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STUDY REPORT

LIGHTSIDE ATMOSPHERIC REVITALIZATION SYSTEM

BY

ARTHUR K. COLLING, ROSS J. CUSHMAN,
MARK M. HULTMAN, AND JOHN R. NASON

PREPARED UNDER CONTRACT NO. NAS 9-13624

BY

HAMILTON STANDARD
DIVISION OF UNITED TECHNOLOGIES CORPORATION
WINDSOR LOCKS, CONNECTICUT

FOR

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LYNDON B. JOHNSON SPACE CENTER
HOUSTON, TEXAS

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ABSTRACT

A closed-loop atmosphere revitalization system was studied as a replacement to the present baseline LiOH system for extended duration shuttle missions. The system consists of three subsystems: a solid amine water desorbed regenerable carbon dioxide removal system, a water vapor electrolysis oxygen generating system, and a Sabatier reactor carbon dioxide reduction system. The system is called the Lightside Atmospheric Revitalization System (LARS), since it is designed for use on a solar powered shuttle vehicle. The majority of the system's power requirements are utilized on the sun side of each orbit, when solar power is available.

FOREWORD

This report has been prepared by Hamilton Standard, Division of United Technologies Corporation, for the National Aeronautics and Space Administration's Lyndon B. Johnson Space Center in accordance with Contract NAS 9-13624, "Breadboard and Flight Prototype CO_2 and Humidity Control Systems." The report covers work accomplished on the Lightside Atmospheric Revitalization System study phase of the program between April 1, 1980 and September 30, 1980.

Appreciation is expressed to the Technical Monitor, Mr. Frank Collier of the NASA, Johnson Space Center, for his guidance and advice.

This program was conducted under the direction of Mr. Harlan F. Brose, Program Manager, and Mr. Albert M. Boehm and Mr. Arthur K. Colling, Program Engineers, with the assistance of Messrs. Ross J. Cushman, Mark M. Hultman, and John R. Nason, Analysis and Messrs. David L. Faye and Philip F. Heimlich, Design.

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SUMMARY

The Lightside Atmospheric Revitalization System (LARS) is an attractive improvement to the Shuttle Orbiter ARS for extended duration missions.

The LARS study was divided into seven parts: system requirements, system description, system performance, comparison to present shuttle ECS, system effectiveness studies, subsystem sizing and operating characteristics, and system integration.

The primary requirement for the LARS is to maintain the atmosphere for a crew of six with either a 62.05 or 101.35 kPa (9 or 14.7 psia) cabin pressure. The nominal CO_2 level is 5 mmHg, and oxygen partial pressure limits are 17.58 $\pm$ 1.03 kPa (2.55 $\pm$ .15 psia) for a 62.05 kPa (9 psia) cabin pressure and 22.06 $\pm$ 1.72 kPa (3.2 $\pm$ .25 psia) for a 101.35 kPa (14.7 psia) cabin pressure. Normal limits for cabin temperature and dewpoint are 18.33 to 26.67°C (65-80°F) and 3.89 to 16.11°C (39-61°F), respectively. The LARS must fit into the volume of the existing CO_2 control system and LiOH storage.

The LARS is shown schematically in Figure 1. It consists of three subsystems: a solid amine water desorbed (SAWD) regenerable CO_2 removal subsystem, a water vapor electrolysis (WVE) oxygen generation subsystem, and a Sabatier CO_2 reduction subsystem. The system schematic is similar to the initial concept, except the SAWD subsystem has two beds instead of one. The selection of two beds helps to level the cabin temperature and humidity peaks resulting after adsorption is started on a bed. Additionally, reliability is increased with two beds.

The entire LARS is designed for operation in a solar powered shuttle vehicle. Most of its power utilization is during the light side of each orbit. On fuel cell powered vehicles, the WVE and Sabatier subsystems would not generally be used. However, the SAWD subsystem would be used for CO_2 control. Since the three subsystems are designed for integration into the shuttle vehicle in phases as field installations, the SAWD subsystem should be installed for all missions and the WVE and Sabatier subsystems can be added later for longer missions that use solar power.

An analysis of the LARS was conducted with particular emphasis on the SAWD and WVE subsystems. The complete analysis, design, and testing of a preprototype Sabatier subsystem has recently been completed by Hamilton Standard under Contract NAS 9-15470. A typical profile of SAWD subsystem CO_2 performance for a six-man crew is shown in Figure 2. WVE cell performance was predicted, and oxygen production for various cell voltages and inlet dewpoints is shown in Figure 3. Cabin temperature and dewpoint were predicted for an orbiter with the LARS installed. The results for the design case of a six-man crew, nominal heat loads, and a 62.05 kPa (9 psia) cabin pressure are given in Figure 4. Additionally, cabin air flow charts and Sabatier flow charts were

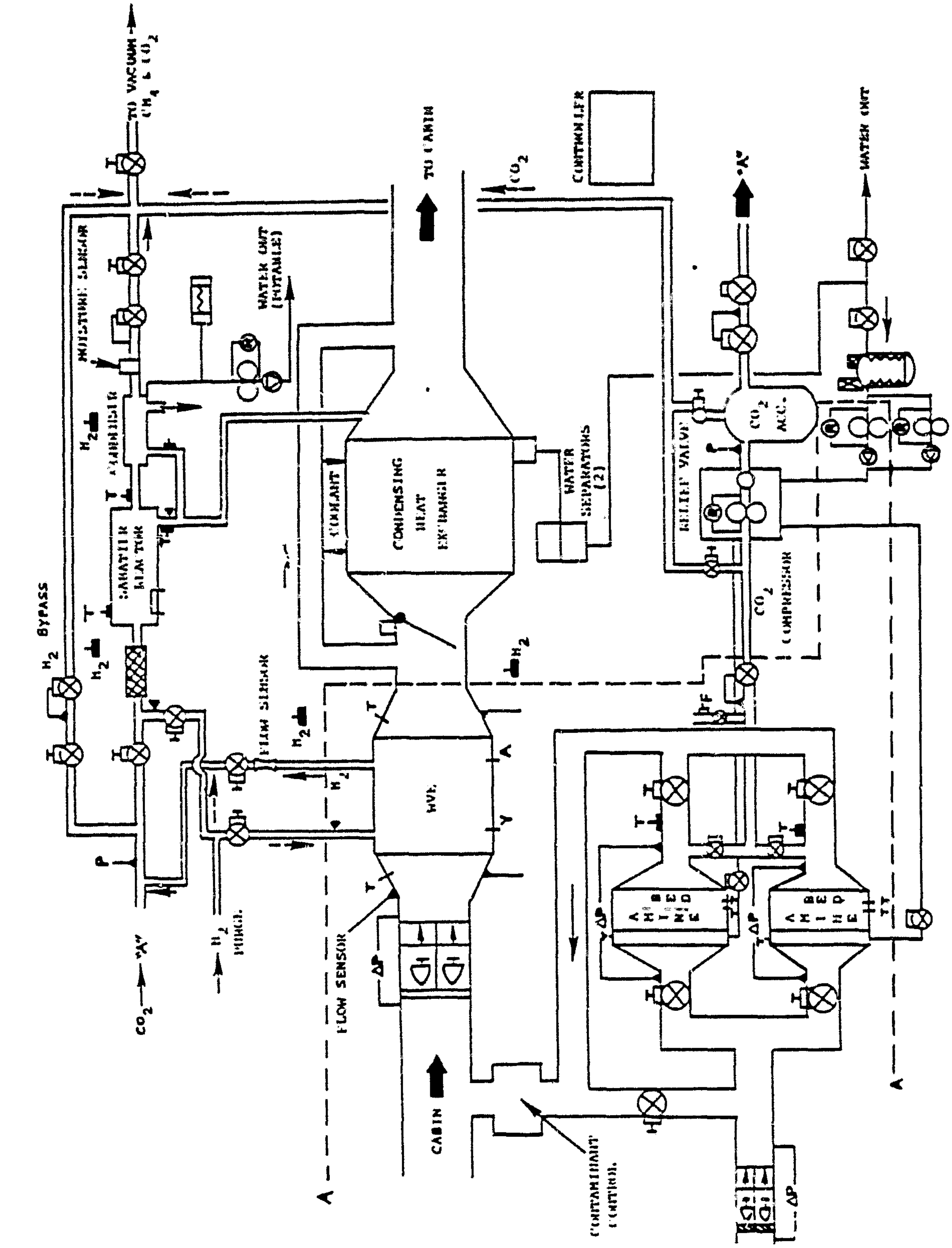


FIGURE 1
LARS SCHEMATIC

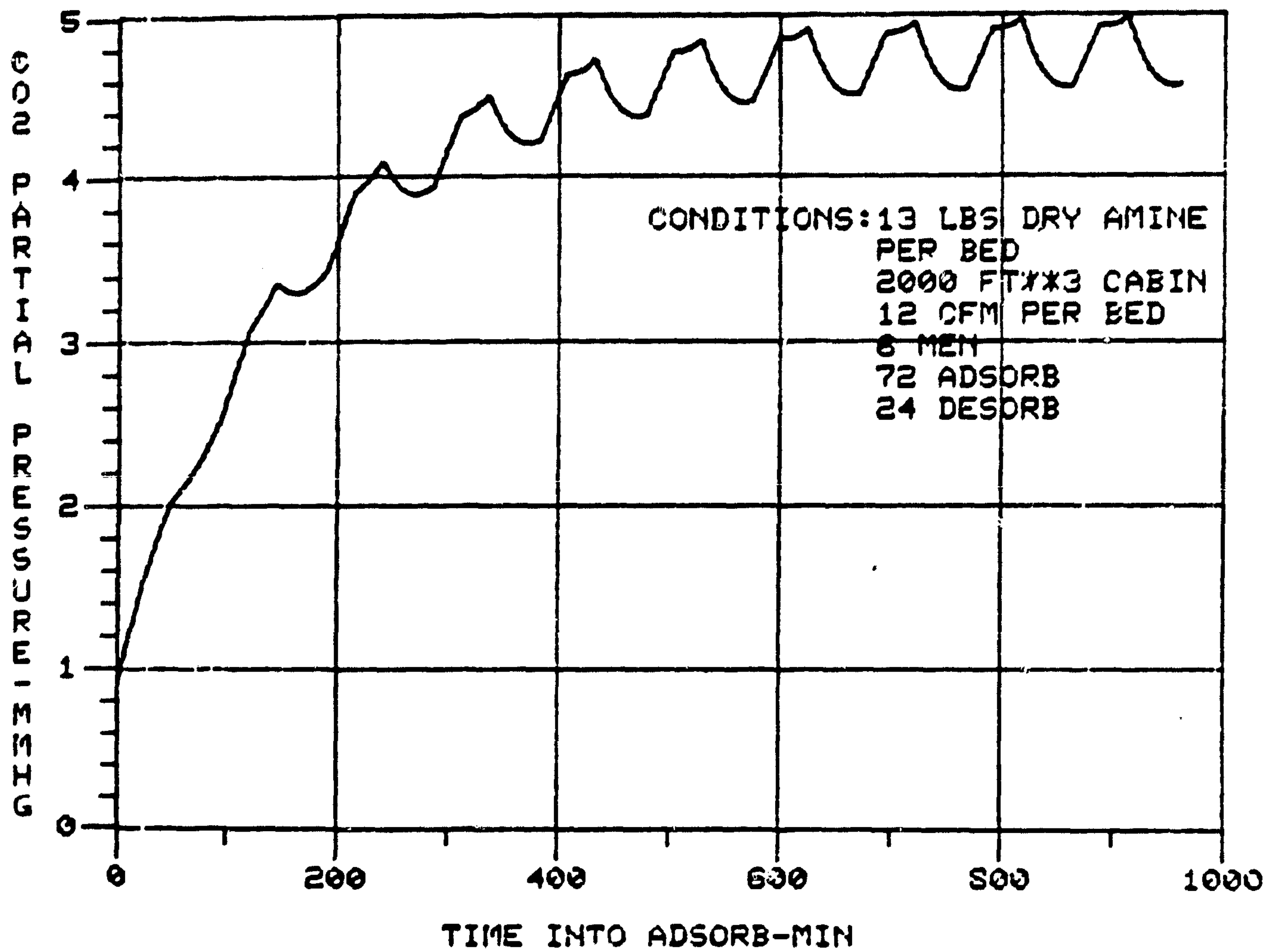


FIGURE 2

CO_2 PARTIAL PRESSURE PROFILE FOR TWO BED LARS SYSTEM

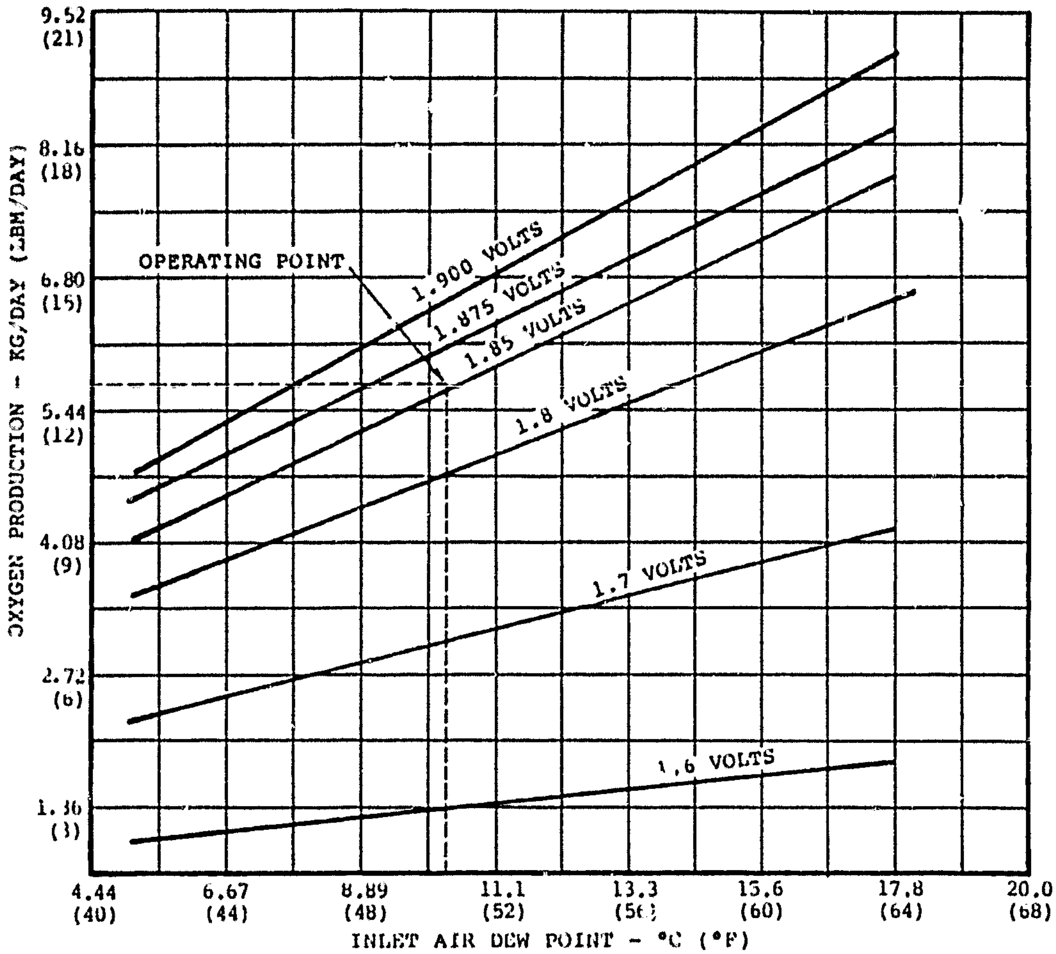
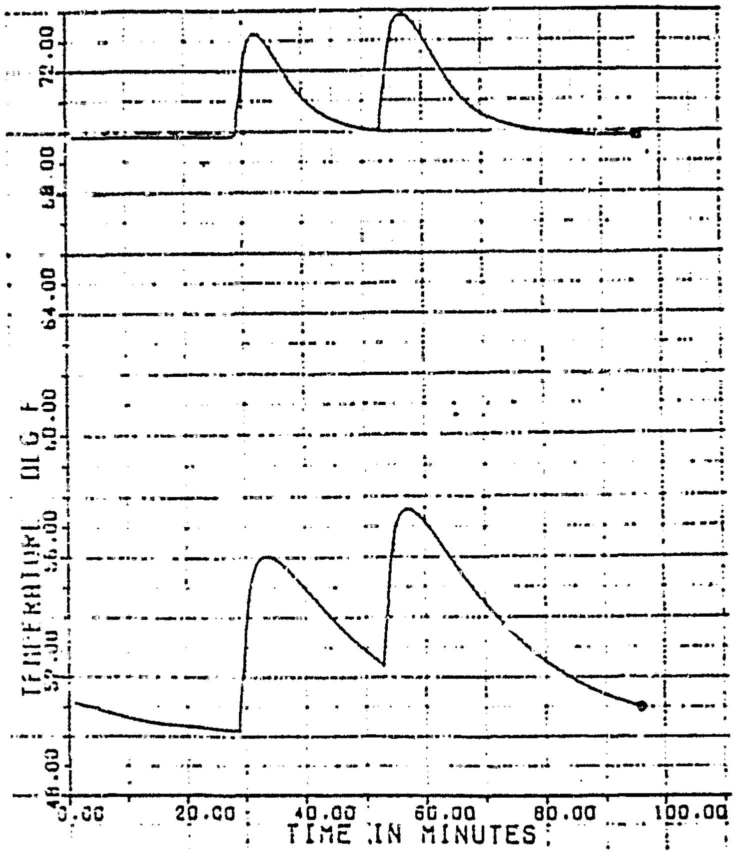


FIGURE 3

WVE 15 CELL PERFORMANCE



□ CABIN TEMPERATURE--DEG F
○ CABIN DEWPOINT--DEG F

FIGURE 4

LARS SYSTEM STUDY
6 MEMBER CREW 9 PSIA
NOMINAL HEAT LOAD
CABIN TEMPERATURE AND DEWPOINT

developed to show the temperatures, dewpoints, and heat loads at various points in the system at the time of the highest cabin dewpoint during an orbit. Sample charts for the six-man, 62.05 kPa (9 psia) cabin pressure, nominal heat load case are given in Figures 5 and 6. Performance curves and charts similar to these, but for various crew sizes and cabin conditions, are provided in the discussion section of this report.

A trade study was conducted to compare the LARS to the baseline LiOH system for PEP and power system missions. Since the LARS can be installed aboard the orbiter in increments of the SAWD subsystem only, the SAWD and WVE subsystems, or the entire LARS, each of these combinations was compared to the baseline LiOH system. For all missions considered the addition of a SAWD subsystem provided significant savings in weight and volume. The addition of the WVE and Sabatier subsystems does not affect weight or volume requirements significantly, but allows large increases in mission length for PEP missions using a sun synchronous orbit or for power system missions. A summary of the trade study results is given in Table 1.

All of the components of the LARS are designed as line replacement items. No in-flight maintenance is required, except the periodic replacement of the contaminant control canister (approximately every 10 days).

The subsystem sizing and operating characteristics portion of the study provided necessary data for the other sections of the study. The requirements for the SAWD subsystem were determined to be two canisters, each containing 5.90 kg (13 lbm) of dry solid amine material. Nominal flow for each canister is .340 m^3/min (12 CFM), provided by one IMU fan. An analysis of solid amine drying characteristics has shown that for the various cabin temperature and relative humidity conditions experienced, the SAWD beds maintain moisture stability. Each bed operates on a 72 minute adsorption and 24 minute desorption cycle. The two beds' cycles are offset by approximately 24 minutes to limit peak power requirements by only desorbing one bed at a time.

Based on the WVE cell performance curves of Figure 3, the WVE subsystem was sized at 15 cells. This will supply the cabin leakage and metabolic oxygen for a six-man crew without exceeding 1.90 volts per cell.

Power requirement profiles for an orbit were generated from subsystem performance and operating characteristics. The profile for the six-man crew, 62.05 kPa (9.0 psia) cabin pressure case is shown in Figure 7.

Since installation of the LARS into the shuttle will potentially be accomplished in phases, packaging drawings have been prepared for both an installation of the SAWD subsystem alone and for the installation of the entire LARS. The packaging drawings are shown in Figures 8 through 13. The goal of locating the system within the volume presently used for CO_2 control and LiOH storage was achieved in both cases.

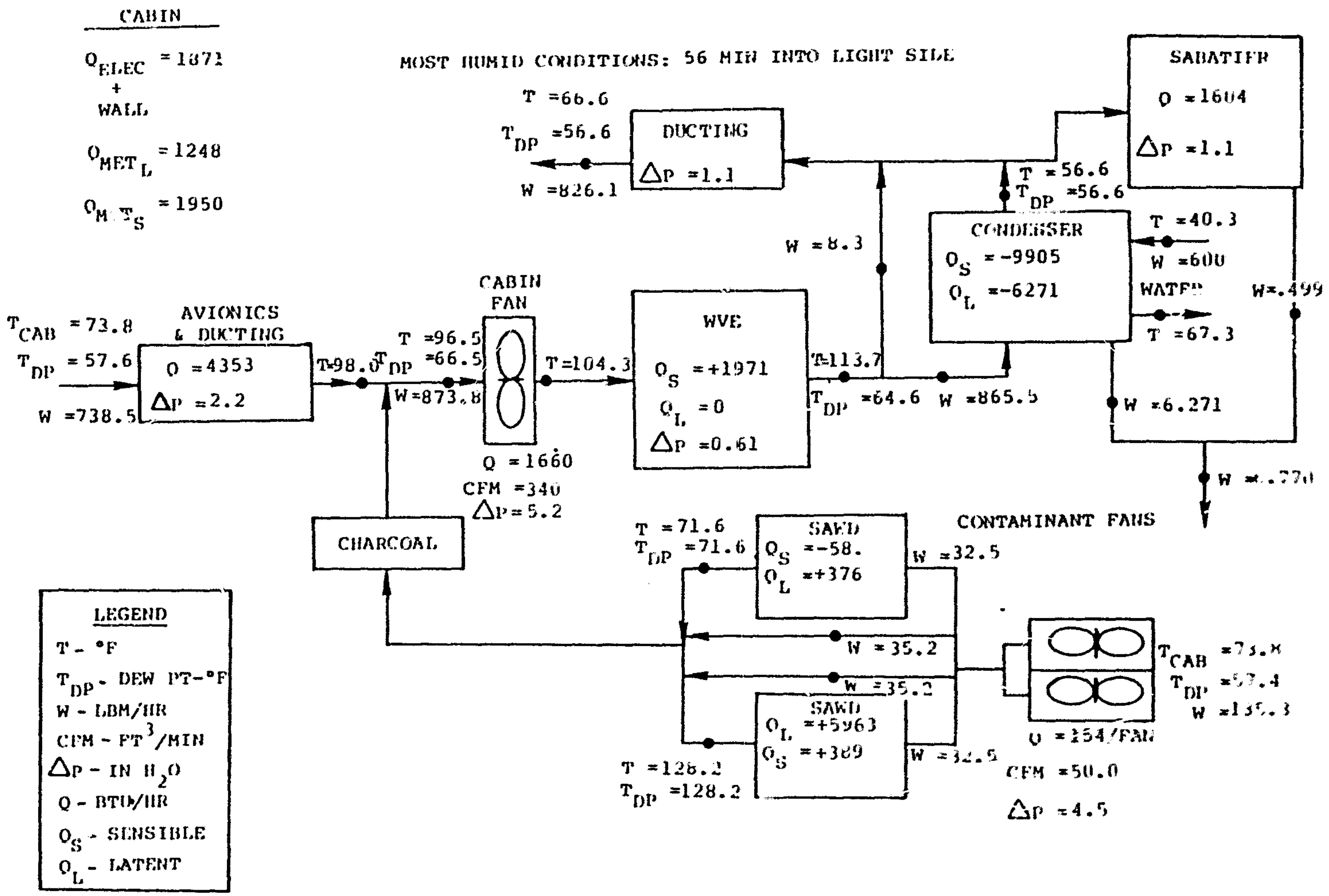


FIGURE 5
CABIN AIR FLOW CHART NOMINAL HEAT LOADS
6 MEMBER CREW 9 PSIA (BASELINE)

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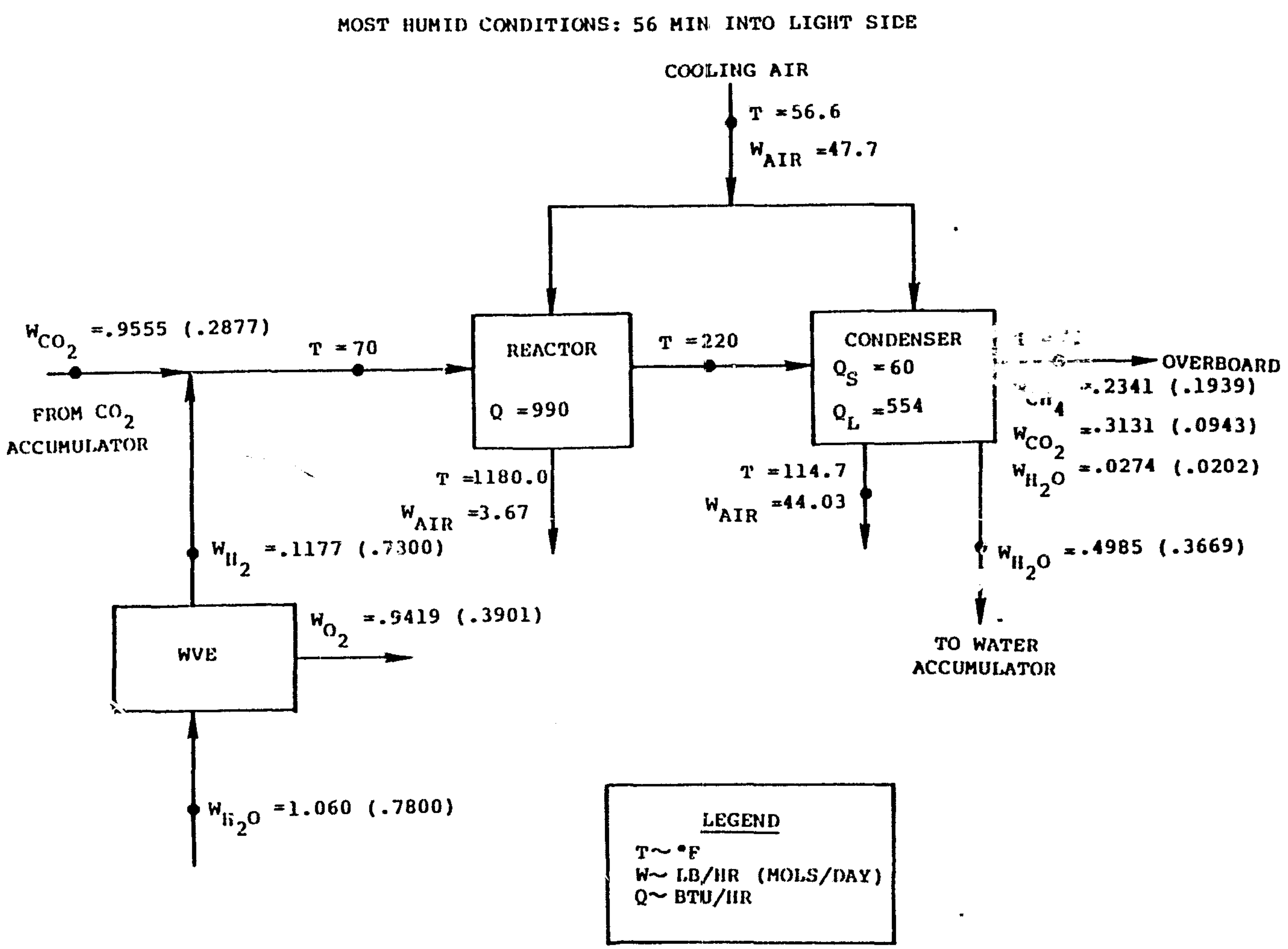


