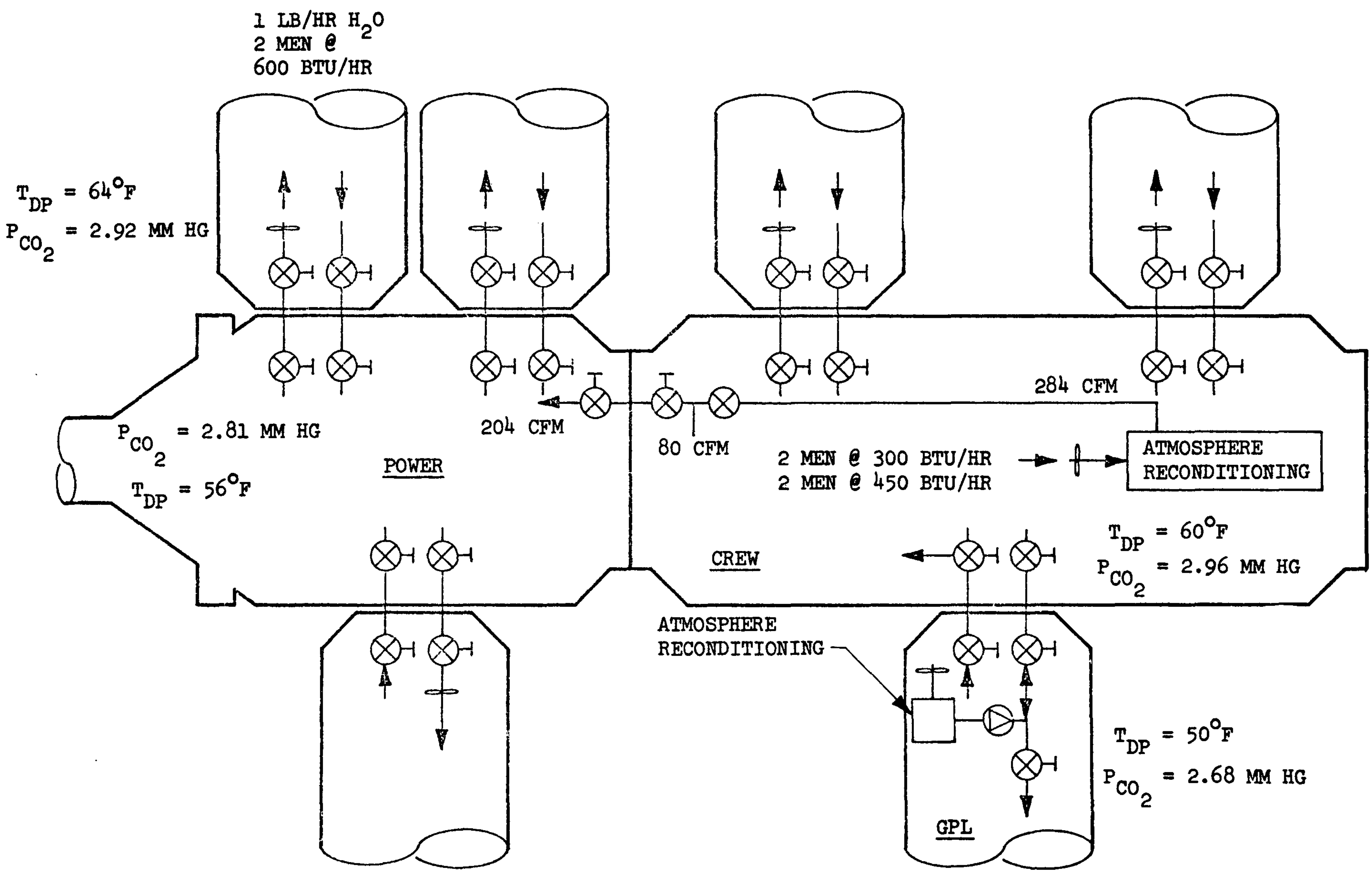

FIGURE 3.10 PARALLEL FLOW CASE 4 CONDITIONS

that in several cases the CO_2 level climbs above the design level of 0.4 kN/m^2 (3.0 mm Hg). In order to maintain the design level, an increased atmospheric flow rate is required. Table 3.1 indicates the flow rate required for each module in order to maintain a CO_2 partial pressure of 0.4 kN/m^2 (3.0 mm Hg) or below.