FIGURE 6
SABATIER FLOW CHART
6 MEMBER CREW 9 PSIA

Table 1
TRADE STUDY SUMMARY

MISSION W/4 CRYO KITS	BASELINE MISSION LENGTH DAYS	ADVANTAGES FOR ADDITION OF SAWD SUBSYSTEM	ADVANTAGES FOR ADDITION OF WVE & SABATIER SUBSYSTEMS
PEP 57° INCLINATION FUEL CELL POWER ON DARK SIDE WITH SOLAR CELL PENALTY	17	SAVINGS WEIGHT = 102.95 KG (227 LBM) VOLUME = 0.340 M^3 (12.0 FT^3)	NOT SIGNIFICANT
PEP SUN SYNCHRONOUS FUEL CELLS 2 COLD, 1 HOT START WITH SOLAR CELL PENALTY	57	SAVINGS WEIGHT = 699 KG (1541 LBM) VOLUME = 1.78 M^3 (63 FT^3)	INCREASE MISSION LENGTH BY 14 DAYS
POWER SYSTEM FUEL CELLS ALL COLD START NO SOLAR CELL PENALTY INCLUDES SUPPLEMENTARY WATER STORAGE	80	SAVINGS WEIGHT = 1005 KG (2217 LBM) VOLUME = 2.52 M^3 (89 FT^3)	INCREASE MISSION LENGTH BY 47 DAYS

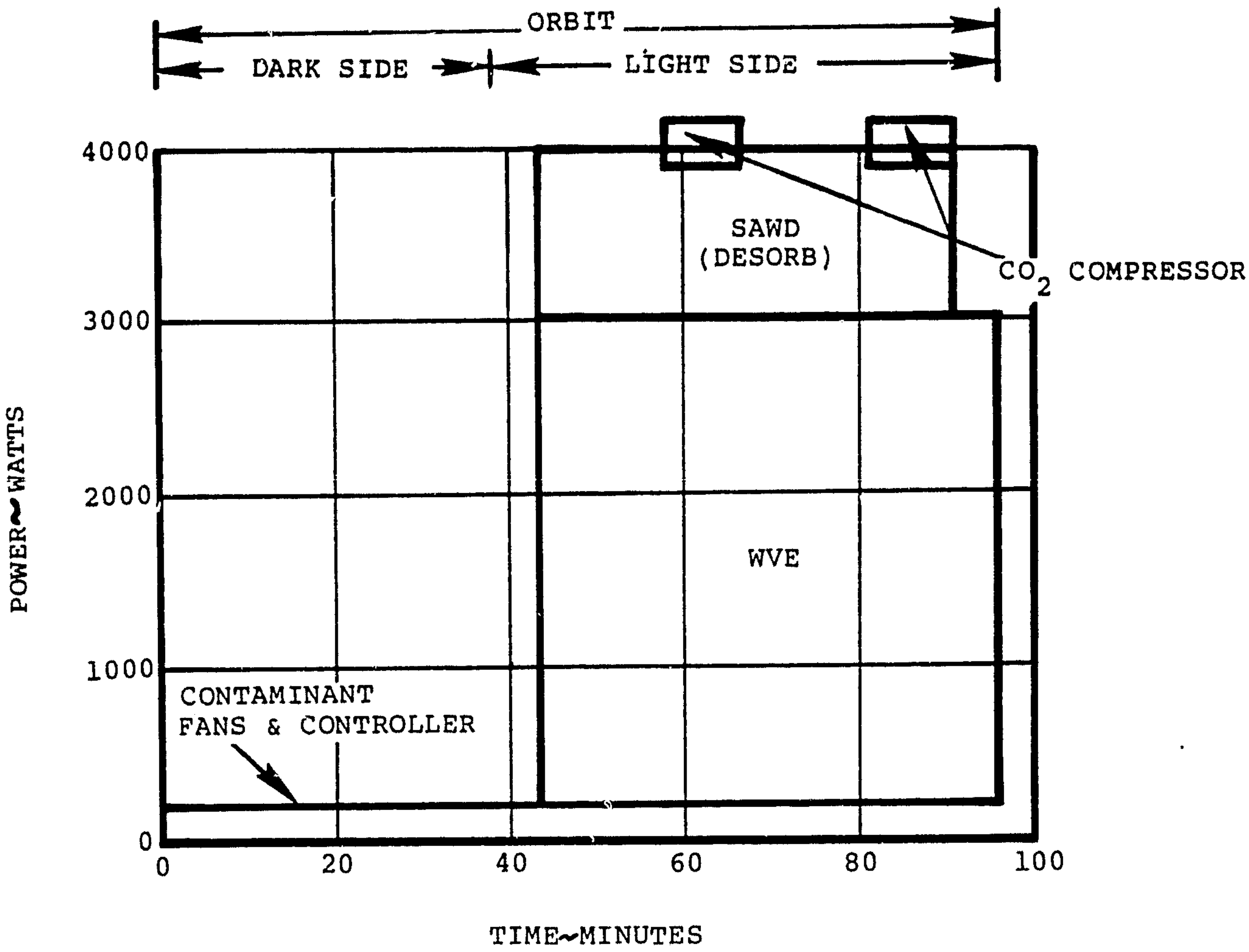


FIGURE 7

LARS SYSTEM STUDY
POWER PROFILE
6 MEMBER CREW 9 PSIA

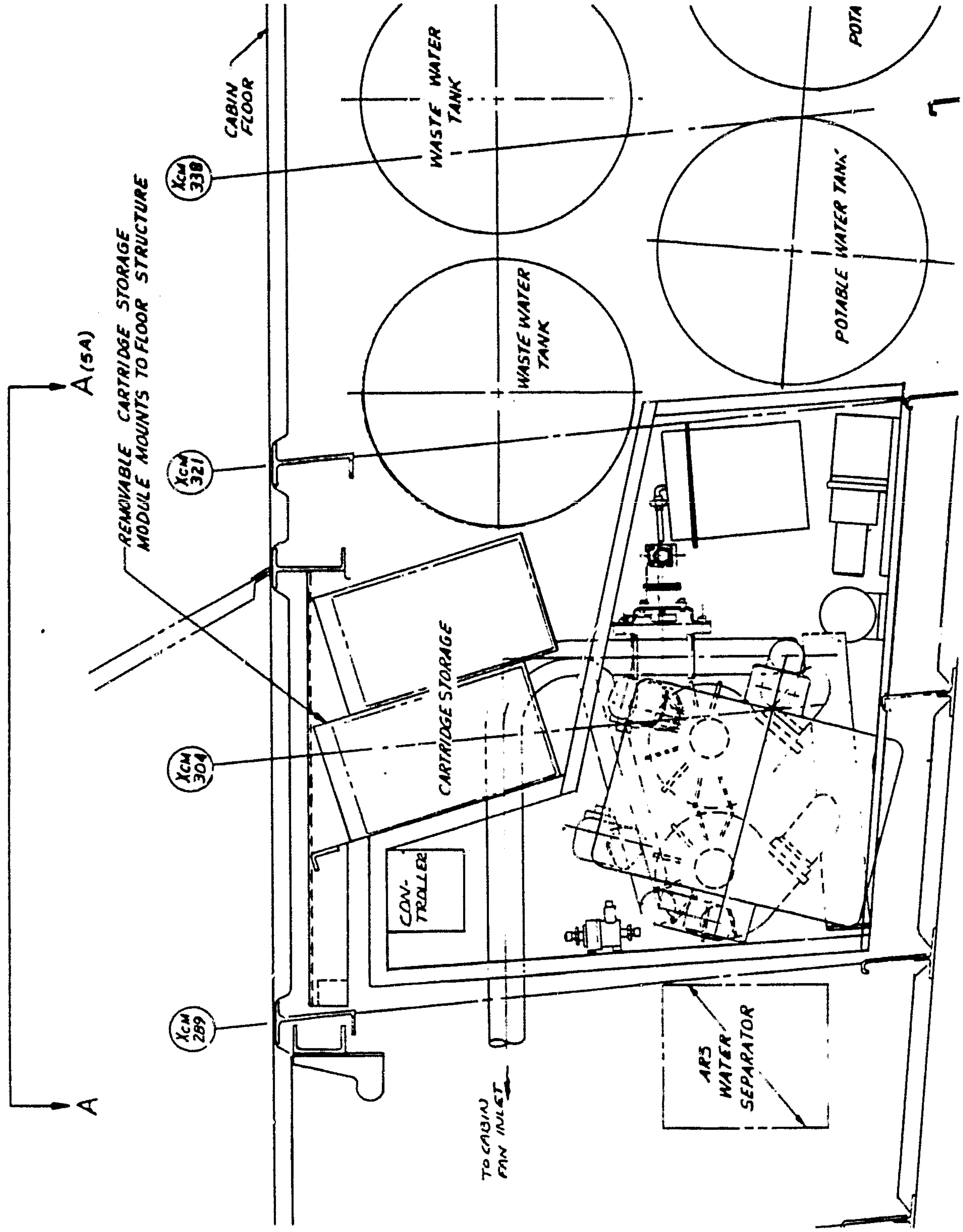


FIGURE 8
SAWD INSTALLATION DRAWING (SHEET 1)

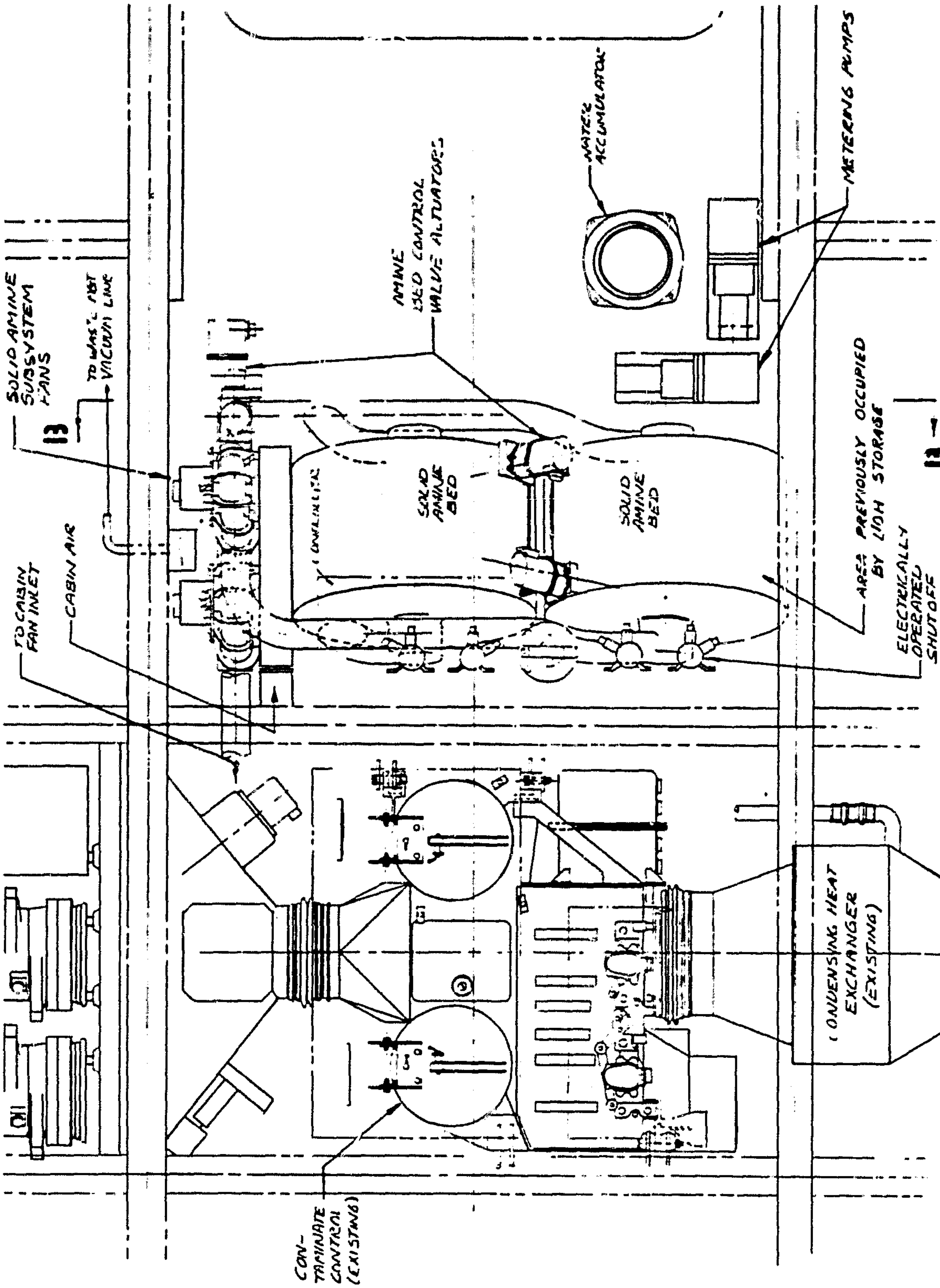


FIGURE 9
SAWD INSTALLATION DRAWING (SHEET 2)

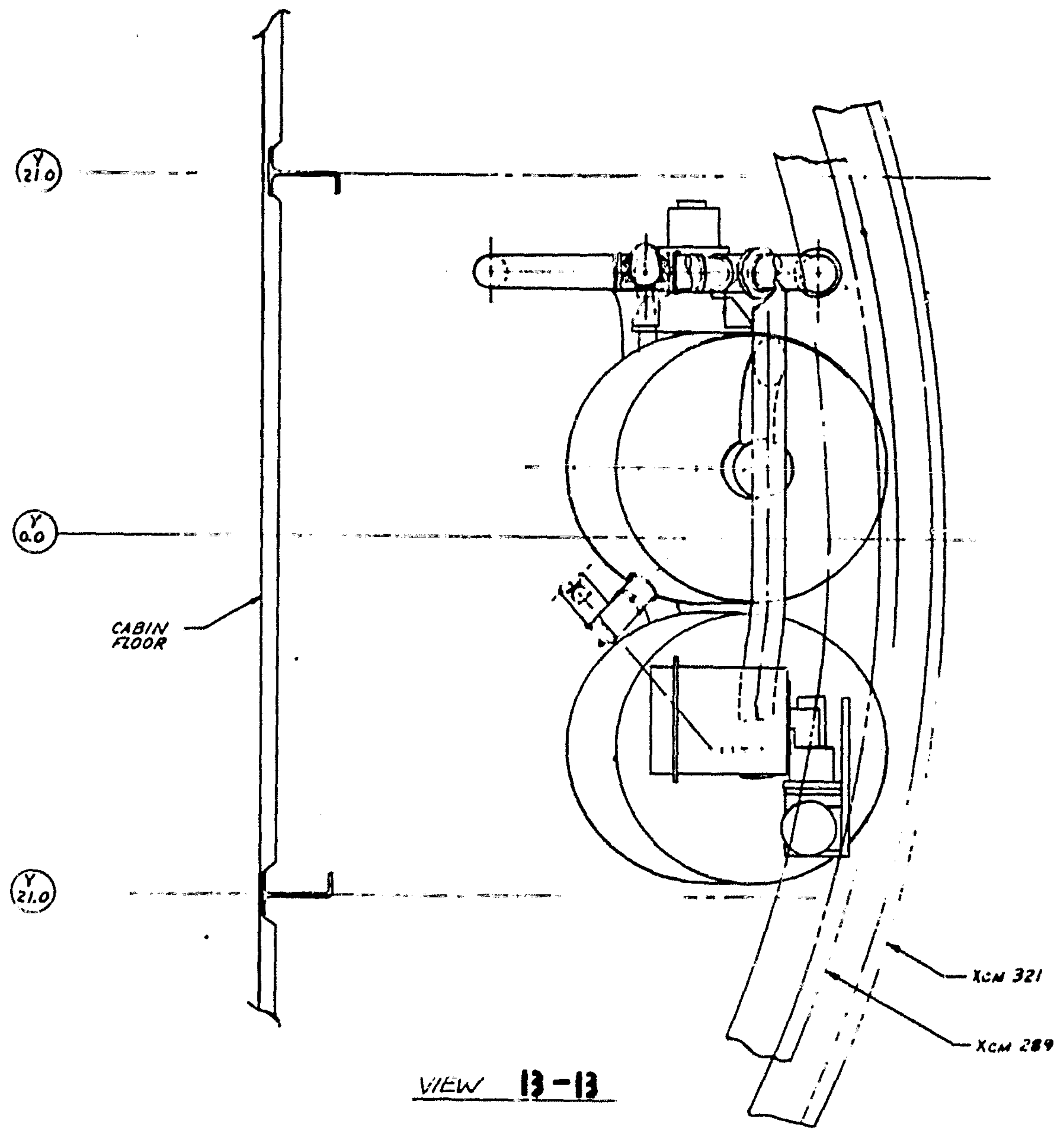


FIGURE 10

SAWD INSTALLATION DRAWING (SHEET 3)

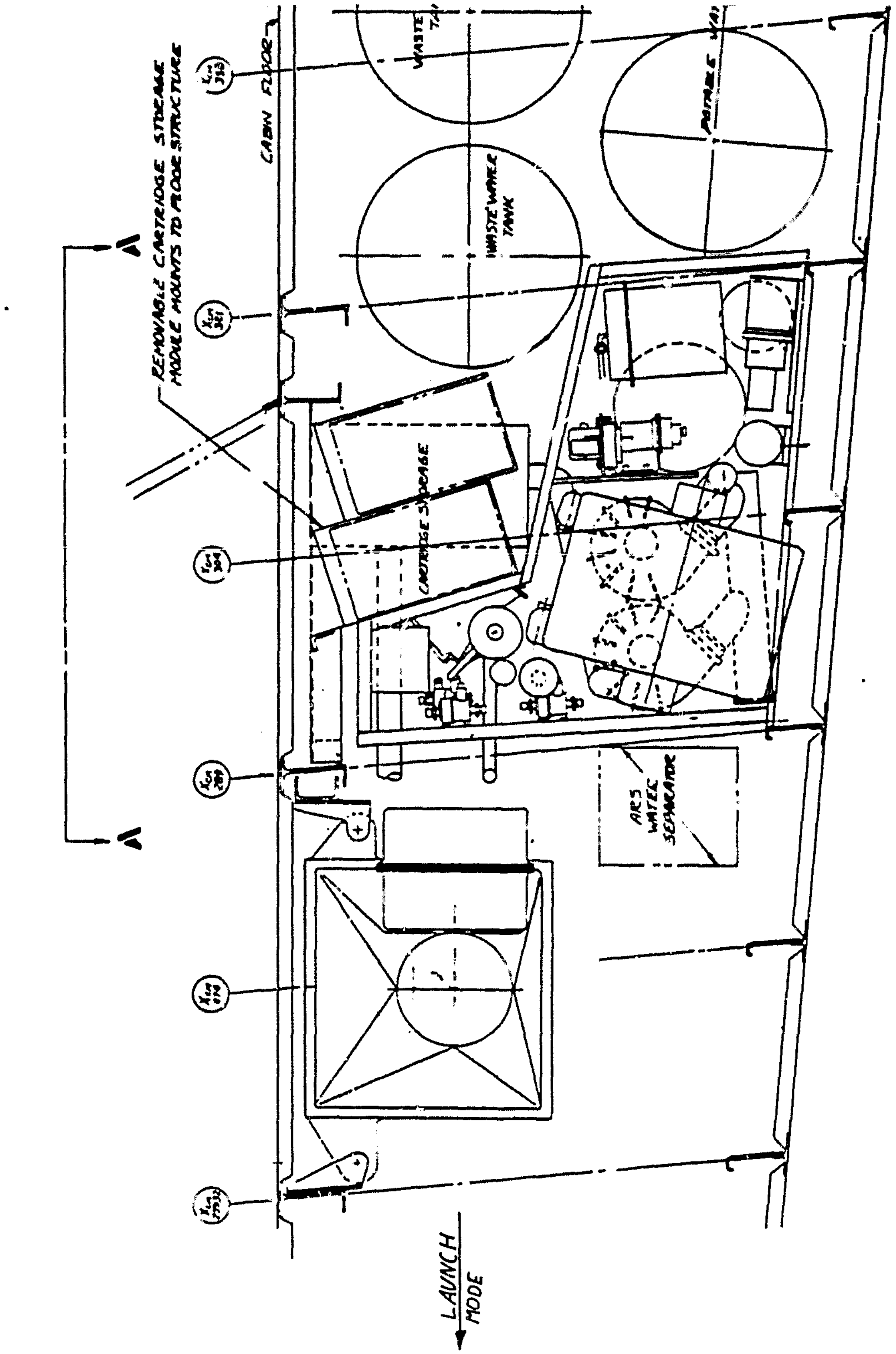


FIGURE 11
LARS INSTALLATION DRAWING (SHEET 1)

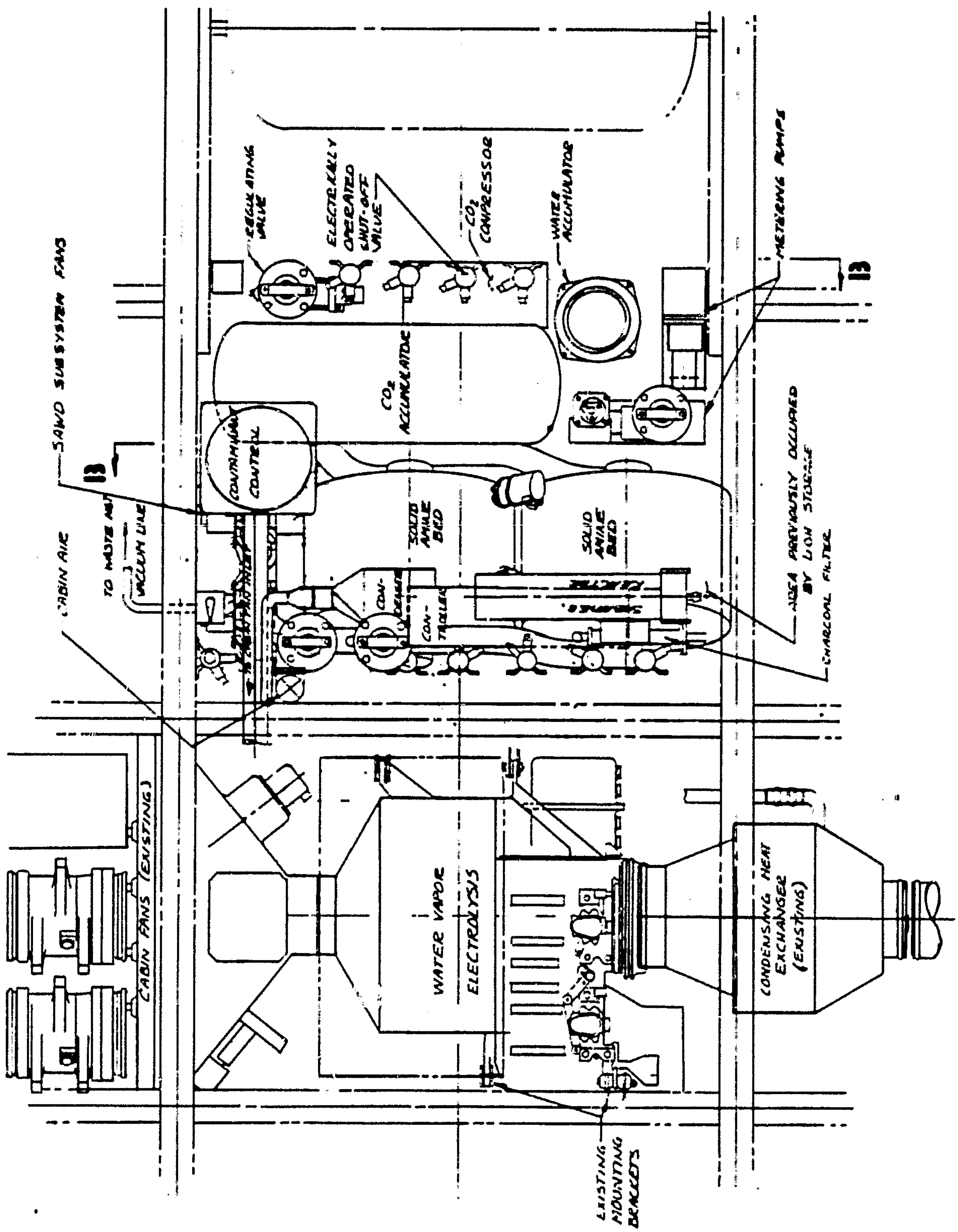


FIGURE 12
LARS INSTALLATION DRAWING (SHEET 2)

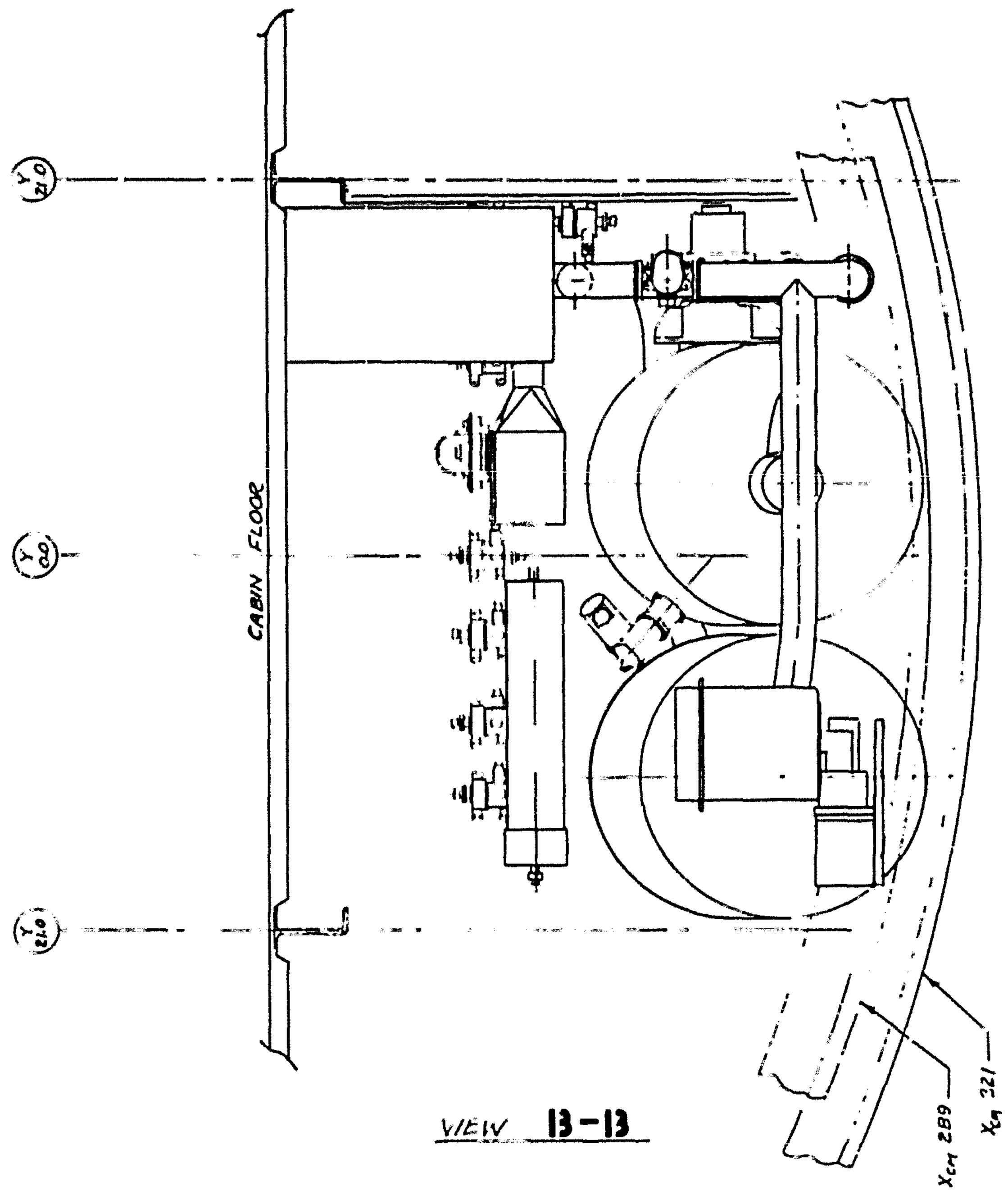


FIGURE 13

LARS INSTALLATION DRAWING (SHEET 3)

INTRODUCTION

An improved atmospheric revitalization system was studied for use on the shuttle for extended duration orbiter missions. The system consists of three subsystems: a solid amine water desorbed (SAWD) CO_2 removal subsystem; a water vapor electrolysis (WVE) oxygen generating subsystem; and a Sabatier CO_2 reduction subsystem. The analysis and preliminary design assumed a six-man metabolic load controlled to a 5.0 mmHg partial pressure of CO_2. Baseline cabin pressure was assumed to be 62.05 kPa (9.0 psia). However, 101.35 kPa (14.7 psia) cabin pressure cases were also considered.

The system is called the Lightside Atmospheric Revitalization System (LARS). It is designed to utilize the volume on the shuttle vehicle presently used for CO_2 control and LiOH storage. Most of the power consumed by the LARS is used on the light side of each orbit, and it can be unregulated solar cell DC power.

The study included the development of computer models to predict the WVE system performance, the SAWD system CO_2 performance, and the cabin temperature and humidity with the LARS installed. The program listings are provided in Appendix A.

The system integration portion of the study resulted in package drawings showing the SAWD subsystem individually and the entire LARS installed in the shuttle orbiter.

OBJECTIVES

The primary objective of the LARS study was to define the integration of the LARS into the shuttle orbiter utilizing space now occupied by the shuttle ECS and the LiOH storage. The study defines the weight, power, volume, and interface impacts of installing the system and includes trade studies, performance predictions, and installation arrangements.

The study was divided into seven parts:

System Requirements
System Description
System Performance
Comparison to Present Shuttle ECS
System Effectiveness Studies
Subsystem Sizing and Operating Characteristics
System Integration Studies

The objectives of each part are listed below:

System Requirements

- List the system requirements

System Description

- Describe the selected system
- Describe the modes of system operation including operation during launch and landing

System Performance

- Describe cabin temperature and humidity control as affected by LARS
- Discuss cabin carbon dioxide control
- Discuss cabin oxygen partial pressure control
- Summarize system p er requirements and profiles

Comparison to Present Shuttle ECS

- Trade-off the LARS against the baseline shuttle LiOH ECS for various projected missions
  - PEP/spacelab mission
  - Power system mission

System Effectiveness Studies

- Evaluate system safety
- Discuss system maintainability

Subsystem Sizing and Operating Characteristics

- Discuss the SAWD subsystem sizing the operating characteristics
- Discuss the WVE system sizing and operating characteristics
- Describe the Sabatier system and its operating characteristics

System Integration Studies

- Describe the installation of LARS into the shuttle vehicle
- Describe major subsystem components and give a weight summary
- Describe the power distribution to the LARS
- Discuss instrumentation requirements

CONCLUSIONS

1. A 15 cell water vapor electrolysis subsystem, weighing 47.20 kg (104 lbm) and installing within the present ECS volume, provides metabolic and cabin leakage oxygen requirements with a crew of six.

2. A two-bed solid amine subsystem was sized at 5.90 kg (13 lbm) of dry solid amine per bed. The entire SAWD subsystem weighs 59.8 kg (131.8 lbm) and installs within the present ECS volume.

3. With a LARS installed, shuttle cabin temperature and humidity are within specifications for all nominal heat load cases.

4. For the two-hour maximum heat load condition with a six-man crew and a 62.05 kPa (9 psia) cabin pressure, both LARS and baseline LiOH equipped shuttle vehicles exceed the maximum cabin temperature.

5. The solid amine subsystem maintains cabin CO_2 partial pressure below 5 mmHg for a six-man crew.

6. The solid amine subsystem can maintain spacelab CO_2 partial pressure less than 5.4 mmHg without using LiOH in the spacelab.

8. The LARS offers significant weight, volume and mission length advantages over the baseline LiOH system for extended shuttle missions. The SAWD subsystem or the complete LARS can be installed as field installations.

9. The LARS is designed for easy maintenance by use of line replacement components.

10. The LARS operating characteristics are compatible with projected shuttle mission scenarios.

11. The LARS can be installed within the envelope presently used for CO_2 control and LiOH storage.

12. Drawings have been developed showing the installations of the solid amine subsystem only and of the entire LARS.

13. The LARS power requirements can be supplied by the present shuttle vehicle electrical distribution system.

RECOMMENDATIONS

1. The testing under the LARS Program should be undertaken.

2. The shuttle ARS heat exchanger should be tested with a full sized solid amine subsystem to determine its compatibility under all cabin conditions.

3. The Sabatier subsystem should be tested with the other two subsystems.

4. The LARS can be installed aboard the orbiter in phases. The SAWD subsystem should be installed on all orbiters. However, its major benefits will be realized on extended mission duration orbiters. Addition of the WVE and Sabatier subsystems is beneficial for sun synchronous orbit PEP missions or for power system missions.

DISCUSSION

The Lightside Atmospheric Revitalization System study was divided into seven major topics. The detailed presentation in this section is divided into subsections corresponding to these topics.

WORK BREAKDOWN STRUCTURE

No.	Topic
I	System Requirements
II	System Description
III	System Performance
IV	Comparison to Present Shuttle ECS
V	System Effectiveness Studies
VI	Subsystem Sizing and Operating Characteristics
VII	System Integration Studies

TOPIC I
System Requirements

The Lightside Atmospheric Revitalization System study is based on the requirements and assumptions given in Table 2.

Table 2
LARS STUDY REQUIREMENTS/ASSUMPTIONS

1	Crew size		6 men
2	Metabolic O_2	0.798 kg/man day	1.76 lbm/man day
3	O_2 Partial pressure	17.58 ± 1.03 or 22.06 ± 1.72 kPa	2.55 ± .15 or 3.2 ± .25 psia
4	Cabin pressure	62.05 ∓ 1.38 or 101.35 ± 1.38 kPa	9 ± .2 psia or 14.7 ± .2 psia
5	Leakage O_2	0.871 kg/day	1.92 lbm/day
6	Launch & reentry O_2	38.10 kg	84 lbm (20 kw, 6 men, 5 hr)
7	Reentry hold O_2	58.97 kg	130 lbm (6 men, 20 hr, 7.35 kw)
8	EVA O_2	0.590 kg	1.3 lbm (7 hrs)
9	Kit tank O_2	321.15 kg	708 lbm usable, (354.26 kg 781 lbm total)
10	Fuel cell O_2 consumption	0.367 kg/kw hr	0.81 lbm/kw hr
11	Launch & reentry H_2	4.58 kg	10.1 lbm (20 kw, 5 hr)
12	Fuel Cell H_2 consumption	0.0454 kg/kw hr	0.10 lbm/kw hr
13	Kit tank H_2	37.42 kg	82.5 lbm (usable)
14	Metabolic CO_2	0.957 kg/man day	2.11 lbm/man day
15	CO_2 partial pressure average		5 mmHg (7.6 mmHg max)
16	LiOH per cartridge	2.27 kg	5.0 lbm, (0.113 kg .25 lbm charcoal)
17	LiOH cartridge weight	0.907 kg	2.0 lbm (less LiOH & charcoal)
18	LiOH rack weight	3.63 kg	8.0 lbm (3 cartridges)
19	LiOH rack volume	0.0311 m^3	1.1 ft^3 (3 cartridges)
20	LiOH storage existing capability		27 cartridges
21	LiOH change out - 4 Men		12 hr/cartridge
22	LiOH change out - 6 Men		7.6 hr/cartridge
23	LiOH H_2O production	0.390 kg/man day	0.86 lbm/man day
24	Food & drink H_2O	2.59 kg/man day	5.7 lbm/man day
25	Wash H_2O	1.16 kg/man day	2.55 lbm/man day
26	EVA H_2O	4.35 kg	9.6 lbm (7 hr)
27	Condensate H_2O (metabolic only, 70°F cabin)	1.58 kg/man day	3.49 lbm/man day
28	Urine H_2O	1.50 kg/man day	3.3 lbm/man day
29	Fuel cell H_2O/kw hr	0.413 kg	0.91 lbm
30	Reentry & contingency H_2O	149.69 kg	330 lbm (usable, 2 out of 3 tanks)
31	Water/waste tank capacity	74.84 kg	165 lbm (usable)
32	Water/waste tank weight	20.87 kg	46 lbm (includes structure)
33	Potable water tanks baseline		3
34	Wastewater tanks baseline		2
35	Reentry hold contingency		20 hr
36	Fuel cell hot start idle		3 kw (3 cells)
37	Fuel cell cold start idle		1 kw (3 cells)
38	Cryo kit weight O_2 & H_2	318.88 kg	703 lb (no usable O_2 or H_2)
39	Charcoal requirement	0.0567 kg/man day	0.125 lbm/man day
40	Metabolic sensible heat load average	3.408 X 10^5 Joules/man hr	323 Btu/man hr (70°F cabin)
41	Metabolic Latent Load Average	1.308 X 10^5 Joules/man hr	124 Btu/man hr (70°F cabin)
42	Cabin electrical and wall load average	1.974 X 10^6 Joules/hr	1871 Btu/hr
43	Avionics load average	4.593 X 10^6 Joules/hr	4353 Btu/hr
44	Cooling water outlet temp. from interface HX	4.61°C	40.3°F
45	Cooling water flow	272.16 kg/hr	600 lbm/hr
46	Cabin temperature range	18.33-26.67°C	65-80°F
47	Cabin temperature average	21.11°C	70°F
48	Cabin dewpoint range	3.89-16.11°C	39-61°F
49	Cabin dewpoint average	10°C	50°F
50	Power-minimum shuttle services		14 kw
51	Flash evaporator topping duct power		170 watts average
52	Solar cell penalty	56.25 kg/kw	124 lbm/kw
53	Cabin repressure from 62.05 kPa/9.0 psia) to 101.35 kPa (14.7 psia)		part of contingency
54	Air lock manned	3.68 m^3	130 ft^3

TOPIC II
System Description

The Lightside Atmospheric Revitalization System (LARS) is designed for extended duration orbiter missions, during which the fuel cells are idled and solar power is utilized. This system is well suited to these conditions, since with the fuel cells idled, water can become the limiting consumable. The LARS includes a regenerable subsystem for carbon dioxide control and an oxygen generating subsystem capable of supplying oxygen for metabolic usage and cabin leakage makeup. Additionally, hydrogen from the oxygen generating subsystem and carbon dioxide are processed in a Sabatier reactor to produce potable water for crew use and methane, which is vented overboard.

The LARS, as it would be integrated into the shuttle orbiter ECS, is shown schematically in Figure 14. The LARS consists of three subsystems; the SAWD, solid amine water desorbed CO_2 removal subsystem; the WVE, water vapor electrolysis subsystem; and the Sabatier CO_2 reduction subsystem. The system is designed to draw the majority of its electrical power requirement during the sun side of each orbit. During the CO_2 adsorption cycle, cabin air enters the amine canisters through one of two shuttle IMU fans and exits through an activated charcoal contaminant control cartridge into the main cabin return airstream. The combined main cabin air and SAWD discharge air flow through a shuttle cabin fan into the water vapor electrolysis cells and exit into the shuttle condensing heat exchanger or bypass line, depending on the cabin air temperature requirements. The water vapor electrolysis cells absorb water from the air stream and produce oxygen and hydrogen. The oxygen is discharged directly into the cabin air stream for metabolic use or to account for cabin leakage. The hydrogen is mixed with a regulated flow of carbon dioxide, and the gas mixture is fed into the Sabatier reactor, where water and methane are produced. The water is condensed and pumped to the shuttle water storage tanks. The methane gas and any excess carbon dioxide are vented overboard. The SAWD beds are steam desorbed one at a time, and the WVE system and Sabatier reactor are operated only on the sun side of an orbit. Fan flow is continued through the WVE, SAWD canisters, and contaminant control canister on the dark side of the orbit.

Carbon dioxide is desorbed from the solid amine by heating the bed with steam. Water drawn from the SAWD water accumulator is pumped over the carbon dioxide compressor, adsorbing the heat of compression, and into the steam generator for the bed to be desorbed. Water vapor from the steam generator enters the amine bed and heats the solid amine material. While the bed is being heated, residual air is driven out and returned to the cabin via a solenoid operated ullage valve. Once carbon dioxide starts

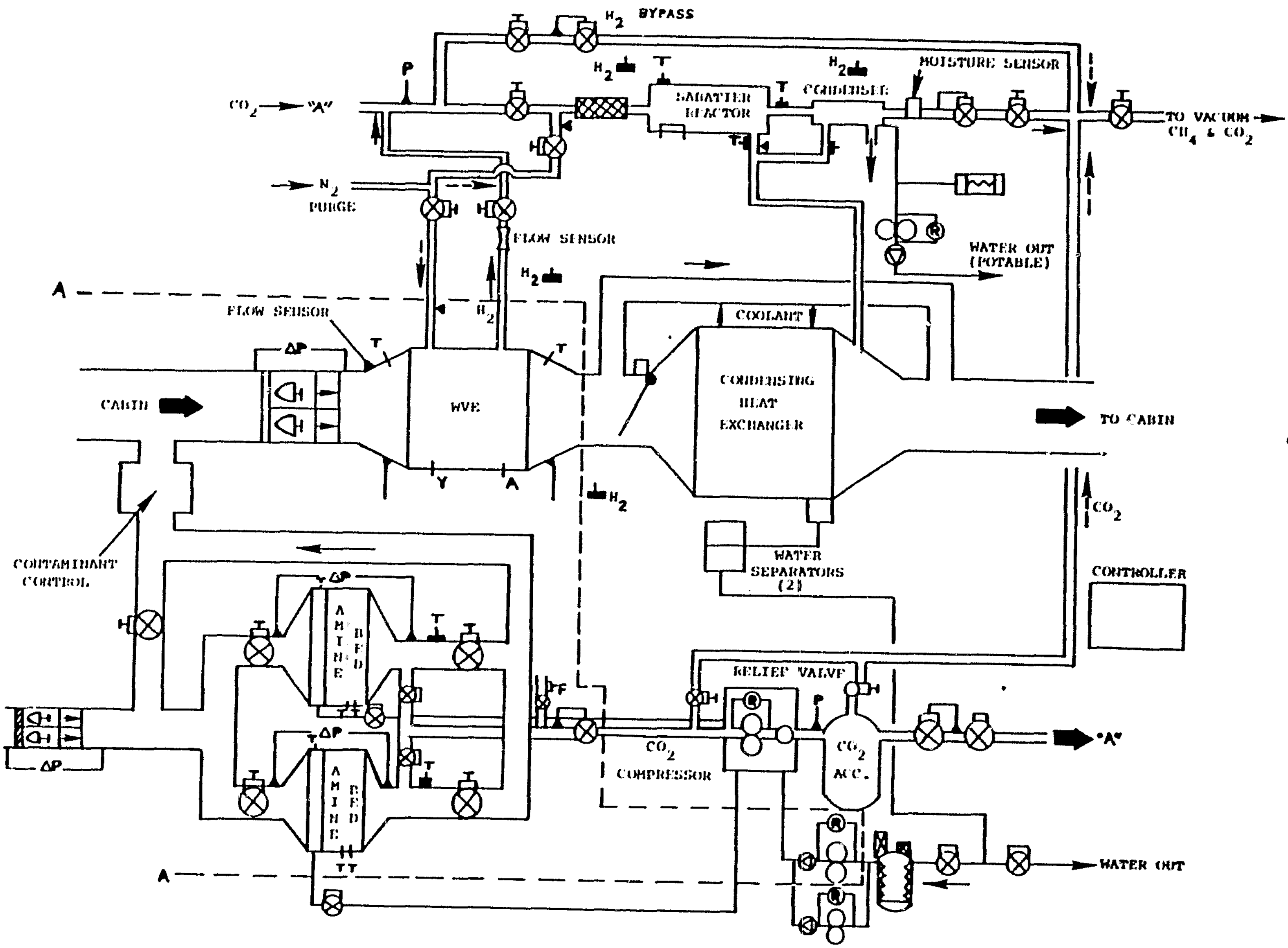


FIGURE 14
LARS SCHEMATIC

being driven from the bed, the ullage valve shuts and the carbon dioxide is directed to a compressor. The compressor sends the carbon dioxide to an accumulator for later reduction in the Sabatier reactor. Excess carbon dioxide can be dumped overboard either directly from the bed or through a relief valve from the accumulator. A detailed discussion of solid amine steam desorption is given in the Subsystem Sizing and Operating Characteristics section of this report.

The operation of the entire LARS, as described above, is applicable to a mission utilizing solar power. For a mission using fuel cell power, excess water is available, and the WVE and Sabatier subsystems would not be used. The operation of the SAWD subsystem for carbon dioxide removal would be similar to that described previously. However, the carbon dioxide would be dumped directly overboard during desorption. Also, the SAWD subsystem cycle timing would not be fixed by orbit considerations, allowing more flexibility in system operation. For example, allowing more time between the desorption of the two amine canisters would moderate the cabin humidity increase, when adsorption is started on a canister. Additionally, desorption time can be increased, reducing peak power requirements.

Since the WVE and Sabatier subsystems are designed for use with solar power, they are not used during launch or reentry. The SAWD subsystem is designed to be operated during launch and reentry, if necessary. However, if before launch the cabin air is initially free of CO_2, the combination of the cabin capacitance and the first 72 minute adsorption period for the amine canisters provides four hours before steam desorption is necessary. Therefore, the only power requirements of the SAWD subsystem during this time are one IMU fan and the controller. A LiOH cartridge can be installed in the contaminant control canister, if additional CO_2 control is required before the SAWD canisters are desorbed. If power is critical during reentry, SAWD steam desorption can be stopped, and LiOH can be used as necessary.

TOPIC III
System Performance

Cabin Temperature and Humidity Control

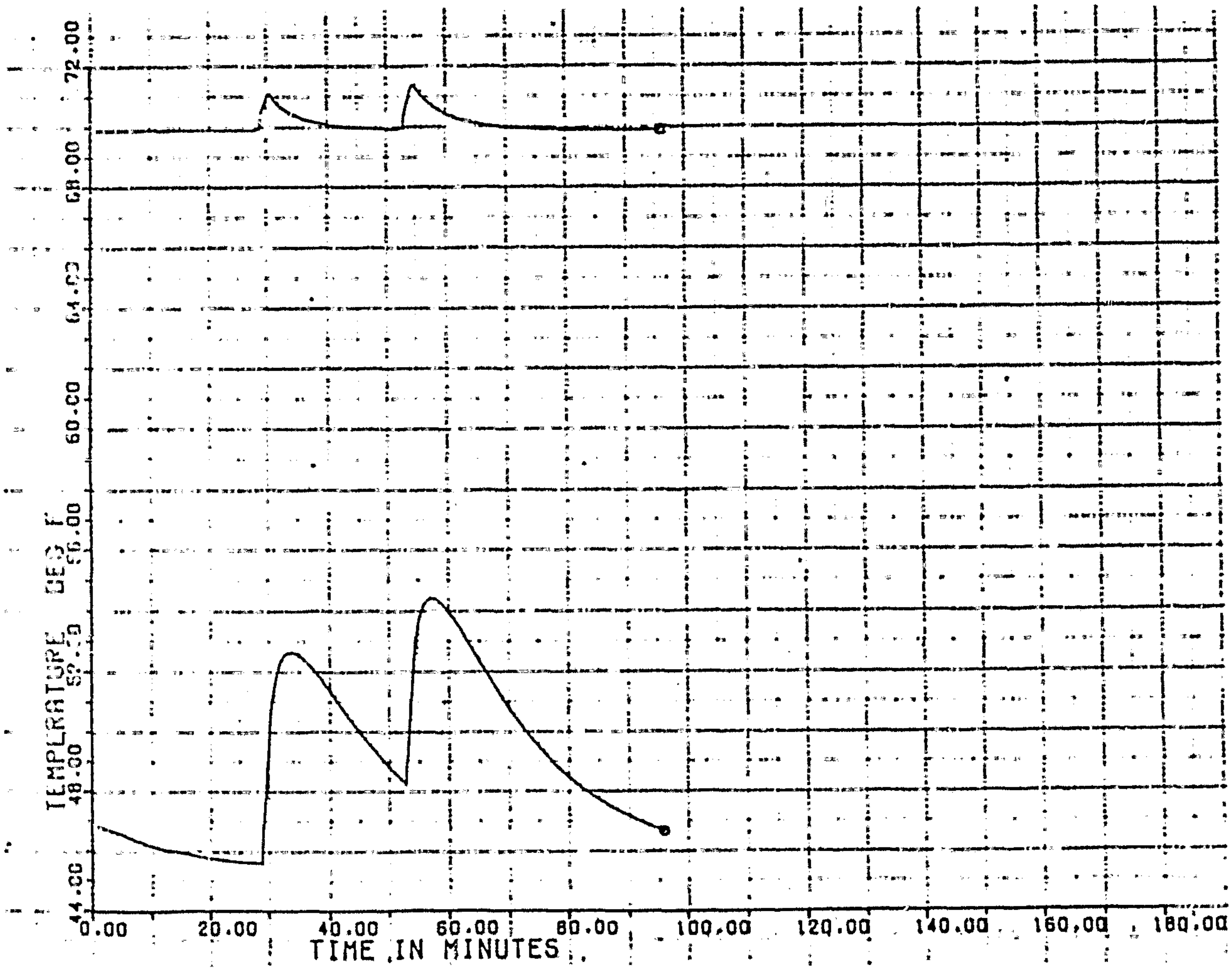
The effects of operating the LARS on cabin humidity and temperature during the various stages of an orbit have been studied for the following conditions:

1) 2,4,6* member crew, 62.05 kPa (9.0 psia) total pressure;
2) 2,4,6 member crew, 101.35 kPa (14.7 psia) total pressure.

As seen in Figures 15 through 20, the most humid condition occurs at approximately fifty-six minutes into light side operation. Here, the first SAWD bed to be desorbed has been returned to adsorption for twenty-six minutes, and the second bed has only been on adsorption for two minutes. The peak latent heat load of the moist air leaving the SAWD bed immediately after the start of adsorption cannot be removed completely by the main condenser, causing cabin temperature and dewpoint to rise. A smaller peak can be noted at approximately thirty-one minutes into the light side, when the only SAWD moisture contribution is from the first bed, which has just returned to adsorption. The second bed, at this time, has already begun its desorption, and is isolated from air flow.