As stated previously no increase in mass flow from the ARA will be required if a series arrangement is utilized. The higher than design flow required in some modules to maintain a 0.4 kN/m^2 (3.0 mm Hg) CO_2 level and 14.5°C (58°F) dew point can be met by drawing a larger quantity of air from the series duct serving the experiment modules. Table 3-1 for example shows that 8.46×10^{-2} m^3/sec (180 cfm) would be required in experiment module 1 if the conditions in case 1 were to occur. This increase from the 6.4×10^{-2} m^3/sec (136 cfm) design could easily be met from the available 9.6×10^{-2} m^3/sec (204 cfm) being handled in the series duct. The parallel arrangement, however, will require an increase in primary air from the ARA if the off-design conditions are to be satisfied and not exceed 0.4 kN/m^2 (3.0 mm Hg) and 14.5°C (58°F) dew point. Table 3-1 indicates that 18.6 m^3/sec (396 cfm) of primary air would be required to satisfy case 2. To supply this larger flow would create additional weight, volume, and power penalties for the ARA.

Trade-off Results

A trade-off analysis was made between the series and parallel arrangement to determine overall penalties for each. Calculations for the parallel arrangements show that an increased mass flow is required from the ARA. Transport duct requirements, however, are reduced from that needed with the series arrangement. Results of the analysis for both arrangements are shown in Table 3.2. Initial ARA weight, volume and power requirements have been taken from Reference 1 for the series arrangement. Transport duct weight and volume have been calculated. All values given for both the series and parallel arrangement were calculated based on meeting the off-design conditions listed in Table 2.1. Penalties were assigned and the results indicate that the series arrangement has approximately a 26% lower dollar valuation than the parallel arrangements.

Table 3.1

PRIMARY AIR FLOW REQUIRED FOR MAINTAINING

$P_{co_2} \leq 0.4$ kN/m^2(3.0 mm Hg) & $T_{DP} \leq 15.6°C(60°F)$

CASE I.D.	SERIES ARRANGEMENT				PARALLEL ARRANGEMENT			
	POWER MODULE	EXP. MOD. 1	EXP.MOD. (OTHER)	CREW MODULE	POWER MODULE	EXP. MOD. 1	EXP.MOD. (OTHER)	CREW MODULE
DESIGN	9.6×10^{-2} m^3/sec 204 cfm		6.4×10^{-2} m^3/sec 136 cfm	13.35×10^{-2} m^3/sec 284 cfm	9.6×10^{-2} m^3/sec 204 cfm		6.4×10^{-2} m^3/sec 180 cfm	13.35×10^{-2} m^3/sec 284 cfm
CASE 1	9.6×10^{-2} m^3/sec 204 cfm	6.4×10^{-2} m^3/sec 180 cfm		13.35×16^{-2} m^3/sec 284 cfm	13.35×10^{-2} m^3/sec 284 cfm	12.24×10^{-2} m^3/sec 260 cfm		13.35×10^{-2} m^3/sec 284 cfm
CASE 2	9.6×10^{-2} m^3/sec 204 cfm	6.4×10^{-2} m^3/sec 136 cfm	6.4×10^{-2} m^3/sec 136 cfm	13.35×10^{-2} m^3/sec 284 cfm	18.6×10^{-2} m^3/sec 396 cfm	6.4×10^{-2} m^3/sec 180 cfm	7.76×10^{-2} m^3/sec 165 cfm	18.6×10^{-2} m^3/sec 396 cfm
CASE 3	9.6×10^{-2} m^3/sec 204 cfm	6.4×10^{-2} m^3/sec 136 cfm	6.4×10^{-2} m^3/sec 136 cfm	13.35×10^{-2} m^3/sec 284 cfm	9.6×10^{-2} m^3/sec 204 cfm	10.85×10^{-2} m^3/sec 136 cfm	7.76×10^{-2} m^3/sec 165 cfm	13.35×10^{-2} m^3/sec 284 cfm
(AVERAGE) CASE 4	9.6×10^{-2} m^3/sec 204 cfm	6.4×10^{-2} m^3/sec 136 cfm		13.35×10^{-2} m^3/sec 284 cfm	9.6×10^{-2} m^3/sec 204 cfm	6.4×10^{-2} m^3/sec 136 cfm		13.35×10^{-2} m^3/sec 284 cfm