The predicted cabin temperatures and dewpoints with the LARS installed are within the desired limits for all crew size and cabin pressure cases with nominal heat loads. The maximum heat load condition experienced during a post sleeping/eating period was also analyzed. Figures 21 and 22 show the temperatures and dewpoints for this condition with a crew of six and 62.05 kPa (9.0 psia) and 101.35 kPa (14.7 psia) cabin pressures, respectively. These predictions are based on main condenser performance which has been extrapolated from test data for the high latent heat loads seen for a short time after a SAWD bed desorption. A thorough test program is necessary to predict condenser performances under these short duration high latent heat load conditions. During this program any potential problems, such as flow passage plugging due to condensate build-up, can be identified and corrected. The same maximum heat load cases were analyzed for the baseline LiOH system, and the results are also shown on Figures 21 and 22. The temperature and dewpoint values are near or above the desired limits with either system. However, these are steady state analyses for both systems. Since the high heat load case is only a two hour condition, these steady state values of temperature and dewpoint may not be reached or may be reached only at the end of the period. A detailed transient analysis including cabin and ARS thermal masses is required to accurately predict the temperatures and dewpoints during this high heat load case.

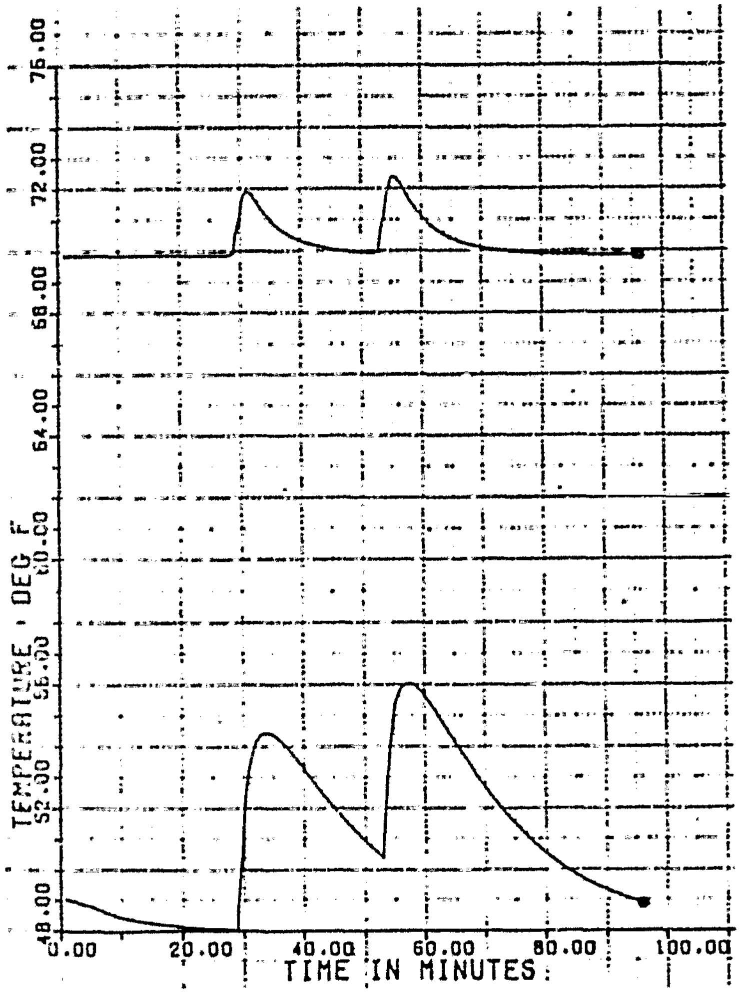
* Baseline Case



□ CABIN TEMPERATURE
○ CABIN DEWPOINT

FIGURE 15

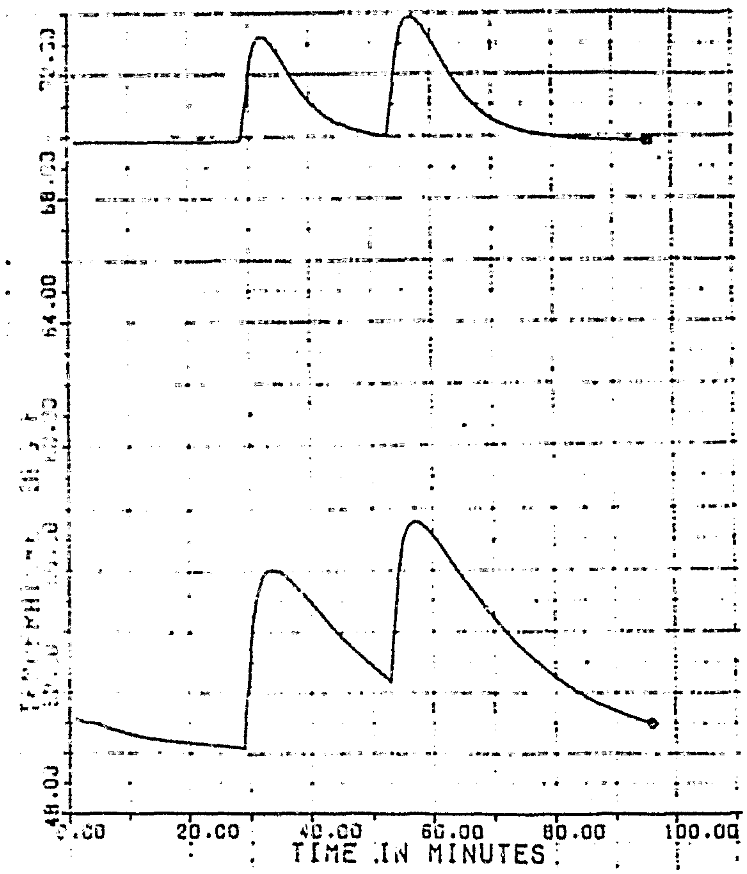
LARS SYSTEM STUDY
2 MEMBER CREW 9 PSIA
NOMINAL HEAT LOAD
CABIN TEMPERATURE AND DEWPOINT



☐ CABIN TEMPERATURE--DEG F
O CABIN DEWPOINT--DEG F

FIGURE 16

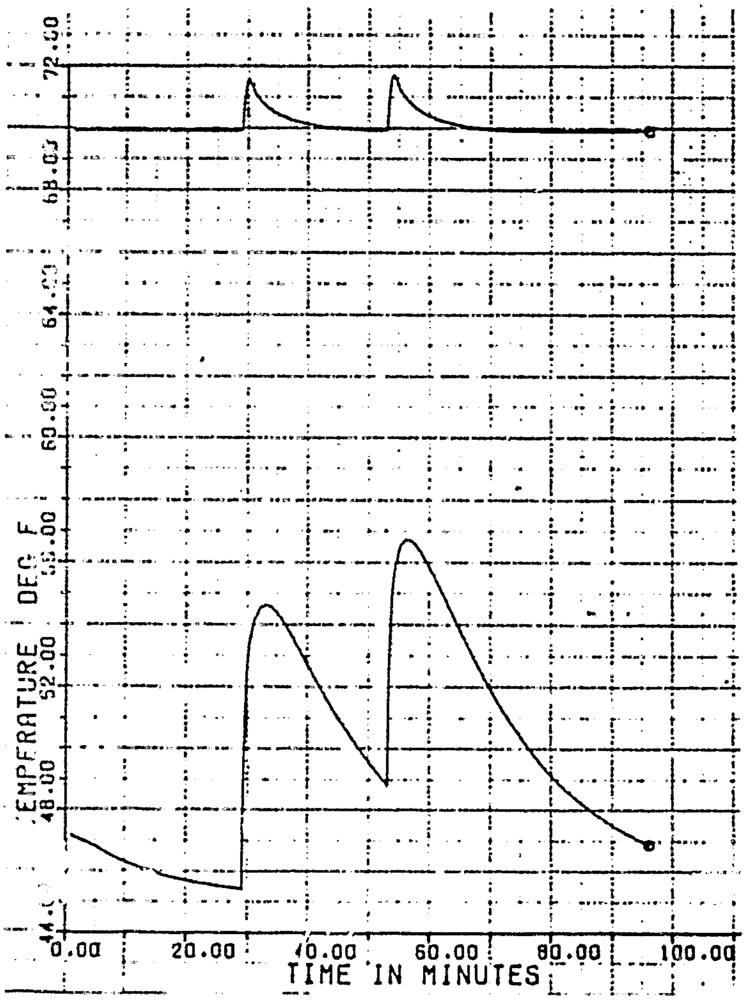
LARS SYSTEM STUDY
4 MEMBER CREW 9 PSIA
NOMINAL HEAT LOAD
CABIN TEMPERATURE AND DEWPOINT



☐ CABIN TEMPERATURE--DEG F
○ CABIN DEWPOINT--DEG F

FIGURE 17

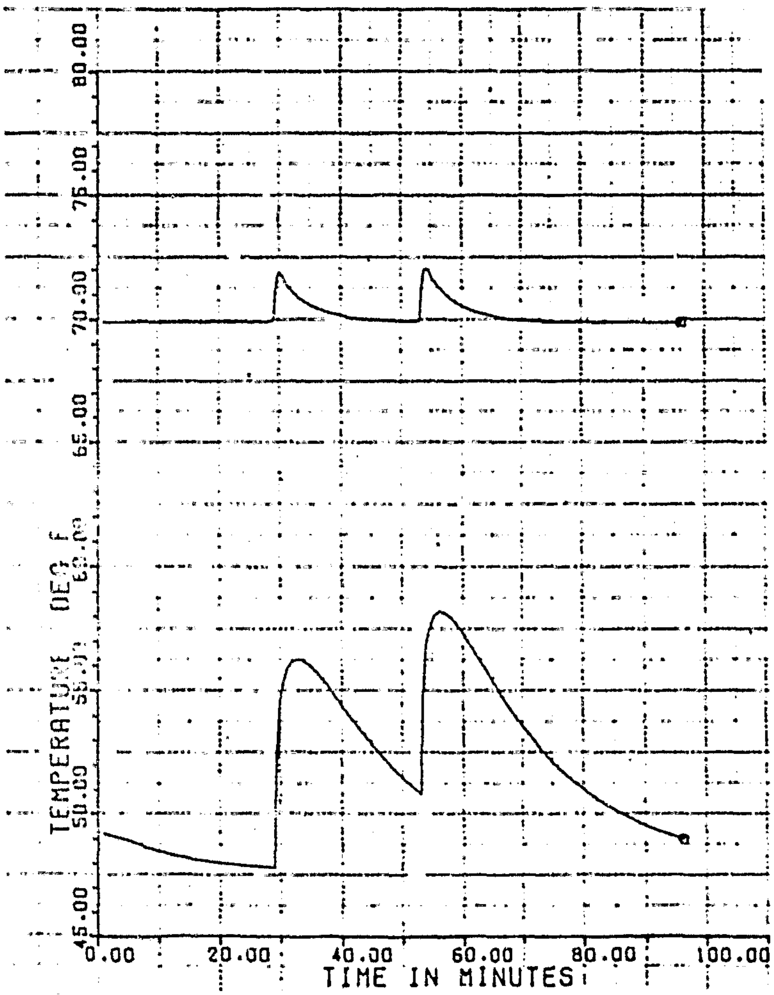
LARS SYSTEM STUDY
6 MEMBER CREW 9 PSIA
NOMINAL HEAT LOAD
CABIN TEMPERATURE AND DEWPOINT



□ CABIN TEMPERATURE--DEG F
○ CABIN DEWPOINT--DEG F

FIGURE 18

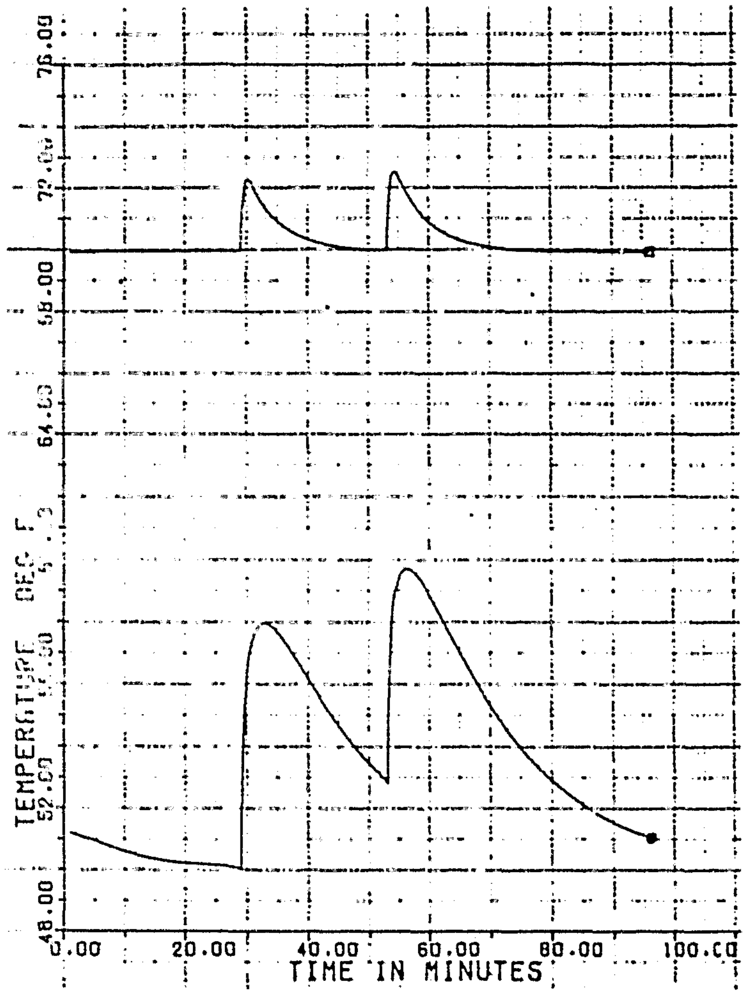
LARS SYSTEM STUDY
2 MEMBER CREW 14.7 PSIA
NOMINAL HEAT LOAD
CABIN TEMPERATURE AND DEWPOINT



□ CABIN TEMPERATURE--DEG F
O CABIN DEWPOINT--DEG F

FIGURE 19

LARS SYSTEM STUDY
4 MEMBER CREW 14.7 PSIA
NOMINAL HEAT LOAD
CABIN TEMPERATURE AND DEWPOINT



□ CABIN TEMPERATURE--DEG F
○ CABIN DEWPOINT--DEG F

FIGURE 20

LARS SYSTEM STUDY
6 MEMBER CREW 14.7 PSIA
NOMINAL HEAT LOAD
CABIN TEMPERATURE AND DEWPOINT

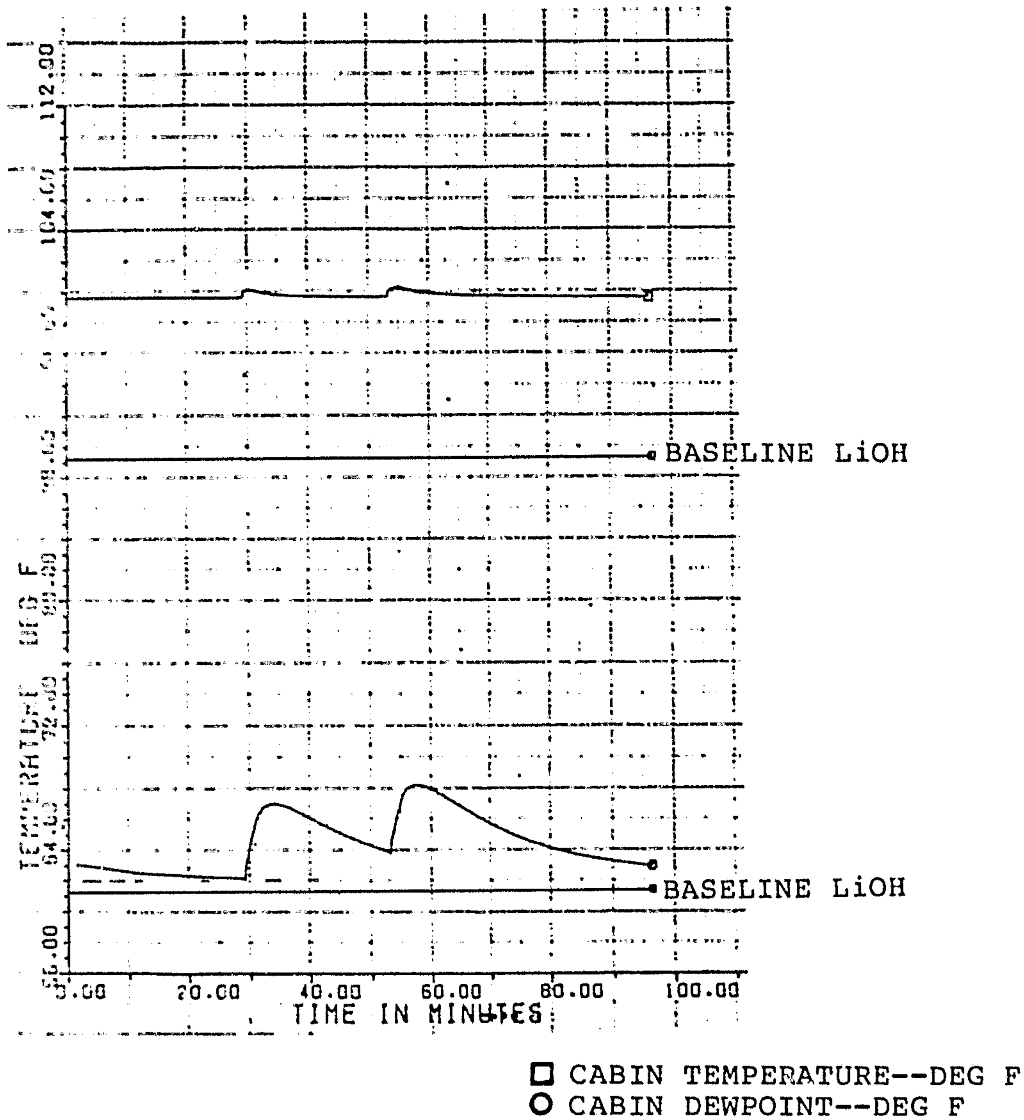
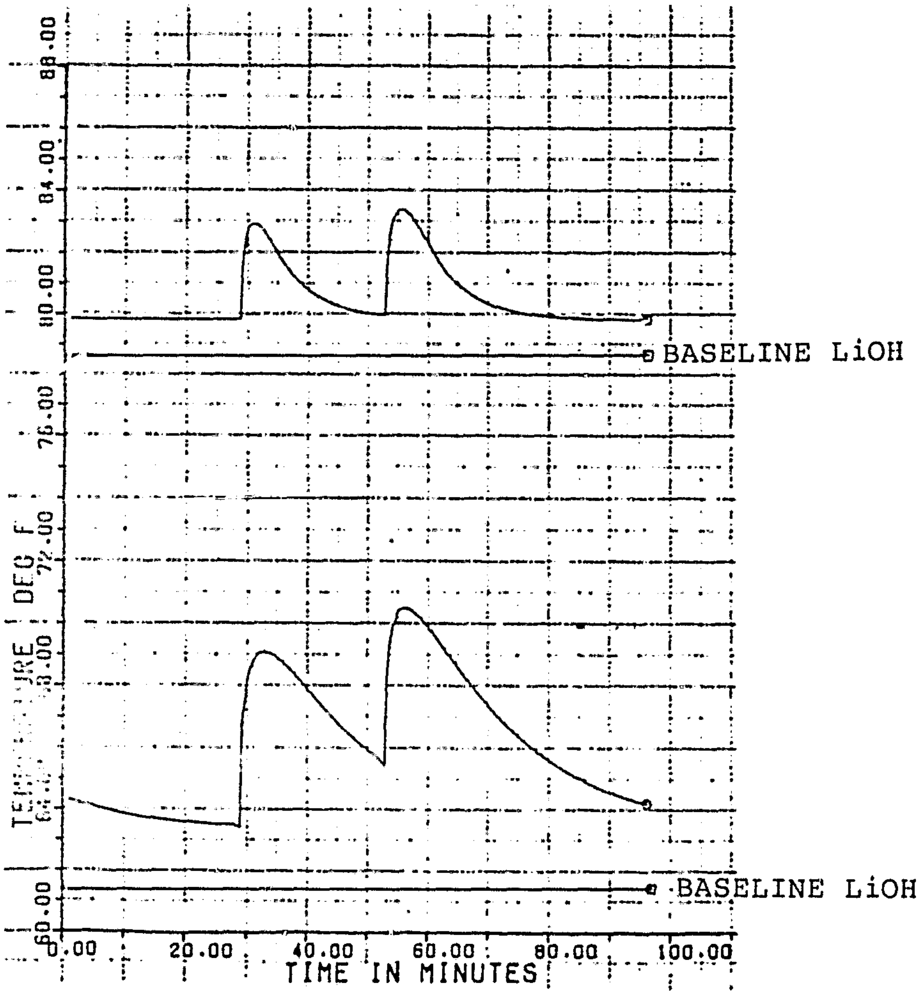


FIGURE 21

LARS SYSTEM STUDY
6 MEMBER CREW 9 PSIA
MAX HEAT LOADS

CABIN TEMPERATURE AND DEWPOINT



□ CABIN TEMPERATURE--DEG F
O CABIN DEWPOINT--DEG F

FIGURE 22

LARS SYSTEM STUDY
6 MEMBER CREW 14.7 PSIA
MAX HEAT LOADS

CABIN TEMPERATURE AND DEWPOINT

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OF POOR QUALITY

For the LARS, steps can be taken to reduce both temperature and dewpoint during this two-hour maximum heat load condition. The peak values can be reduced by gradually reintroducing flow to the SAWD canisters after steam desorption and by stopping all condenser bypass flow during the first few minutes of adsorption. This limits the rate of moisture entering the air stream, and allows the condensing heat exchanger to more effectively remove the moisture. Also, the SAWD canister steam desorption can be stopped for one cycle during the two-hour maximum heat load condition. Even the steady state analysis shows that this maintains cabin temperature and dewpoint within or near the specifications for the 62.05 kPa (9 psia), six-man case with maximum heat loads. The effect of skipping one desorption on SAWD subsystem CO_2 performance is shown in Figure 23. CO_2 partial pressure slightly exceeds 5 mmHg during the transient, but returns to normal within two cycles. Thus, even for the worst case conditions the LARS is equally or more compatible with the shuttle vehicle than the baseline LiOH system.

The six-man, 101.35 kPa (14.7 psia), nominal heat load case was re-analyzed assuming that full adsorption air flow was re-introduced to the SAWD beds gradually over a period of five minutes, rather than almost instantaneously. Results show that maximum cabin dewpoint is reduced from 15.39°C (59.7°F) to 14.61°C (58.3°F), and maximum cabin temperature is reduced from 22.5°C (72.5°F) to 21.5°C (70.7°F). The improvement is due to the reduction in the rate of latent heat load coming from the SAWD beds and the condenser's ability to handle this reduced rate.

Table 3 shows the maximum cabin temperature and humidity during an orbit as well as WVE voltage and WVE and SAWD system power requirements.

Figures 24 through 33 show the LARS transient responses for cases of varying crew size, cabin pressure, and heat loads. They contain system temperatures, dew points, and heat loads at the time of the most humid cabin conditions during an orbit.

Figures 34 through 39 show the power requirements for the LARS with 2, 4, and 6 crew members and 62.05 or 101.35 kPa (9 or 14.7 psia) cabin pressure, for a ninety-six minute orbit having thirty-eight minute dark side and fifty-eight minute light side operation. Included in WVE and SAWD power requirements is an additional 10% necessary for controller operations. Part of the power requirement for the CO_2 compressor appears as a net reduction in SAWD power requirements, since compressor waste heat is used to preheat the water entering the SAWD steam generator.

Table 3
LARS PERFORMANCE SUMMARY

Case No.	# of Crew	Cabin Pressure kPa (psia)	Max. Cabin Temp. °C (°F)	Max. Cabin Dew Point °C (°F)	Max. WVE Voltage (volts) (Total/Cell)	WVE Power* Required (kw/cycle)	Water From SAWD kg (lbm)	SAWD* Heater Power Required (kw/cycle)
I	2	62.05 (9.0)	21.89 (71.4)	12.44 (54.4)	24.81/1.654	.97	1.29 (2.84)	.96
II	4	62.05 (9.0)	22.44 (72.4)	13.39 (56.1)	25.89/1.726	1.74	1.27 (2.91)	.95
III	6	62.05 (9.0)	23.22 (73.8)	14.22 (57.6)	26.88/1.792	2.56	1.27 (2.79)	.94
IV	2	101.35 (14.7)	22.06 (71.7)	13.78 (56.8)	24.72/1.648	1.02	1.43 (3.16)	1.08
V	4	101.35 (14.7)	22.28 (72.1)	14.56 (58.2)	25.71/1.714	1.78	1.42 (3.13)	1.07
VI	6	101.35 (14.7)	22.5 (72.5)	15.39 (59.7)	26.52/1.768	2.57	1.41 (3.11)	1.07

* Does not include controller power.