Table 3.2

OPTION PENALTIES FOR SERIES AND PARALLEL ARRANGEMENT

OPTION	VOLUME $m^3 (ft^3)$	VOLUME PENALTY	WEIGHT kg(lbs)	WEIGHT PENALTY	POWER (WATTS)	POWER PENALTY	TOTAL PENALTY
SERIES							
Crew Module*	.454(16.1)	$24,200	21.1(46.5)	$11,600			
Power Module*	.229(8.1)	$12,140	11.4(25.1)	$6,280	1004		
Experiment Modules*	.0875(3.1)	$4,800	30.4(67.2)	$16,800			
ARA	3.33(118.1)	$177,000	650(1438)	$359,500			
Total	4.1(145.5)	$218,140	714(1576.8)	$394,180		$1,280,000	$1,892,320
PARALLEL							
Crew Module*	.215(7.6)	$11,400	10.02(22.3)	$5,580			
Power Module	.102(3.6)	$5,420	5.0(11.1)	$2,780			
Experiment Module*	.107(3.8)	$5,700	35.6(79.1)	$19,800	1445		
ARA	4.65(164.2)	$246,000	898(1995)	$499,000			
Total	5.08(179.2)	$268,520	948(2107.5)	$527,160		$1,778,000	$2,573,680

Weight - $250/lb Launch, Volume - $1,500/$ft^3$, Power - $1,230/watt

* - includes valves, dampers and diffusers

Section 4.0

FLIGHT DESIGN

A flight design for the ventilation system has been configured around the series arrangement with ducting arranged to allow for contingency operation in event one ARA becomes inoperative.

System Layout

Figures 4.1 thru 4.3 show the transport duct layout for the series configuration in the major modules. Duct sizes are shown in addition to damper/valves.

Contingency Operation

Contingency operation occurs when a reconditioning unit becomes inoperative in one of the core modules. If the Crew/Operations Module unit is inoperative the atmosphere distribution duct valves are opened between compartments and the shut-off valve is closed in the GPL distribution duct which is normally used. Backflow of air through the Crew/Operations Module reconditioning unit is prevented by a check valve. The atmosphere leaving the Power/Subsystems Module passes through the Crew/Operations Module and then to the GPL carrying the generated water vapor and CO_2 back to the GPL reconditioning unit.

If the GPL reconditioning unit fails, the atmosphere ducting valves are opened between the GPL and Crew/Operations Modules and a portion of the reconditioned air from the Crew/Operations Module is directed to the GPL. Backflow is prevented through the GPL reconditioning unit by a check valve. The flow split between the GPL and Crew/Operations Modules is adjusted with the shut-off valves located in the distribution ducts to correspond to the water vapor and CO_2 loads in the modules.