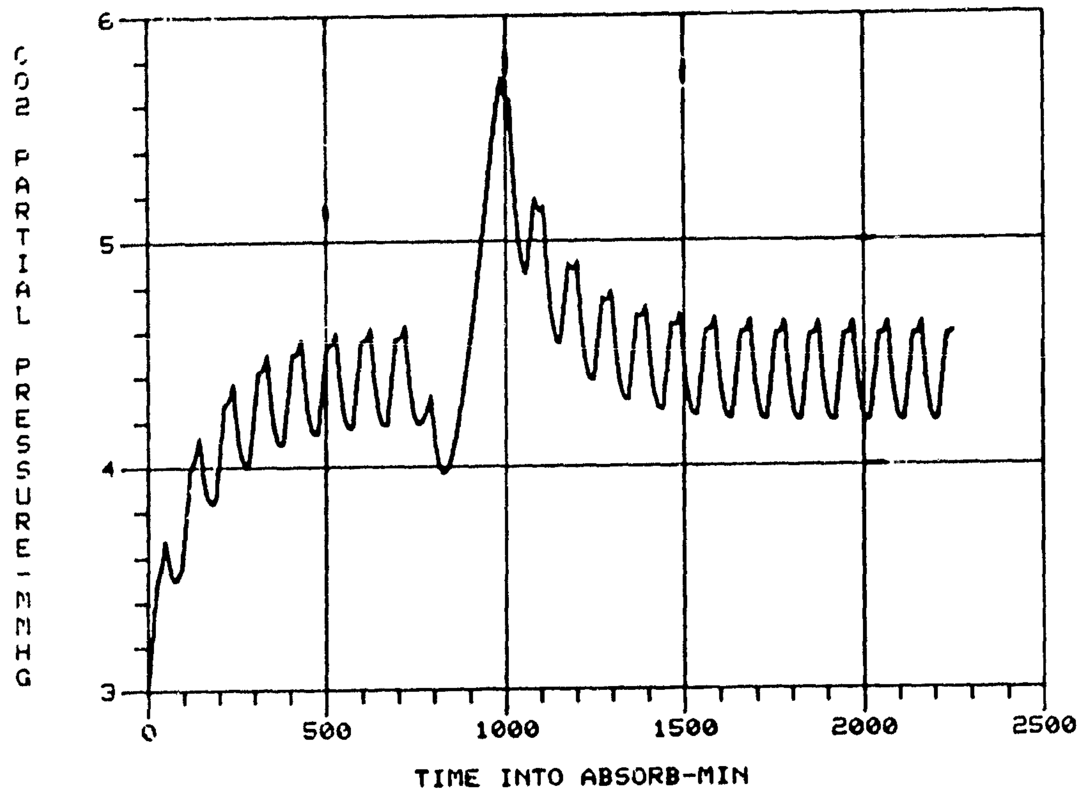

FIGURE 23

PCO_2 TRANSIENT DUE TO SKIPPING ONE DESORB - 6 MEN

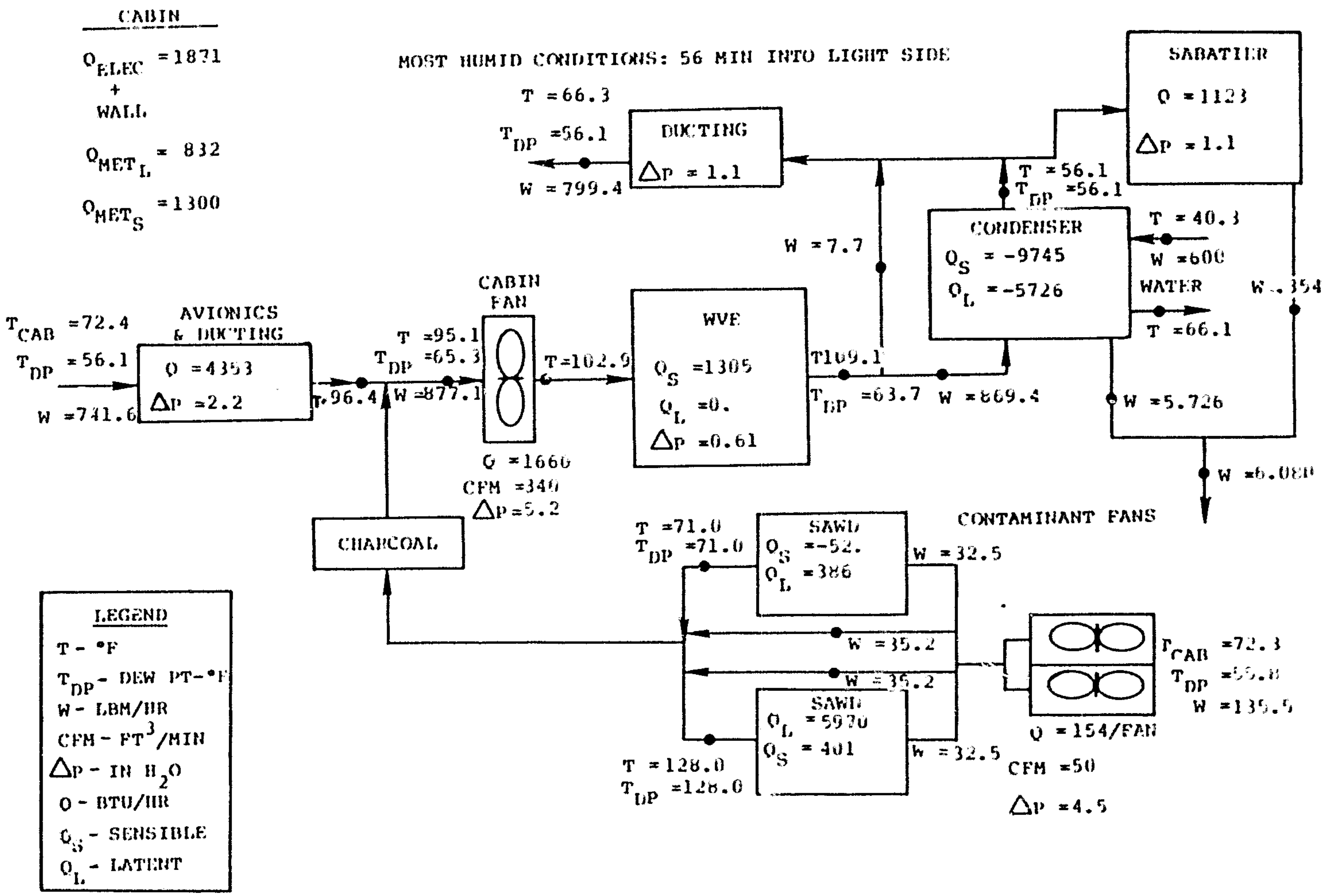

FIGURE 24
CABIN AIR FLOW CHART NOMINAL HEAT LOADS
4 MEMBER CREW 9 PSIA

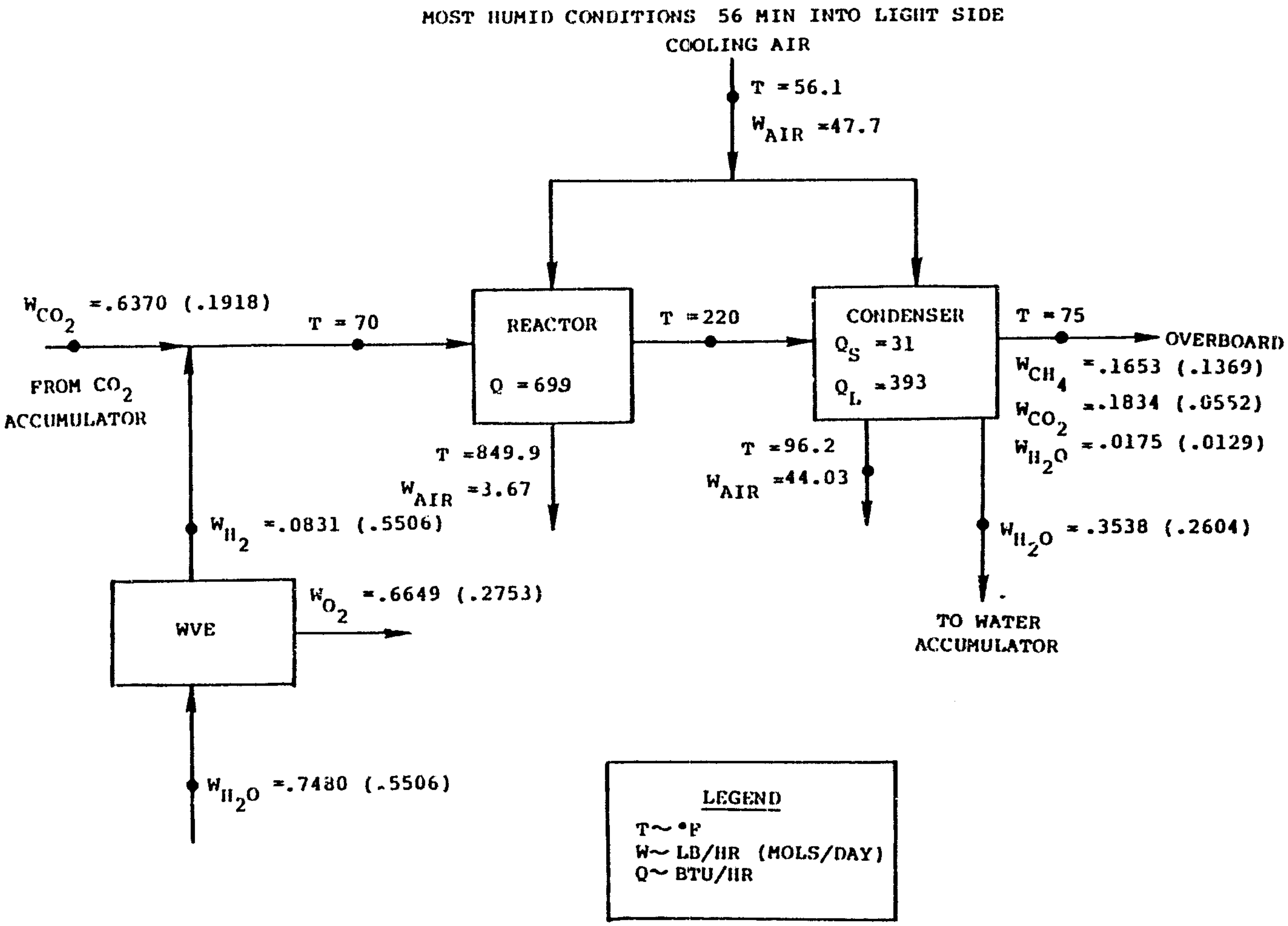

FIGURE 25
SABATIER FLOW CHART
4 MEMBER CREW 9 PSIA

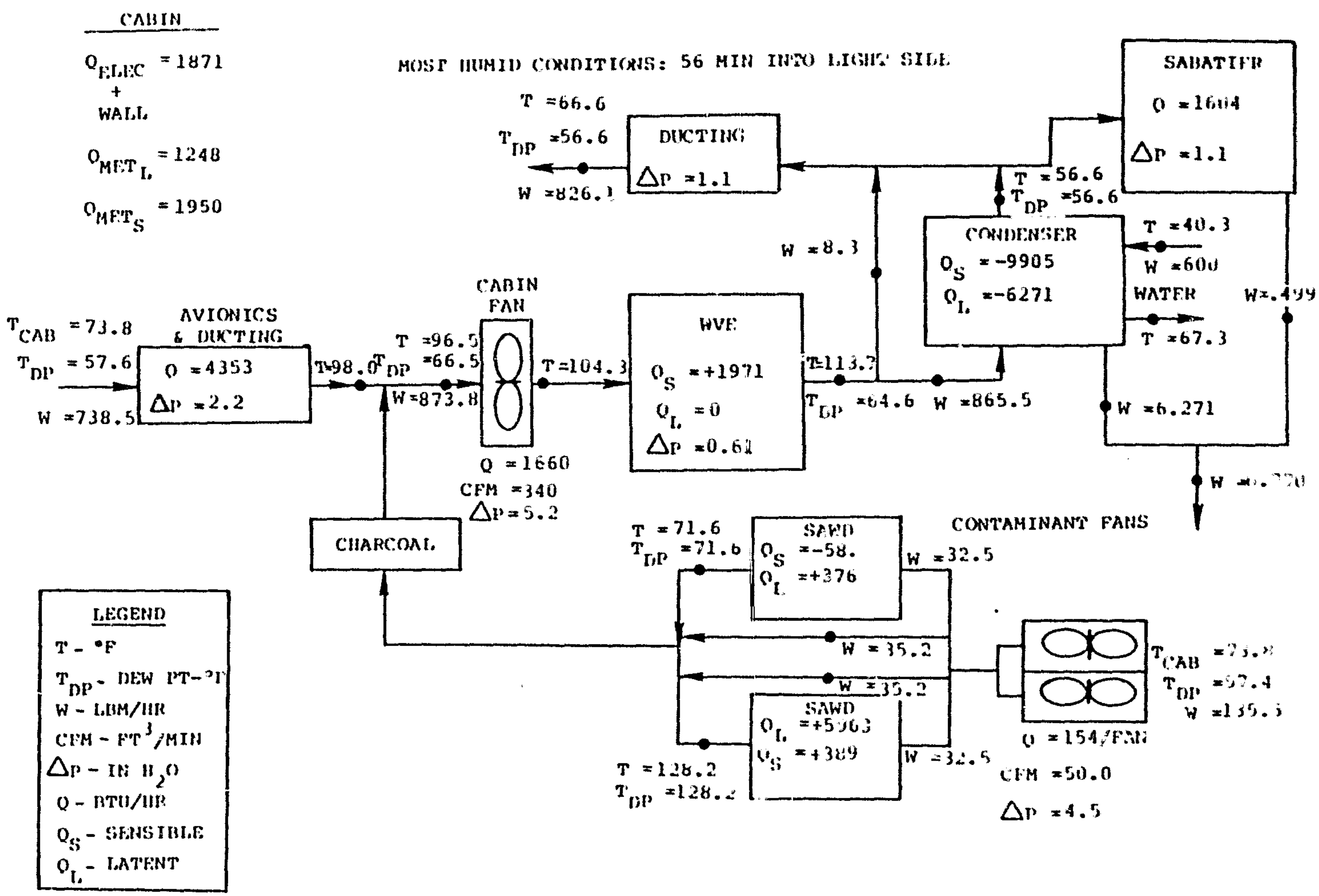

FIGURE 26
CABIN AIR FLOW CHART NOMINAL HEAT LOADS
6 MEMBER CREW 9 PSIA (BASELINE)

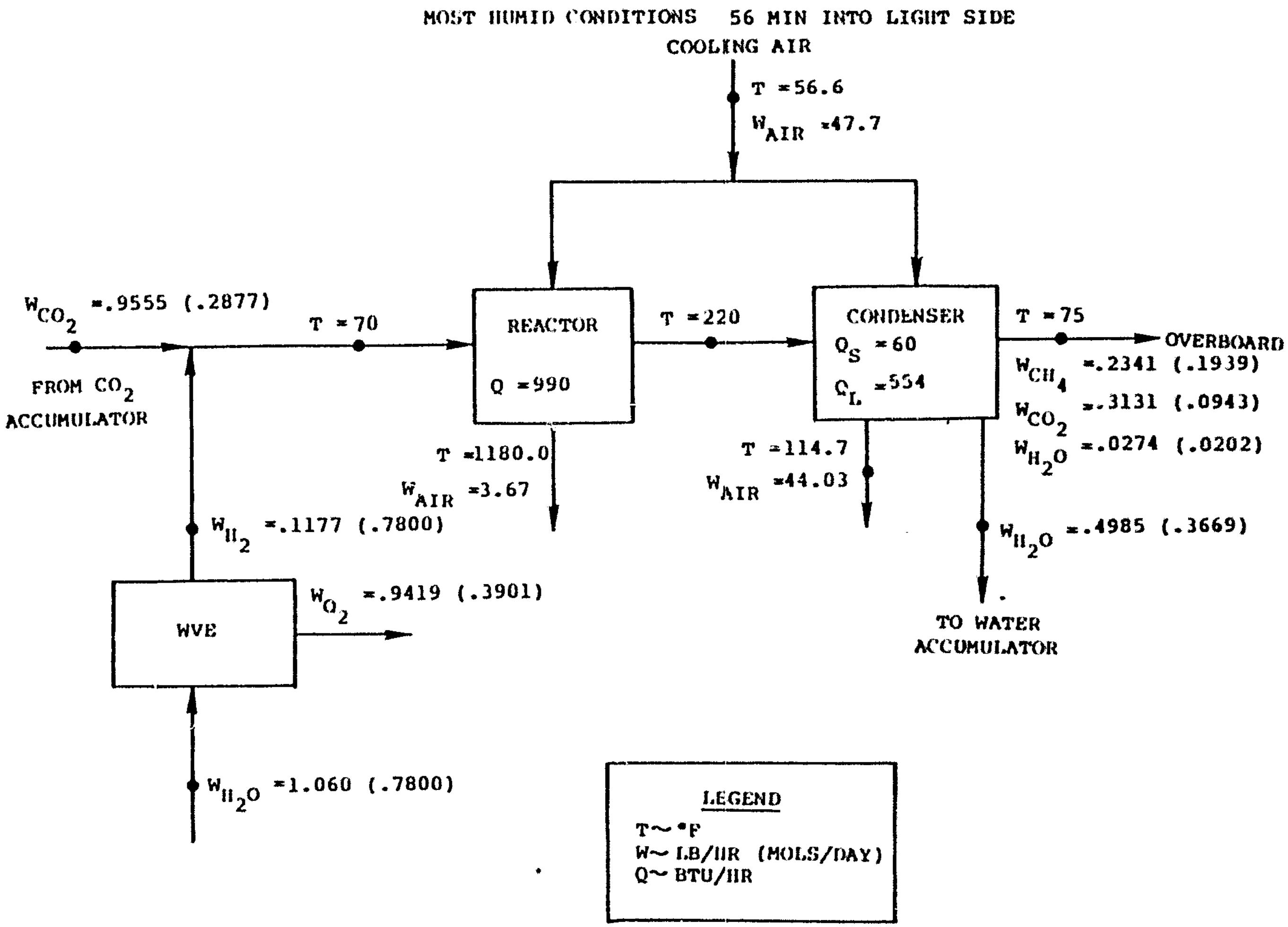

FIGURE 27
SABATIER FLOW CHART
6 MEMBER CREW 9 PSIA

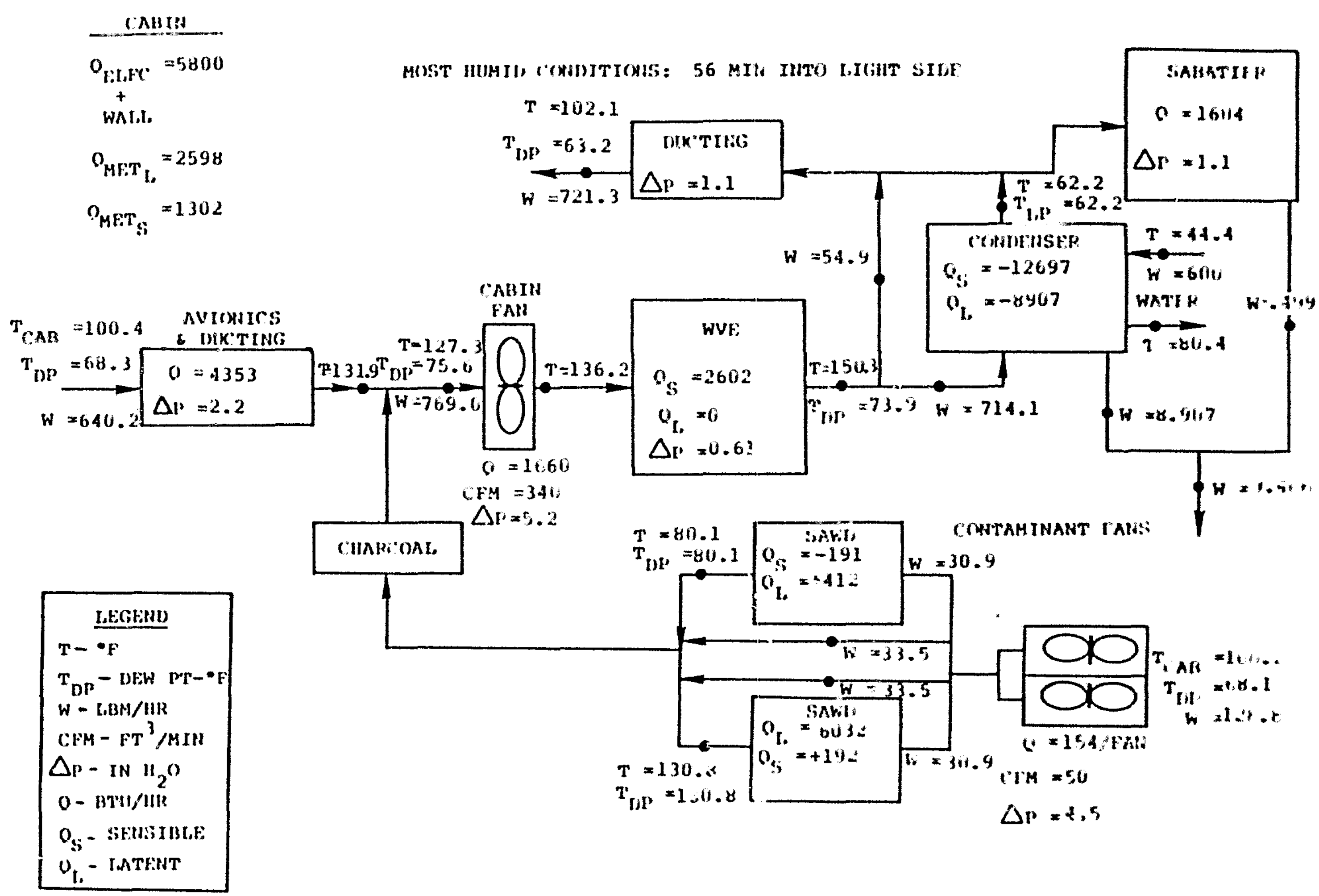

FIGURE 28
CABIN AIR FLOW CHART MAXIMUM HEAT LOADS
6 MEMBER CREW 9 PSIA

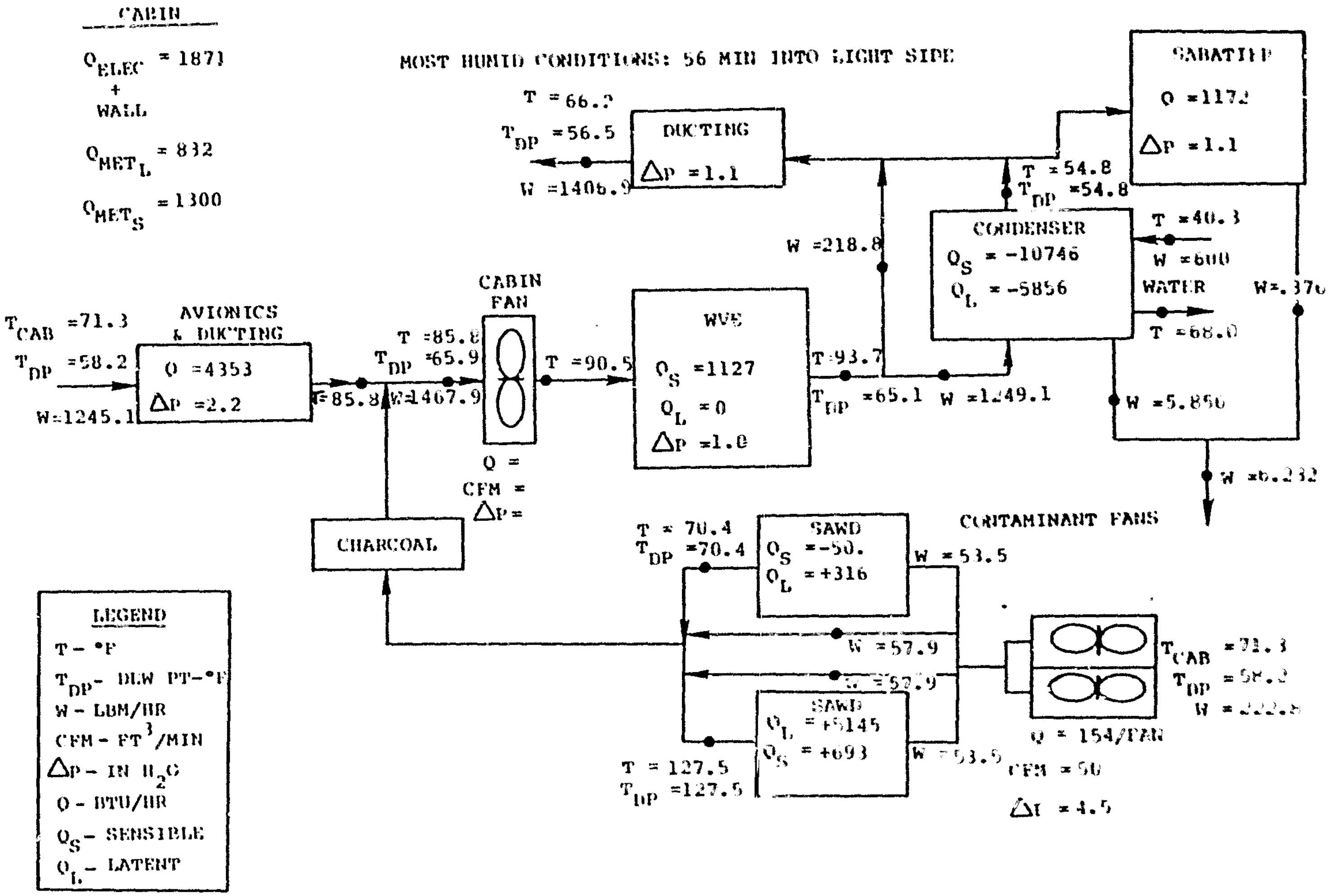

FIGURE 29
CABIN AIR FLOW CHART NOMINAL HEAT LOADS
4 MEMBER CREW 14.7 PSIA

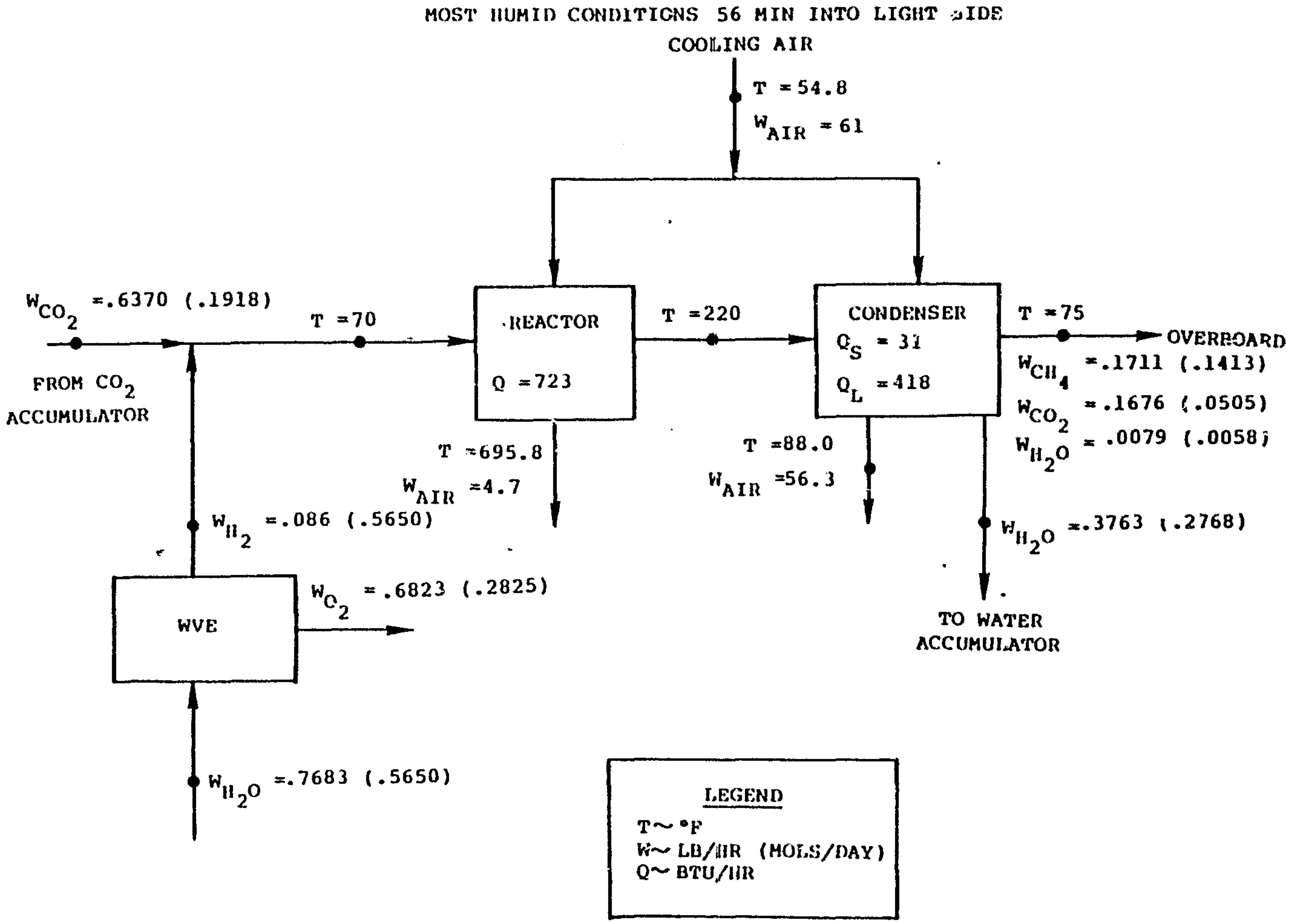

FIGURE 30
SABATIER FLOW CHART
4 MEMBER CREW 14.7 PSIA

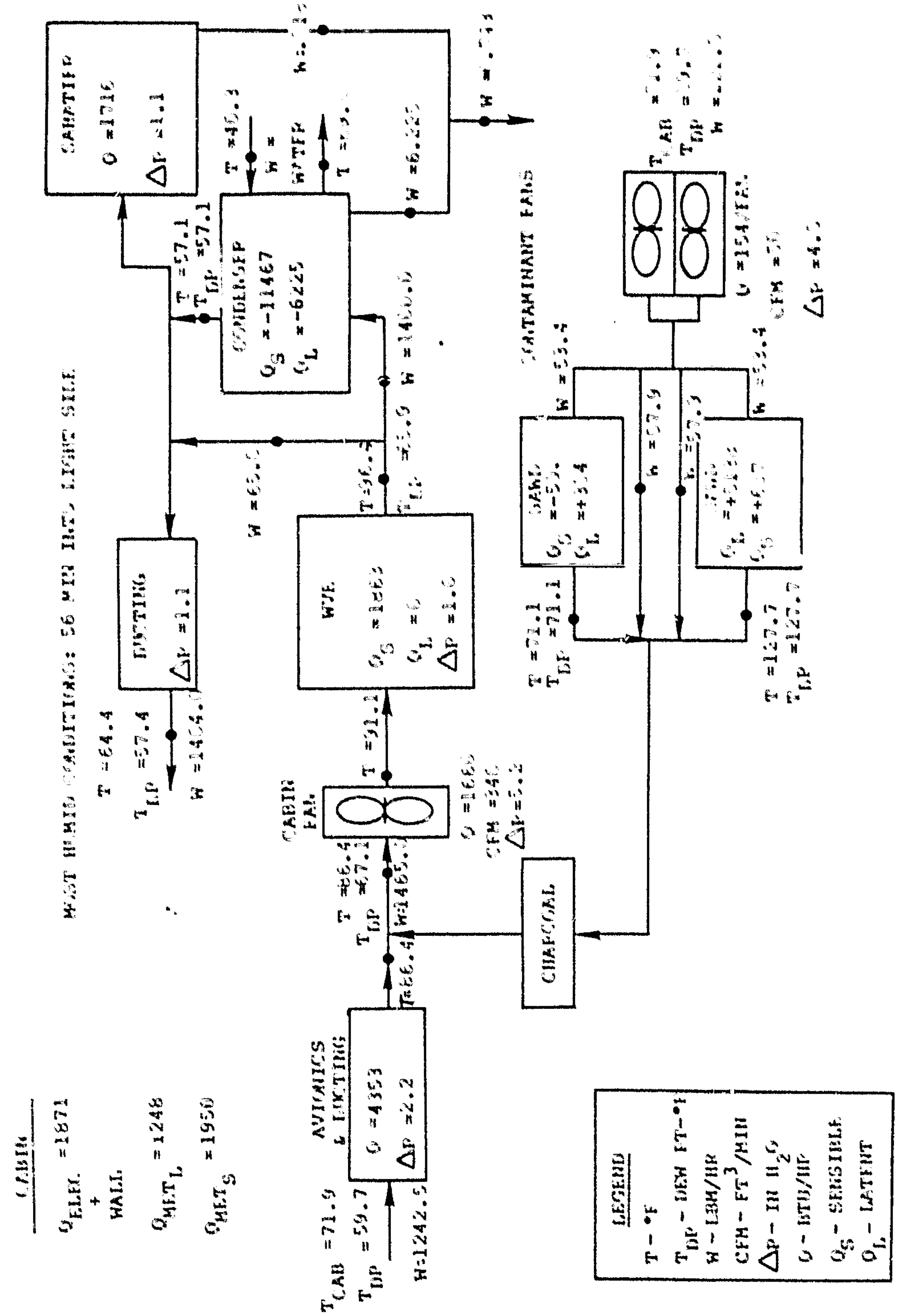

FIGURE 31

CABIN AIR FLOW CHART NOMINAL HEAT LOADS
6 MEMBER CREW 14.7 PSIA

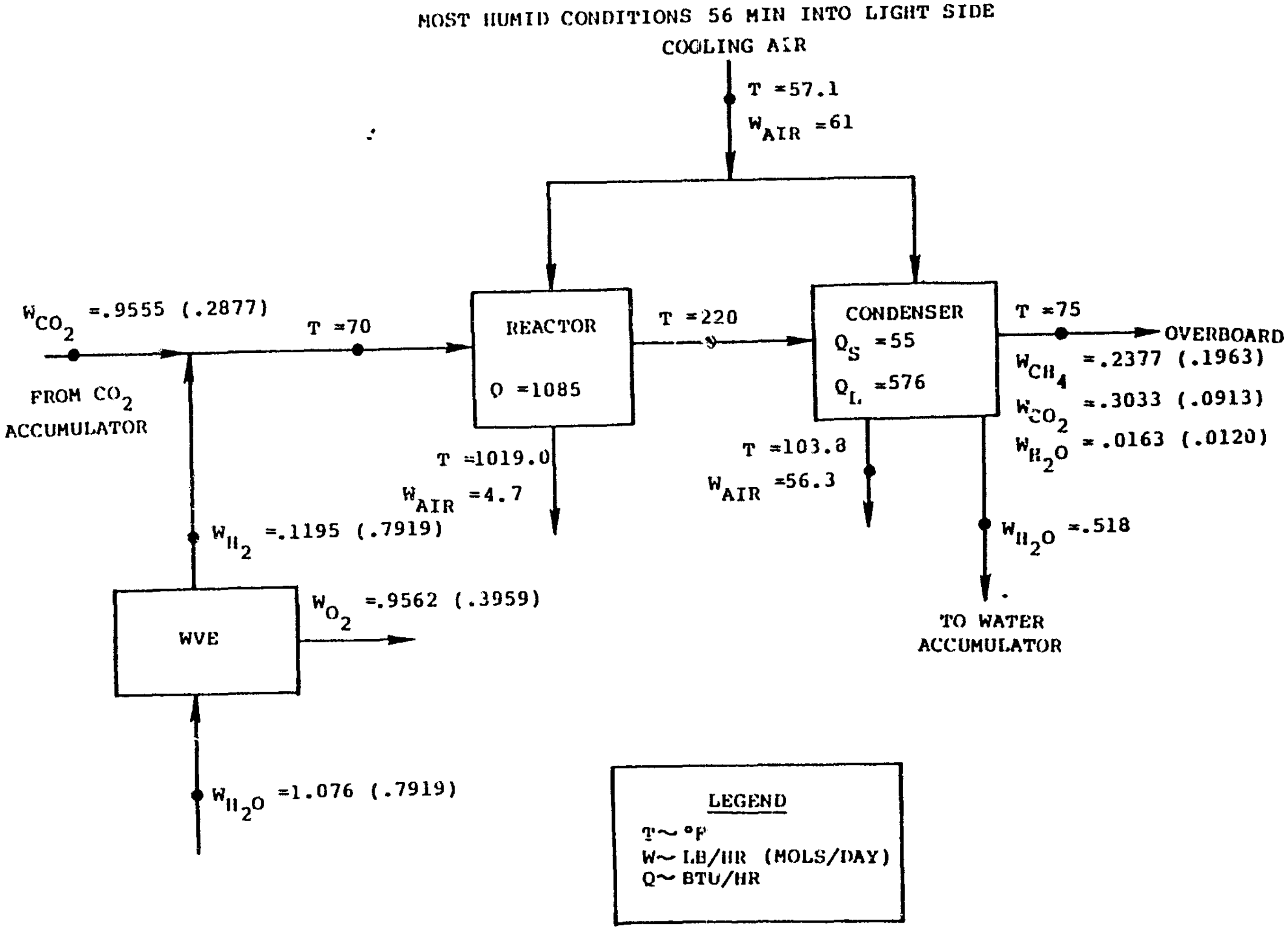

FIGURE 32
SABATIER FLOW CHART
6 MEMBER CREW 14.7 PSIA

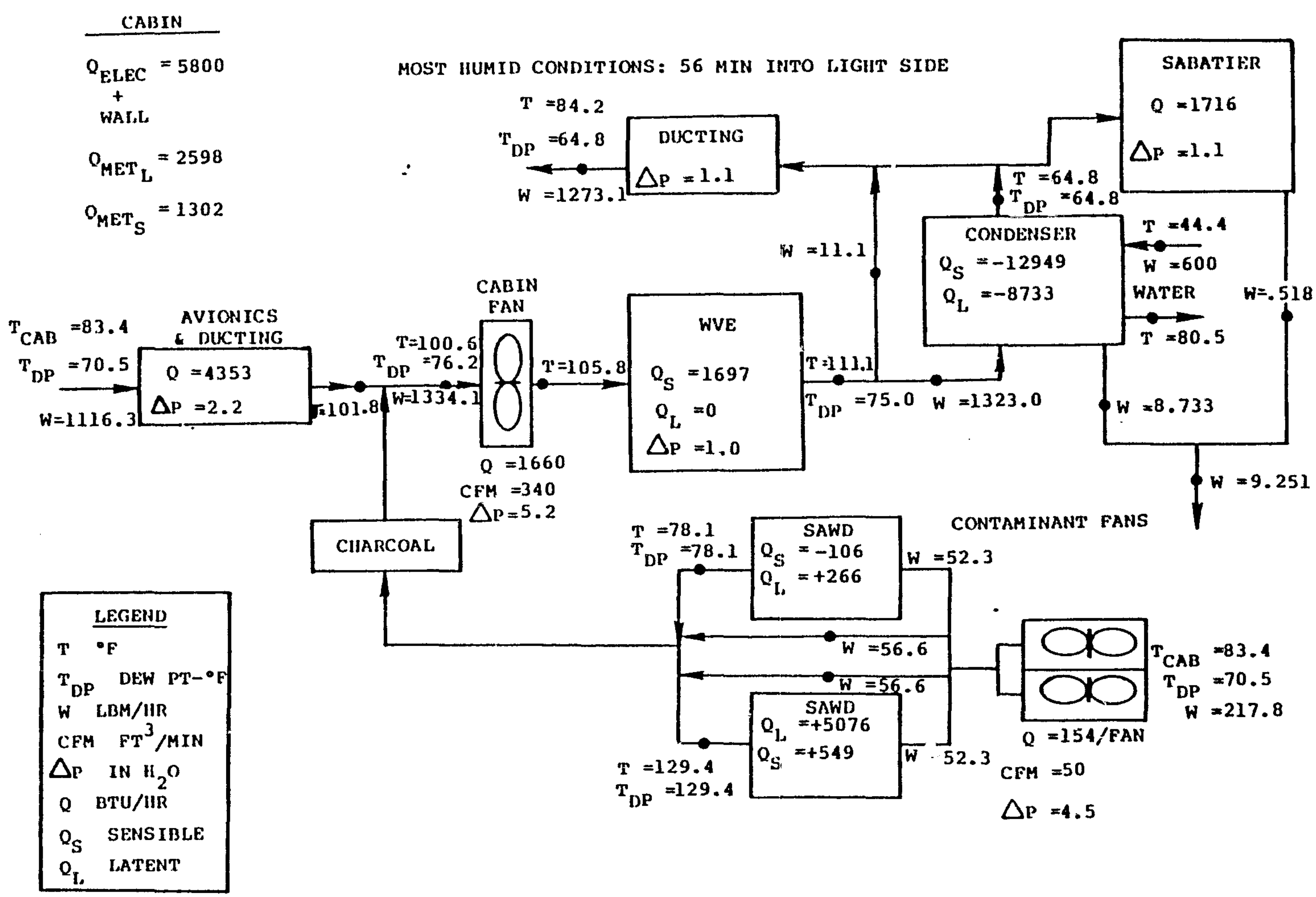

FIGURE 33
CABIN AIR FLOW CHART MAXIMUM HEAT LOADS
6 MEMBER CREW 14.7 PSIA

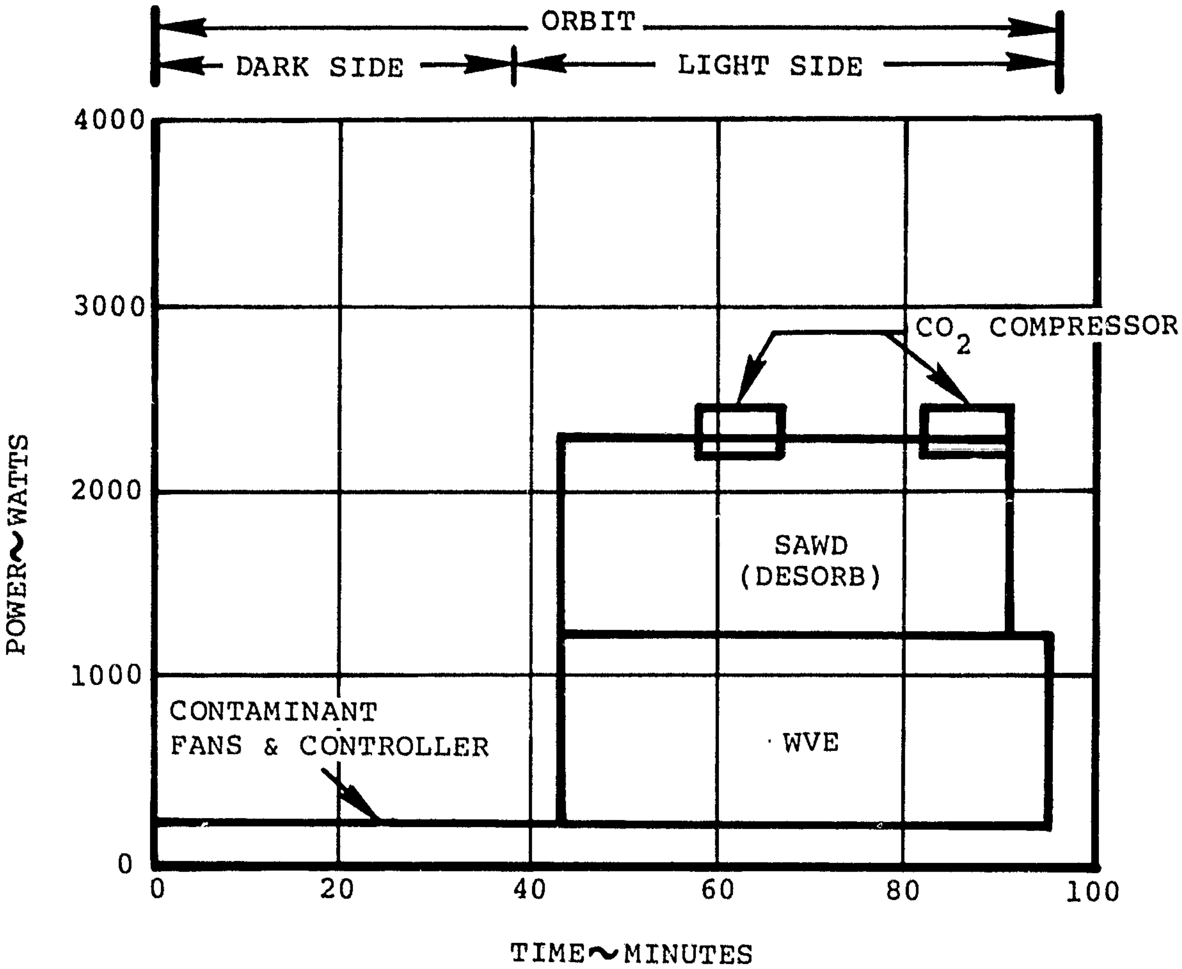

FIGURE 34

LARS SYSTEM STUDY
POWER PROFILE
2 MEMBER CREW 9 PSIA

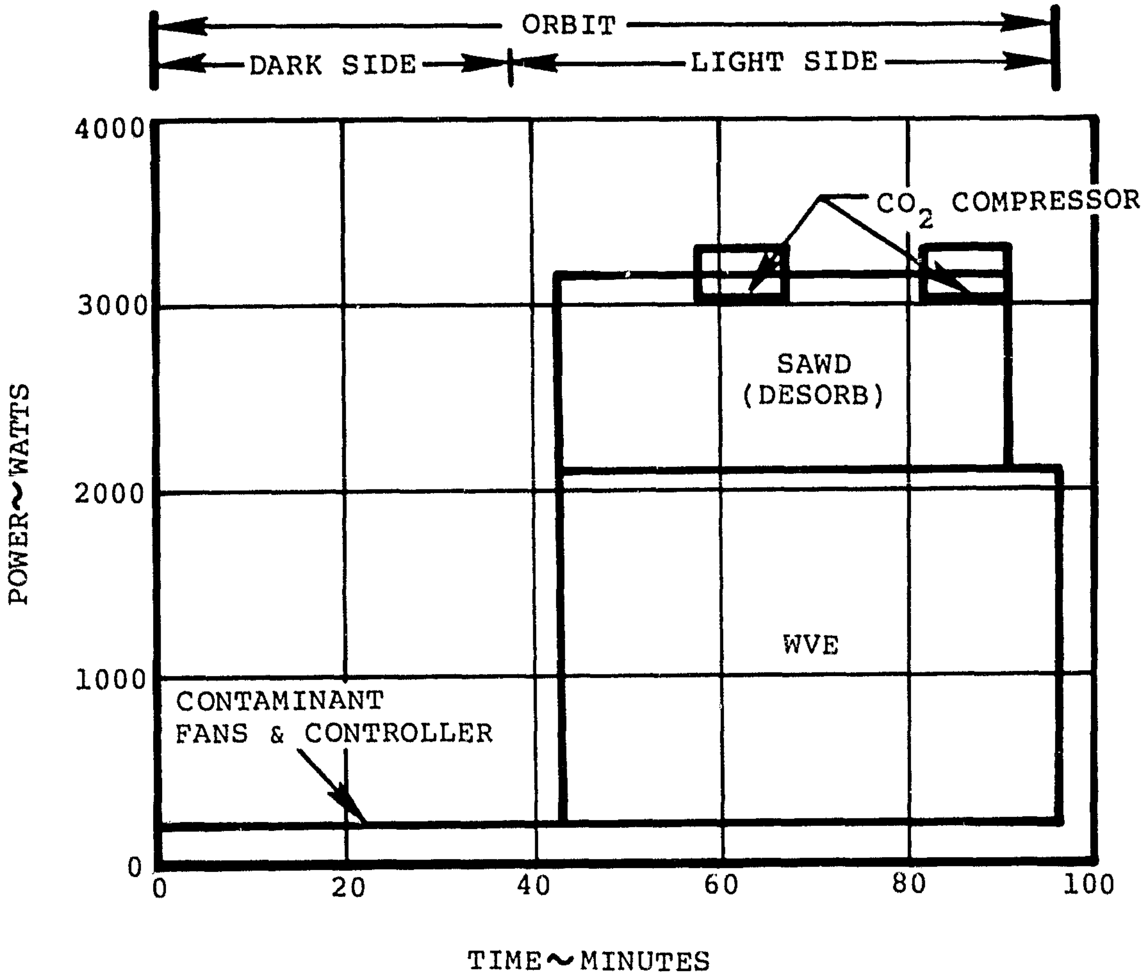

FIGURE 35

LARS SYSTEM STUDY
POWER PROFILE
4 MEMBER CREW 9 PSIA

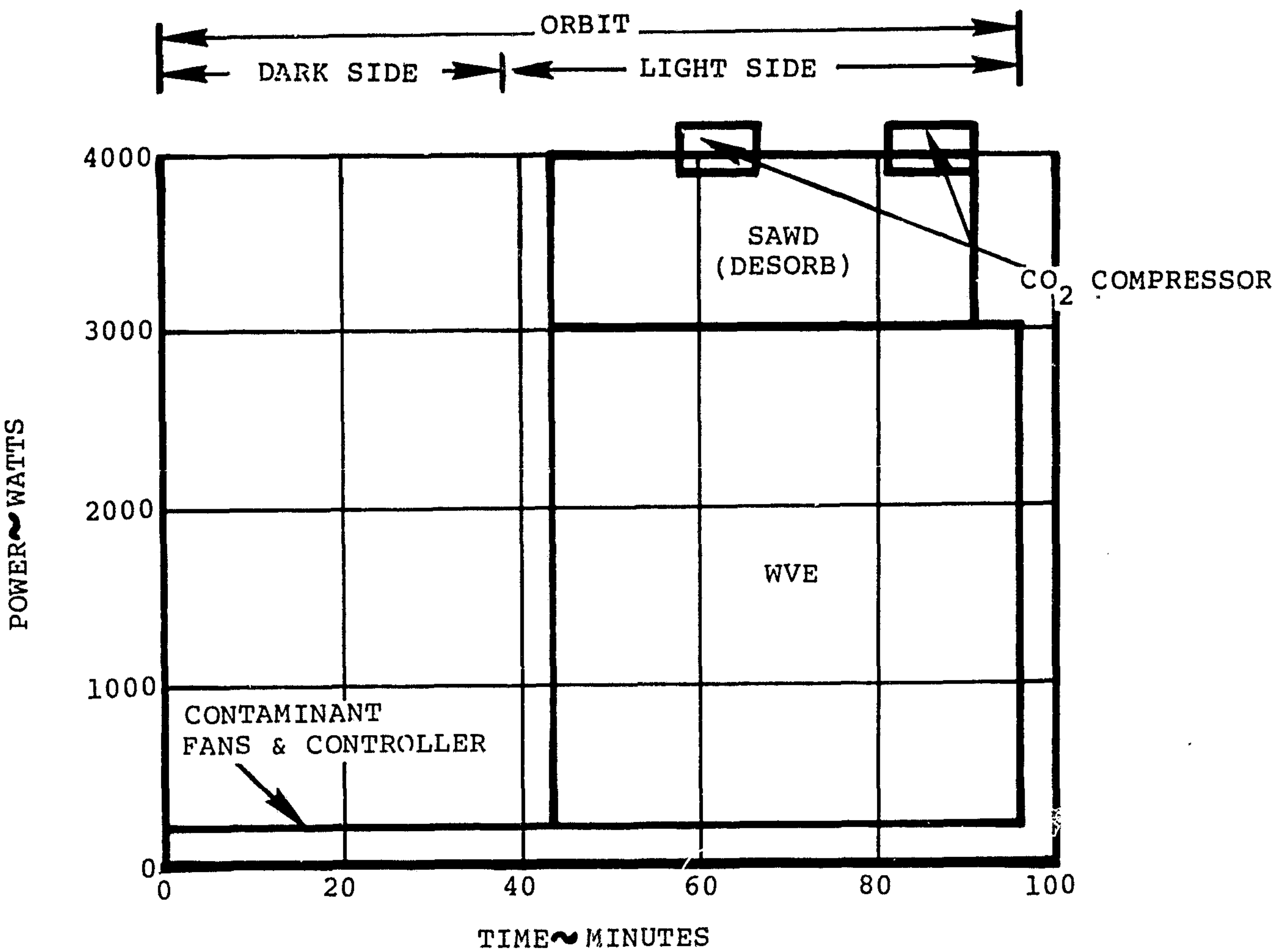

FIGURE 36

LARS SYSTEM STUDY
POWER PROFILE
6 MEMBER CREW 9 PSIA

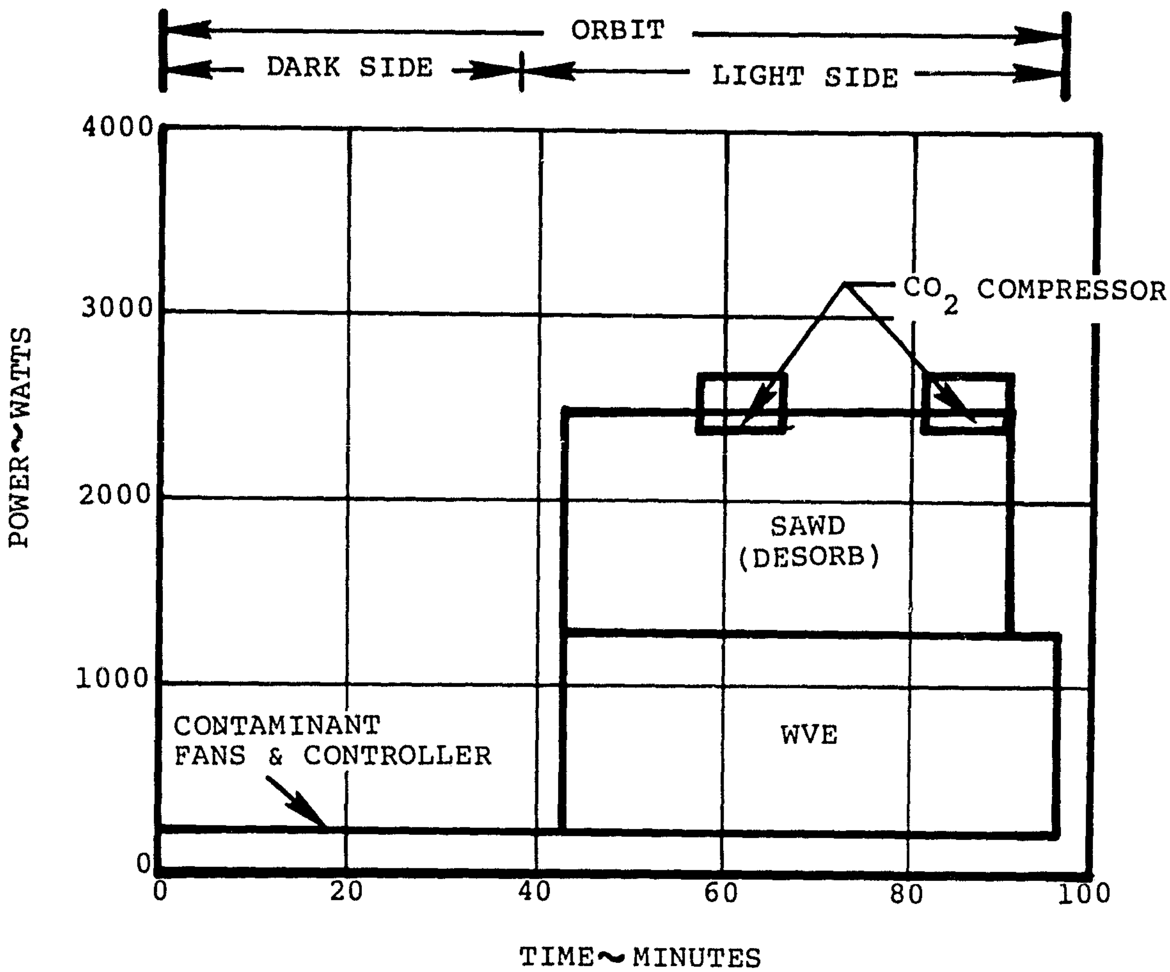

FIGURE 37

LARS SYSTEM STUDY
POWER PROFILE
2 MEMBER CREW 14.7 PSIA

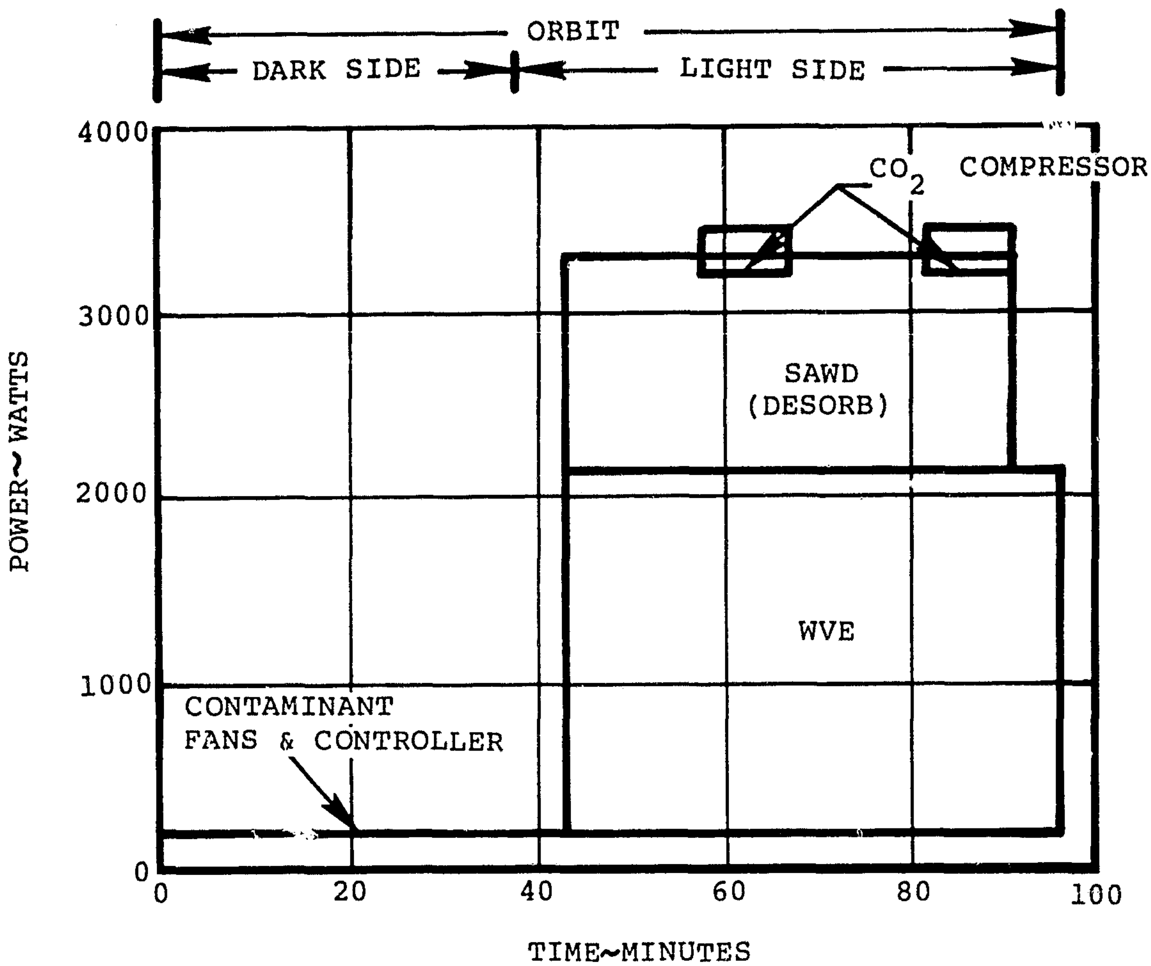

FIGURE 38

LARS SYSTEM STUDY
POWER PROFILE
4 MEMBER CREW 14.7 PSIA

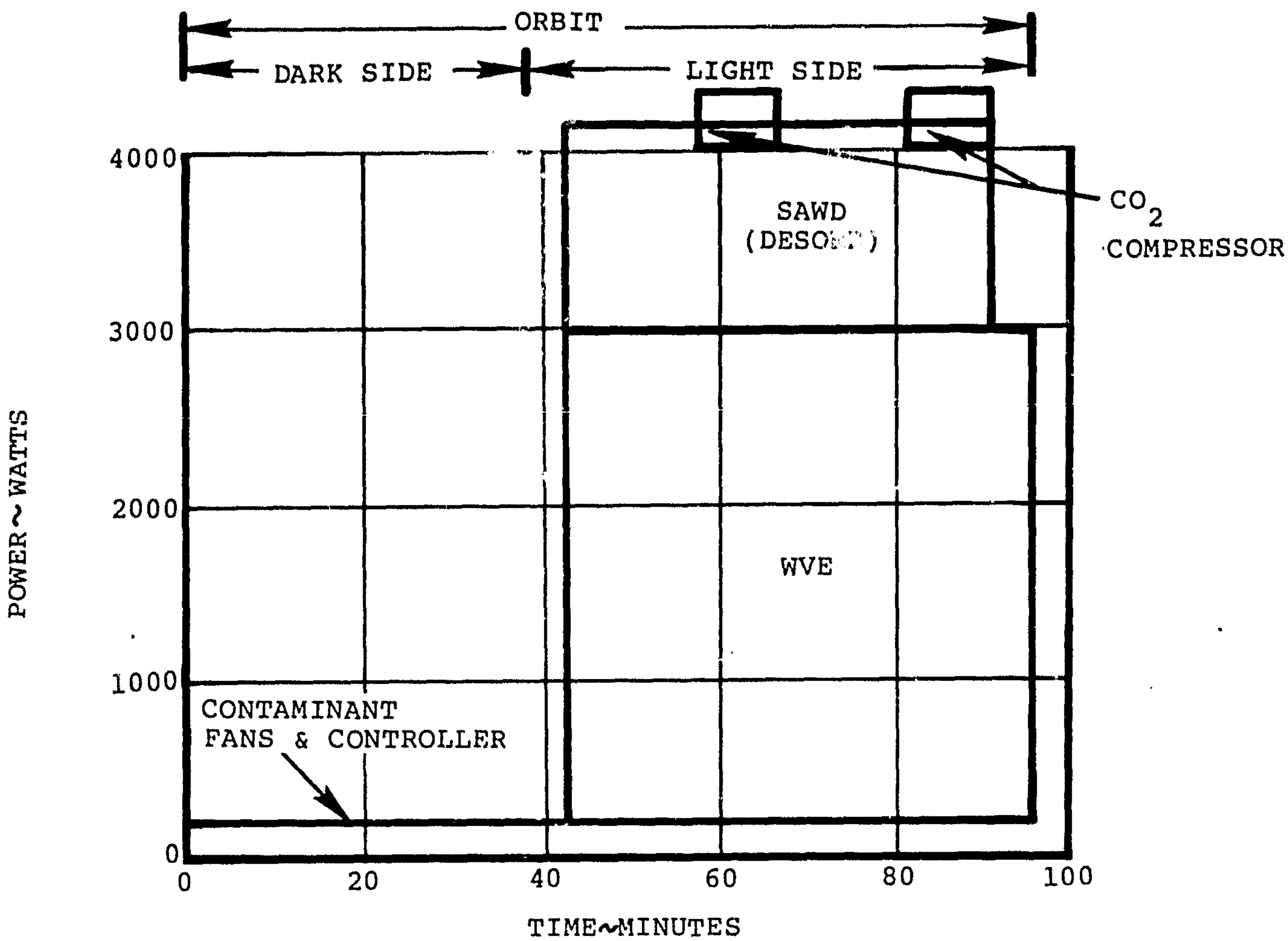

FIGURE 39

LARS SYSTEM STUDY
POWER PROFILE
6 MEMBER CREW 14.7 PSIA

For polar orbit operation, since SAWD bed desorption times can be doubled, SAWD peak power requirements would be reduced by 50%. WVE peak power requirements would be reduced by 47.5%, since operation would be continuous rather than fifty-three out of ninety-six minutes.

Cabin Temperature and Humidity Computer Model

The computer model used in the cabin temperature and humidity control study incorporates the functioning of the condenser, condenser bypass valve, water vapor electrolysis module and accounts for the temperature and humidity of the air leaving the solid amine water desorbed (SAWD) CO_2 removal subsystem. A listing of the computer program is given in Appendix A.

The program initializes at the beginning of the light side of the orbit. The condenser is removing heat and moisture transferred into the cabin from equipment (electrical, avionics, fans) as well as metabolic sensible and latent heat. Water is also being removed from the circulating air stream by absorption into the electrolysis cells. At five minutes into the transient, the WVE subsystem is started and one of the SAWD beds begins steam desorption. Complete desorption of the bed requires approximately twenty-four minutes. After desorption, full bed air flow is re-introduced, and the second SAWD bed begins its desorption cycle. At fifty-three minutes from the beginning of light side operation, the second bed is finished desorbing, and its air flow is restarted. After fifty-eight minutes of light side operation, the WVE is deactivated. It continues replenishing its stored water supply by taking moisture from the cabin air stream, which is receiving water vapor from the second SAWD bed, just returning to adsorption.