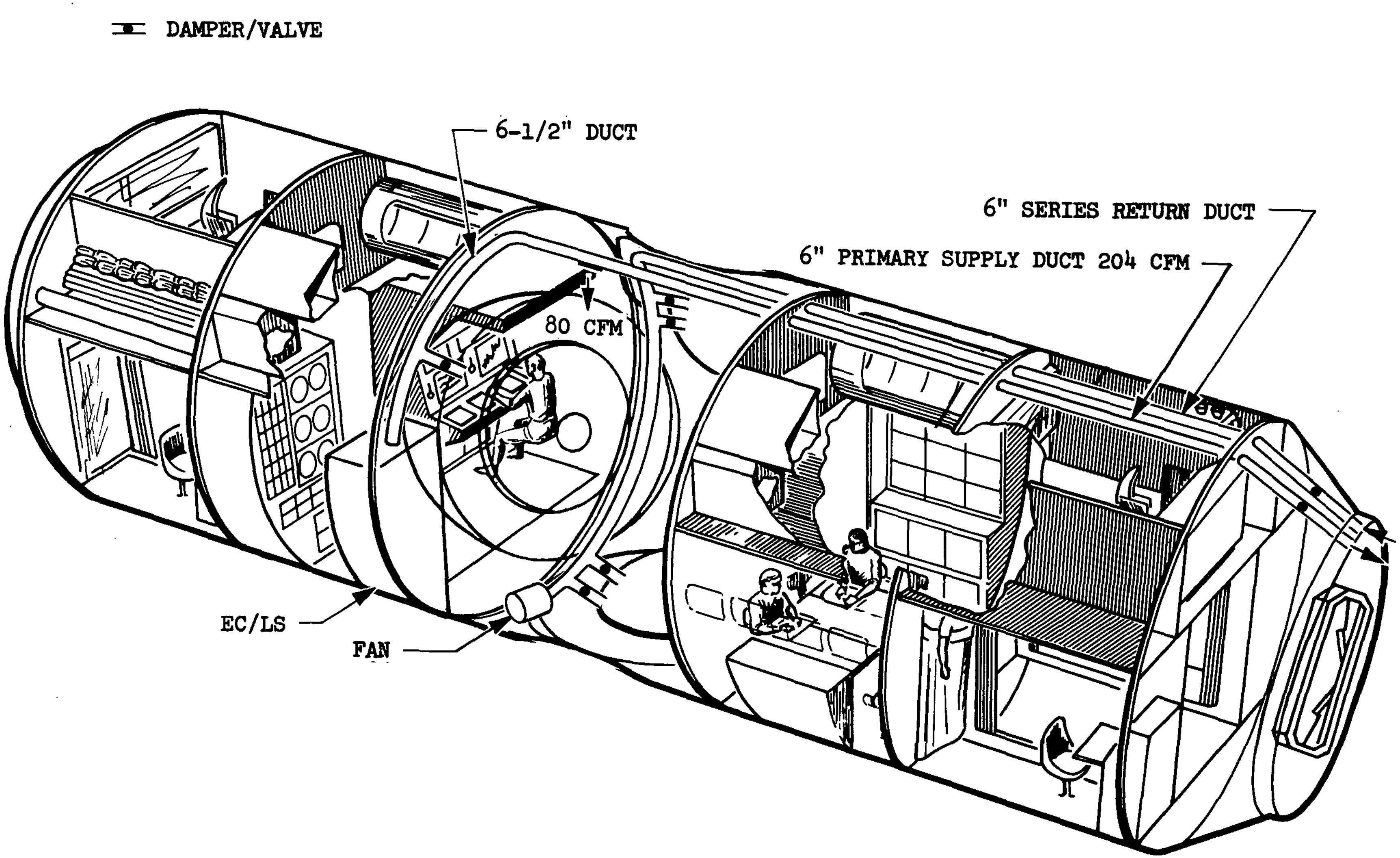

FIGURE 4.1 CREW MODULE PRIMARY AIR DUCT LAYOUT

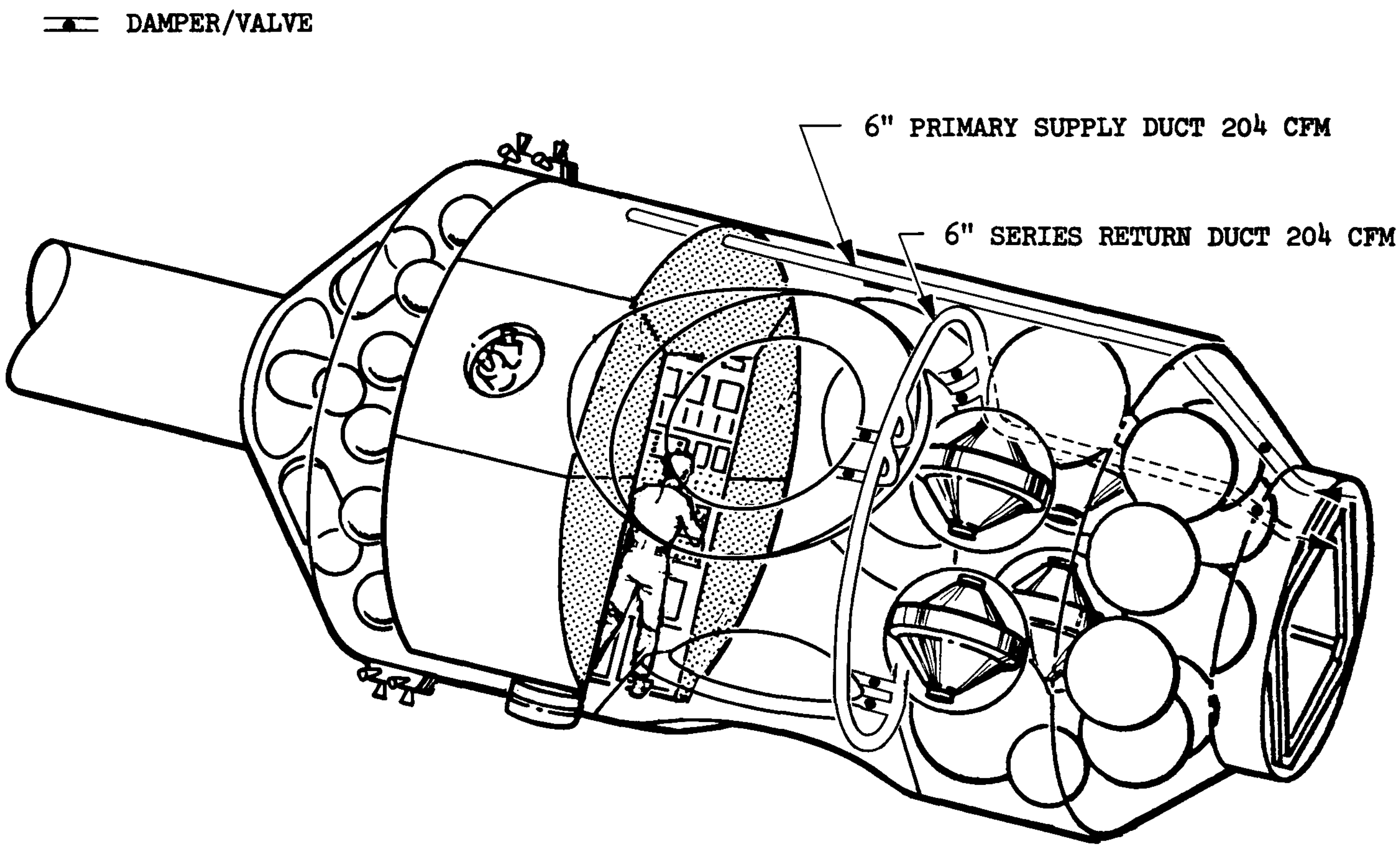

FIGURE 4.2 POWER MODULE PRIMARY AIR DUCT LAYOUT

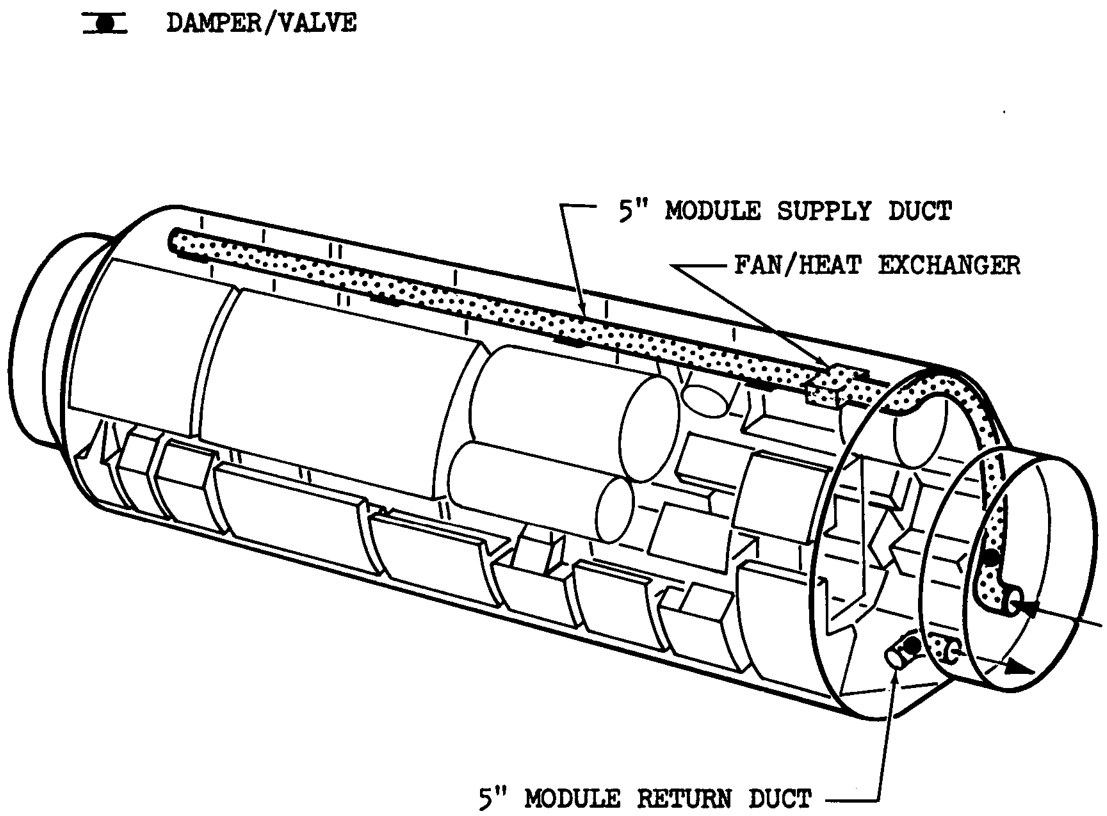

FIGURE 4.3 TYPICAL EXPERIMENT MODULE DUCT LAYOUT

A diverter valve is located in the Crew/Operations Module which allows the Power/Subsystems Module to be isolated if unoccupied. Distribution duct shut-off valves are closed between the Crew/Operations Module and Power/ Subsystems Module and the diverter valve is positioned so that the entire flow from the reconditioning unit is distributed within the Crew/Operations Module.

<u>References</u>:

1. Modular Space Station Detailed Preliminary Design - Vol. II, MDC G2582, Nov. 1971.