Most of the additional sensible and latent heat loads of the LARS system are removed by the main condenser. The condenser bypass control senses a temperature rise in the mixed condenser and bypass flow stream and begins closing the bypass valve. The rate of closing/opening is proportional to the deviation from the set point temperature, the maximum rate being .714% of full valve range per second for a deviation of ± 2.5 degrees or more.

The following information is plotted and/or printed versus time into orbit:

1) Cabin Temperature (°F)
2) Cabin Dew Point (°F)
3) Cabin Fan Inlet Temperature (°F)
4) Cabin Fan Outlet Temperature (°F)
5) Condenser Air Inlet Temperature (°F)
6) Condenser Air Outlet Temperature (°F)

7) Cabin Inlet Temperature (°F)
8) Condenser Inlet Dew Point (°F)
9) Condenser Heat Loads (Total, Sensible, Latent) (BTU/HR)
10) Cabin Fan Air Flow Rate (LBM/HR)
11) Condenser Air Flow Rate (LBM/HR)
12) Condenser Coolant Inlet Temperature (°F)
13) Condenser Coolant Outlet Temperature (°F)
14) Condensate Flow (LBM/HR)
15) Cabin Air Weight Flow (LBM/HR)
16) Condenser Air Weight Flow (LBM/HR)
17) Condenser Bypass Air Weight Flow (LBM/HR)
18) Sensible Metabolic Load (BTU/HR)
19) Latent Metabolic Load (BTU/HR)
20) Condenser UA (BTU/HR/°F)
21) Total Water from SAWD Beds (LBM)
22) Required WVE Cell Voltage (VOLTS)

The amount of water entering the SAWD air flow stream has been determined by extensive testing and data analysis to be proportional to the difference between the vapor partial pressure in the incoming air stream and the partial pressure of the stream, assuming it is saturated at the SAWD bed temperature.

Cabin CO_2 Partial Pressure Profiles

SAWD testing was performed at an adsorption cycle time of 52 minutes and an average CO_2 partial pressure of 0.4% by volume or 3.0 mmHg. The baseline case for LARS is 0.67% by volume or 5.0 mmHg average, and therefore, extrapolation of the experimental data was required.

CO_2 performance was assumed to follow that of a typical SAWD test, which shows stable bed moisture conditions and CO_2 removal performance. The breakthrough curve for this run is shown in Figure 40, and the adsorption performance has been extended to an adsorption time of 72 minutes. The curve of removal efficiency versus adsorption time, shown in Figure 41, was also extended to 72 minutes.

The two bed SAWD subsystem has three phases of operation. The first phase begins with the steam desorption of one of the beds, while the other bed continues the final 24 minutes of its adsorption. After the 24 minute desorption of the first bed, it is returned to adsorption, and the second bed starts its steam desorption. The freshly desorbed bed is now adsorbing CO_2 at peak efficiency. When the second bed completes its 24 minute desorption, it is returned to adsorption, and both beds are adsorbing simultaneously for the next 48 minutes. With these three cycle phases, transient cabin carbon dioxide partial pressure profiles for crews of 2, 4, and 6 men are shown in Figures 42, 43, and 44.

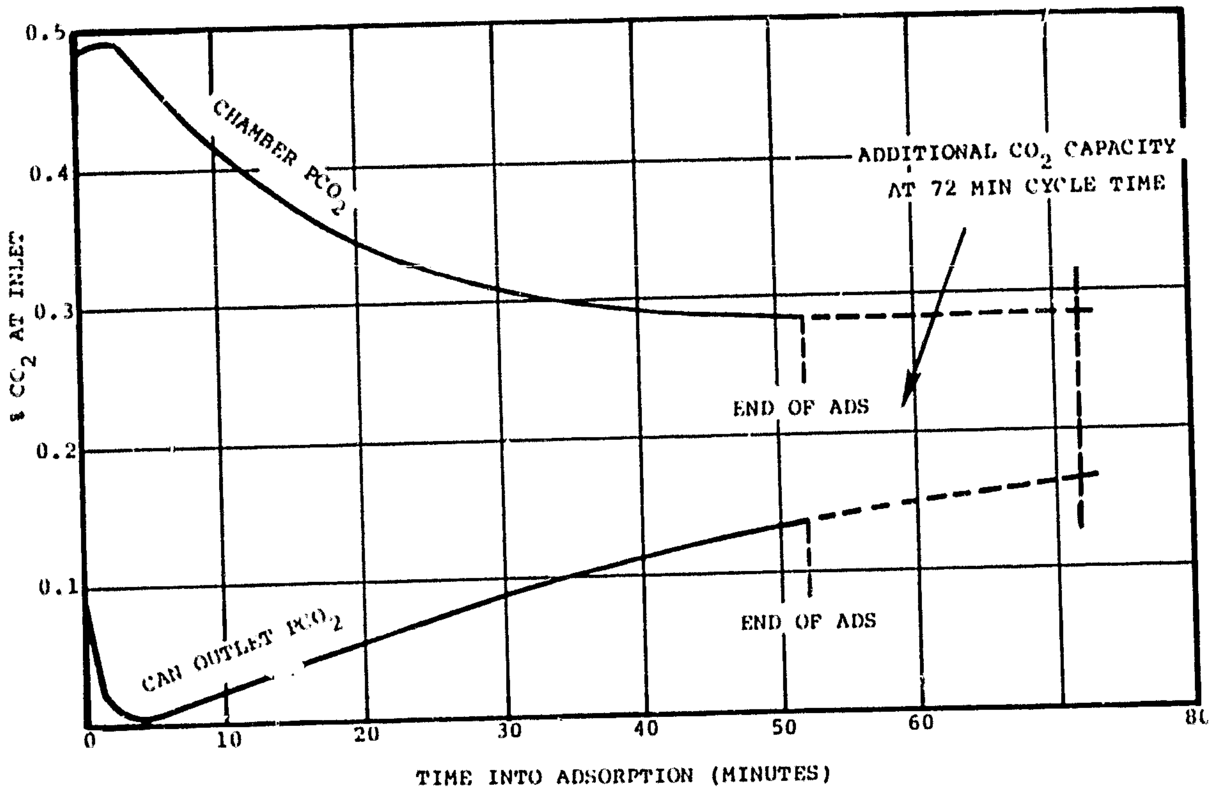

FIGURE 40

TYPICAL SAWD TEST BREAKTHROUGH CURVE

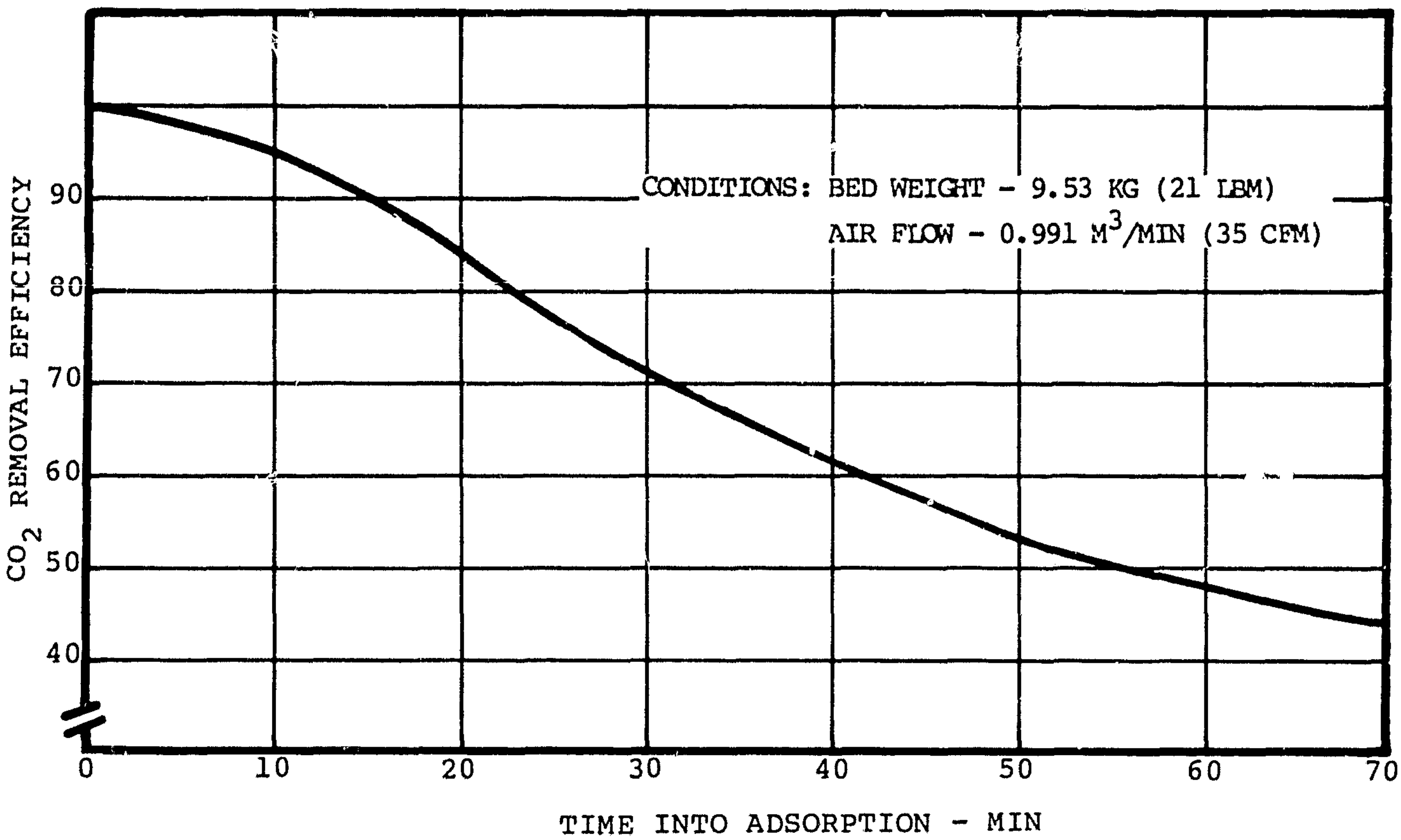

FIGURE 41

CO_2 REMOVAL EFFICIENCY VS. TIME

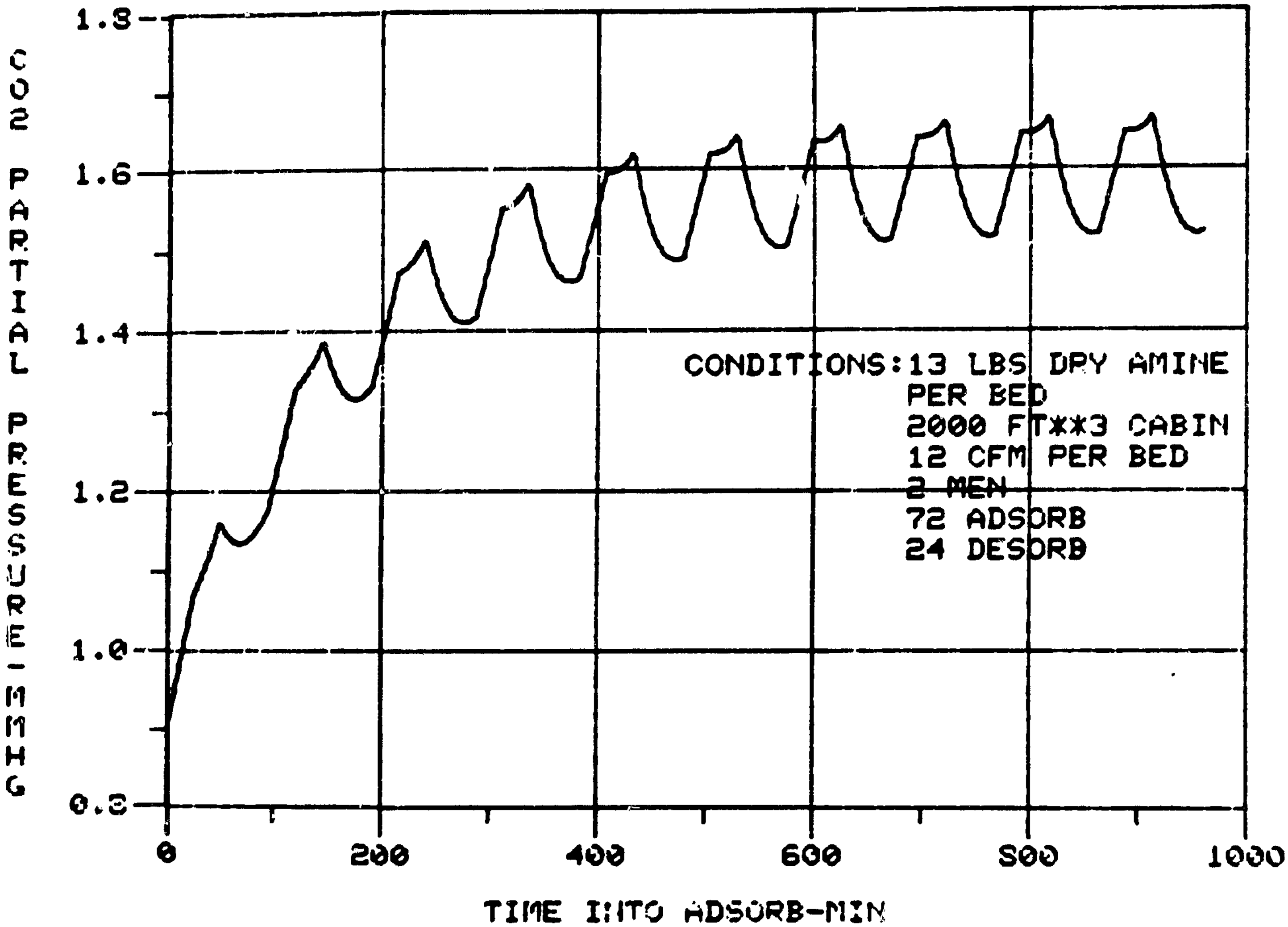

FIGURE 42

CO_2 PARTIAL PRESSURE PROFILE FOR TWO BED LARS SYSTEM

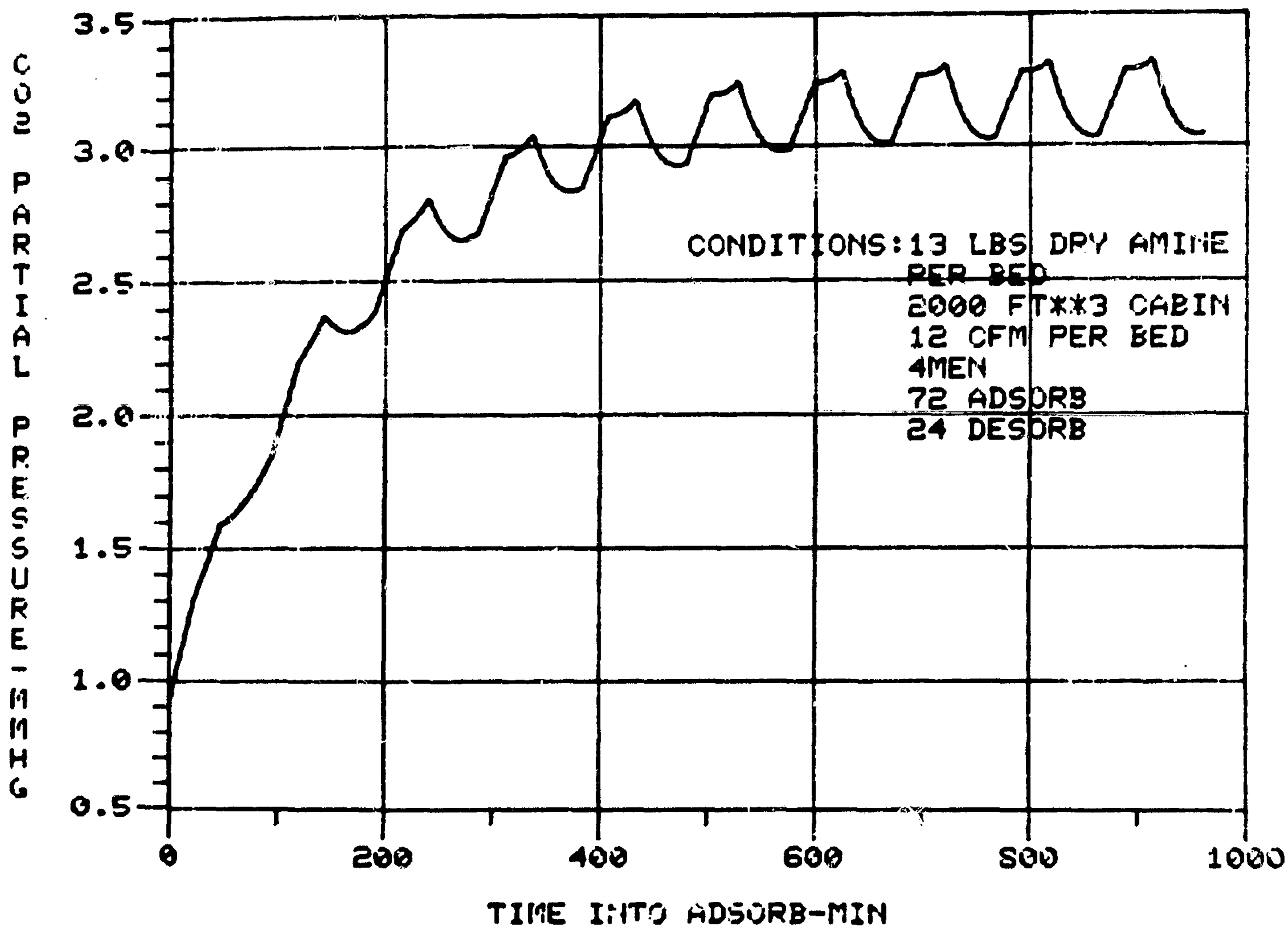

FIGURE 43

CO_2 PARTIAL PRESSURE PROFILE FOR TWO BED LARS SYSTEM

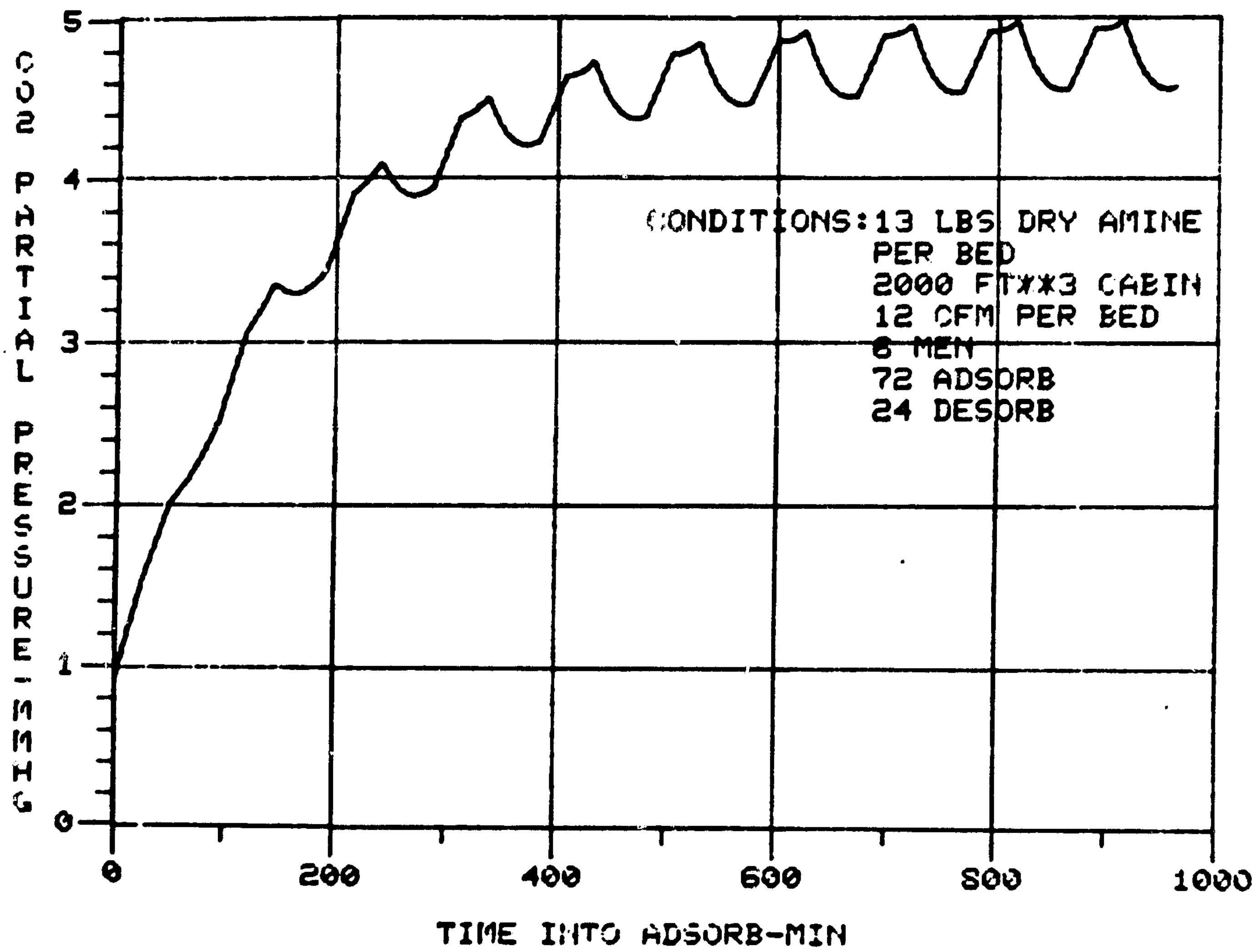

FIGURE 44

CO_2 PARTIAL PRESSURE PROFILE FOR TWO BED LARS SYSTEM

Examining Figure 42, there is a point in each cycle where the slope increases suddenly after reaching the minimum CO_2 partial pressure. This marks the beginning of the CO_2 performance model cycle. At this minimum point, one of the beds begins desorption. With the other bed nearing the end of its adsorption cycle, removal efficiency is low, and the crew CO_2 input rate is greater than the removal rate, resulting in the rapid rise of CO_2 partial pressure. After the 24 minute desorption, the second bed begins desorption, and the rapid rise in CO_2 partial pressure is stopped as the fresh bed returns to service. With completion of desorption of the second bed, both beds adsorb together for 48 minutes, resulting in a smooth decrease in cabin CO_2 partial pressure until the start of the next desorption phase.

The baseline case will maintain average cabin CO_2 partial pressure below 4.7 mmHg. The two man and four man cases maintain average CO_2 partial pressure below 1.6 mmHg and below 3.3 mmHg, respectively. During an emergency rescue situation, there may be a ten-man crew. Analysis indicates that the baseline system does not maintain acceptable CO_2 partial pressures for the ten-man case using the operating cycle described above. For the ten-man case CO_2 partial pressure rises until the bed capacity becomes high enough to accommodate the 10 man production rate. This happens, because solid amine loading is significantly increased for higher inlet CO_2 partial pressures. At the 10 man rate, the bed capacity must be .054 kg CO_2/kg (lbm CO_2/lbm) dry solid amine. Available data indicates that the required capacity is not realized until the cabin CO_2 partial pressure has exceeded 15 mmHg, and therefore LiOH is required to supplement the SAWD for the 10 man case. However, if flow is increased and cycle time is decreased, the SAWD system can maintain acceptable CO_2 levels for the 10 man case. These changes can be easily accommodated by the SAWD subsystem if power is available.

The effect of installing a SAWD subsystem in the orbiter on spacelab CO_2 control was investigated. With a crew of six, average CO_2 partial pressure in the orbiter is maintained below 4.7 mmHg. If three of the crew members are in the spacelab and there is a constant air exchange of 1.36 m^3/min. (48 CFM) between the orbiter and spacelab, the CO_2 partial pressure in the spacelab does not exceed 5.4 mmHg. This analysis assumes no LiOH is used in the spacelab.

Cabin Oxygen Partial Pressure Control

The water vapor electrolysis system oxygen production is controlled by regulating the current flow through the cells. The WVE controller requires a cabin oxygen partial pressure measurement from the vehicle. At the beginning of light side operation this measurement is compared with a stored measurement taken at the beginning of the previous WVE operating cycle. The current is then lowered or raised by a predetermined percentage from the previous cycle, based on the difference in measurements, and oxygen partial pressure is maintained within the desired range.

The lower limit on the existing cabin pressure and atmosphere composition control is set at oxygen partial pressures of 22.06 ± 1.72 kPa (3.2 ± .25 psia) and 17.58 ± 1.03 kPa (2.55 ± .15 psia) for total pressures of 101.35 and 62.05 kPa (14.7 and 9.0 psia), respectively. With the addition of the WVE system, these limits for the existing oxygen partial pressure control would be lowered so that no cryogenic oxygen is introduced to the cabin during the normal cyclic changes in oxygen partial pressure. The existing oxygen control system serves as an emergency system to automatically ensure that an adequate level of cabin oxygen partial pressure is maintained, if the WVE system malfunctions.

During normal cyclic WVE operation, the maximum fluctuation in cabin oxygen partial pressure with a six member crew is .200 and .228 kPa (.029 and .033 psi) for total pressures of 101.35 and 62.05 kPa (14.7 and 9.0 psia), respectively. It is, therefore, not expected that cryogenic oxygen make-up would be required unless an upset condition existed. The existing cabin pressure control system would normally have to supply only nitrogen for the maintenance of cabin total pressure for two, four, or six member crews.

For missions during which the WVE would not be in operation (e.g. delivery missions or a rescue mission with a ten member crew) the existing oxygen partial pressure controller would be used to regulate oxygen supply and maintain cabin total pressure from cryogenic supplies.

Power for the WVE controller is approximately 10% of that necessary to operate the WVE cell stack (approximately 260 watts), and is needed for fifty-three minutes during light side operation.

TOPIC IV
Comparison to Present Shuttle ECS

The objective of the trade study was to determine the weight and volume advantages of the LARS over the orbiter baseline LiOH system for both power extension package (PEP) and power system missions. The major variables considered were cryogenic O_2 and H_2 requirements, fuel cell usage, and water requirements. The LARS can be installed in the following three steps:

- Replace LiOH with the SAWD subsystem only and vent carbon dioxide overboard.
- Add the WVE subsystem to produce oxygen for metabolic consumption and cabin leakage, and vent hydrogen produced by the WVE cells overboard with the carbon dioxide.
- Add the Sabatier subsystem to convert carbon dioxide and hydrogen to water and methane. The water is recovered for potable usage, and the methane is vented overboard.

The following mission scenarios were considered for the trade study:

- PEP (57° orbit inclination)
  Solar power is used on the light side, and orbiter fuel cells produce all power on the dark side. The fuel cells are throttled down to hot start mode on the light side. The following is a summary of fuel cell output:

  Light side 58 minutes/orbit 3 kw
  Dark side 38 minutes/orbit 14 kw

  The weight penalty for solar cells to power the SAWD and WVE subsystems must be included.
- PEP (sun synchronous orbit)
  Solar cells provide continuous power. Two fuel cells are throttled down to cold start (.33 kw/cell), and one is throttled down to hot start (1 kw minimum) or to an output that produces enough water to meet all needs. The weight penalty for solar cells to power the SAWD and WVE subsystems must be included.
- Power System (with no additional water storage)
  The power system provides power on the light and dark sides of each orbit. Two fuel cells are throttled down to cold start (.33 kw/cell), and one fuel cell is throttled down to hot start (1 kw minimum) or to an output that produces enough water to meet all needs. No penalty is included for solar cells, since they are not carried with the shuttle at launch.

- Power System (all fuel cells at cold start level)
  The power system provides power on the light and dark sides of each orbit. All three fuel cells are throttled down to cold start (.33 KW/cell). No weight penalty is included for solar cell power.

Since the LARS can be installed in three increments, each of these possible configurations must be compared with the baseline LiOH system. The fixed weights for the four systems for all missions are given below:

- Baseline LiOH System

  - Hardware includes the portion of the ARS CO_2 adsorber and temperature control assembly containing the LiOH cartridges. The temperature control valve and the controller, which form the remainder of the assembly, are common to all systems.

  - Contingency LiOH cartridges and storage racks are included to provide CO_2 removal for six men during a 20 hour contingency period.

The fixed weight summary for the baseline LiOH system is given below:

Item	Weight-kg (lbm)
Hardware	10.43 (23)
Contingency LiOH cartridges (3)	9.52 (21)
Storage racks (1)	3.63 (8)
Total fixed weight	23.58 (52)

- SAWD System

  - Hardware includes the same fixed hardware as the baseline LiOH system, since the CO_2 adsorber assembly is not modified, and the hardware associated with the SAWD subsystem. SAWD hardware includes the SAWD canisters, isolation valves, fans, steam generation equipment, a controller, and structure.

  - LiOH cartridges are included for launch and a 20 hour contingency period. One cartridge is provided for launch. If necessary, it provides approximately 8 hours of prelaunch and launch time before the SAWD cycle is synchronized with the orbital period. The SAWD subsystem can be operated during this time. However, the LiOH cartridge provides additional flexibility, if power is critical. Three LiOH cartridges are required for the 20 hour contingency period.

The fixed weight summary for the SAWD system is given below:

Item	Weight-kg (lbm)
Hardware	
CO_2 adsorber assembly	10.43 (23)
SAWD subsystem	59.86 (132)
LiOH cartridges (4)	12.70 (28)
Storage racks (2)	7.26 (16)
Total fixed weight	90.25 (199)

. SAWD and WVE System

- Hardware includes the SAWD subsystem as described above and the WVE subsystem. The WVE hardware replaces the LiOH canister portion of the CO_2 adsorber assembly.

- The LiOH cartridge requirement for launch and a 20 hour contingency is the same as that for the SAWD system.

The fixed weight summary for the SAWD and WVE system is given below:

Item	Weight-kg (lbm)
Hardware	
SAWD subsystem	59.86 (132)
WVE subsystem	47.17 (104)
LiOH cartridges (4)	12.70 (28)
Storage racks (2)	7.26 (16)
Total fixed weight	126.99 (280)

. LARS System (SAWD, WVE, and Sabatier)

- Hardware includes the SAWD and WVE subsystems as described above and the Sabatier subsystem, including CO_2 storage and CO_2 flow control equipment.

- The LiOH cartridge requirement for launch and contingency is the same as that for the SAWD system.

The fixed weight summary for the LARS is given below:

Item	Weight-kg (lbm)
Hardware	
SAWD subsystem	59.86 (132)
WVE subsystem	47.17 (104)
Sabatier subsystem	45.35 (100)
LiOH cartridges (4)	12.70 (28)
Storage racks (2)	7.26 (16)
Total fixed weight	172.34 (380)

PEP Mission (57° inclination orbit) Trade Study

The expendables considered for the trade study are water, cryogenics, LiOH, and charcoal. The requirements for each of the systems are described below:

- Water requirements

  The fuel cells operate at an average power output 7.35 kw. At this level more than enough water is generated to supply crew needs for all of the systems. Therefore, water storage does not enter into the trade study for this mission.

- Cryogenics usage

  Cryogenics usage is high, due to the high average fuel cell power output. A summary of cryogenics usage for the systems is given below:

	Cryogenic Consumption LiOH or SAWD System	kg/day (lbm/day) SAWD and WVE or LARS
Oxygen		
Metabolic	4.79 (10.56)	--
Leakage	0.87 (1.92)	--
Fuel cell	64.82 (142.90)	64.82 (142.90)
EVA	0.29 (0.64)	0.29 (0.64)
Total	70.77 (156.02)	65.11 (143.54)
Hydrogen		
Fuel cell	8.00 (17.64)	8.00 (17.64)

It is assumed that the baseline orbiter contains three cryogenics kits. Each kit contains 321.15 kg (708 lbm) of usable oxygen and 37.42 kg (82.5 lbm) of usable hydrogen. Part of the cryogenics contained in the three kits is required for launch and reentry and for the 20 hour contingency. This weight is common to all systems and was not included in the hardware fixed weight, but must be subtracted from the total usable quantity to determine the quantity of cryogenics available for the sortie part of the mission.

Usable Cryogenics for Sortie-kg (lbm)
All Systems

Oxygen	
Baseline 3 kits	963.27 (2124)
Less fixed wt.	-97.05 (-214)
Net baseline	866.22 (1910)
Additional kit	321.15 (708)
Hydrogen	
Baseline 3 kits	112.47 (248)
Less fixed wt.	-11.34 (-25)
Net baseline	101.13 (223)
Additional kit	37.65 (83)

The mission duration that can be achieved with the three baseline cryogenics kits for a LiOH or SAWD system equipped orbiter is 12.2 days. The limiting consumable is oxygen rather than hydrogen. With each additional cryogenics kit, the mission can be increased by 4.5 days. Again, oxygen is the limiting consumable.

With a SAWD and WVE system or LARS, the mission duration achievable with the three baseline cryogenics kits is 12.6 days, which is limited by hydrogen. Each additional kit allows a mission extension of 4.7 days. Again, hydrogen is the limiting factor.

- LiOH expendable weight is based on a cartridge life of 1.9 man-days. For a crew of six, including storage racks, the time dependent weight penalty for LiOH is 13.83 kg/day (30.5 lbm/day).

- Charcoal expendable weight for all systems except LiOH is based on a requirement for .227 kg (.50 lbm) of charcoal per day or one LiOH cartridge filled with charcoal for every ten days. The time dependent weight penalty including storage racks is .499 kg/day (1.10 lbm/day).

Figure 45 shows curves of total weight versus mission length for three cases. The solid line is for the baseline LiOH system. The small dashed line is for a LARS system without any penalty for the solar power required. The large dashed line includes the solar panel weight required to supply a LARS with approximately 4 kw of power during light side operations at a power penalty of 56.25 kg/kw (124 lbm/kw). Steps in the curves indicate when additional cryogenics kits must be added.

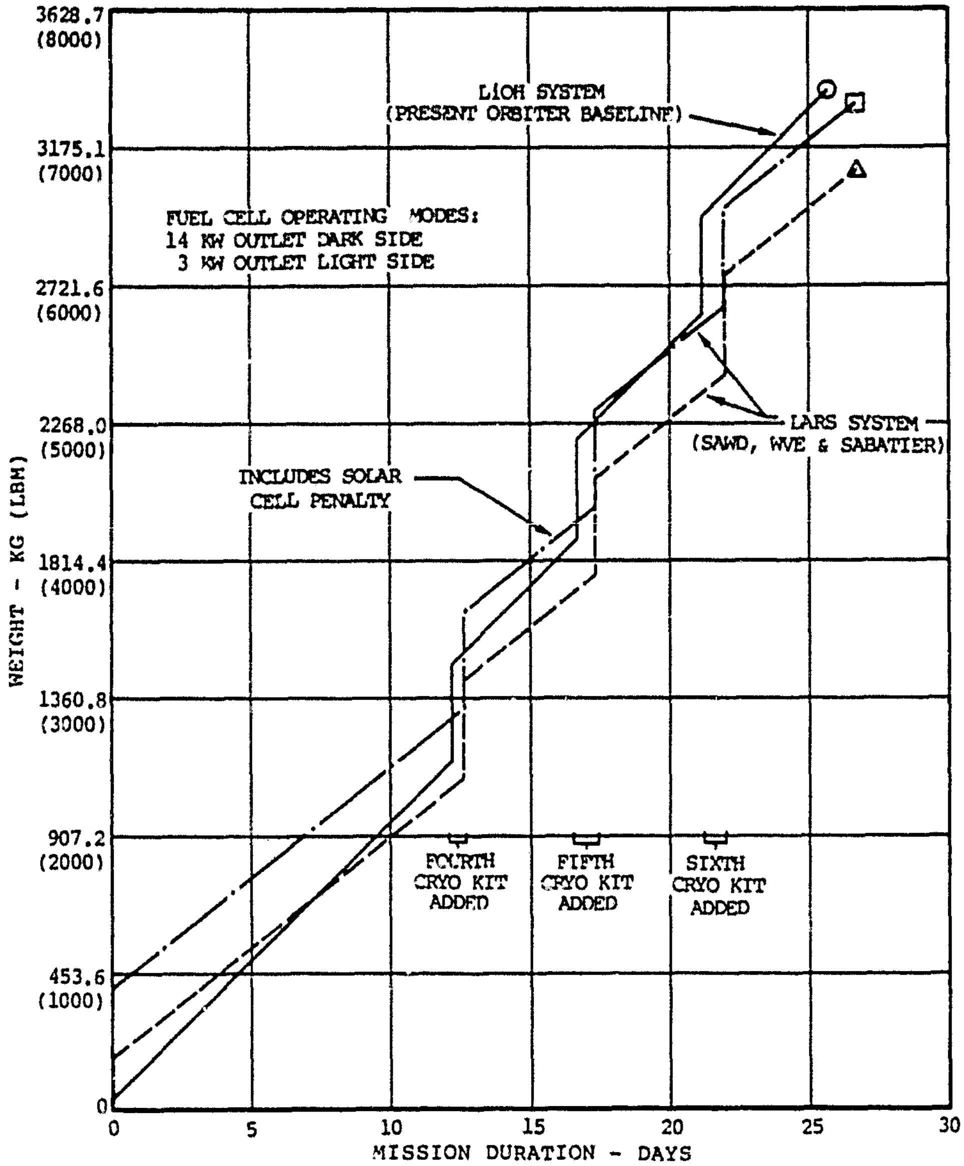

FIGURE 45

LiOH VS. LARS
PEP MISSION
ORBIT 57° INCLINATION

The LARS compares favorably for missions in excess of 7 days when the solar cell penalty is not considered and for missions in excess of 19 days when the penalty is included. At the end of the sixth cryogenics kit, the LARS results in an increased mission length of one day out of 25 and a weight savings of 39.46 kg (87 lbm).

If only the SAWD system is considered, the cryogenics requirements can be eliminated from the comparison, since they are the same for both the LiOH and SAWD systems. Figure 46 shows this comparison. The SAWD system compares favorably after only 5 days without considering the solar cell weight penalty and after 9 days when that penalty is included. The solar cell penalty is for the 1 kw steam generator required to desorb the SAWD beds. The weight savings at 17 days, which is about the time when the fourth cryogenics kit is expended, is 102.95 kg (227 lbm).

The volume penalty for the baseline LiOH system over any of the other systems is shown in Figure 47. Additional volume for LiOH storage is required after 7.6 days, when the 27 baseline cartridges, except those required for contingency, are used. After 17 days the additional volume required is 0.34 cubic meters (12.0 cubic feet). There is no volume penalty for the LARS system, since it is located in the space where the baseline LiOH cartridges are normally stored.

Power System Mission (no additional water storage) or Sun Synchronous PEP Mission Trade Studies

The consumable requirements for each of the systems are described below:

- Water requirements

  A summary of water requirements for the four systems is given in Table 4. The fuel cells are run at a level that provides all of the water needs. Therefore, no additional water storage is required.

- Cryogenics usage

	Consumption--kg/day (lbm/day)		
	LiOH or SAWD System	SAWD and WVE System	LARS
Oxygen			
Metabolic	4.79 (10.56)	---	---
Leakage	0.87 (1.92)	---	---
Fuel cells	14.72 (32.46)	18.34 (40.44)	15.61 (34.41)
EVA	0.29 (0.64)	0.29 (0.64)	0.29 (0.64)
Total	20.68 (45.58)	18.63 (41.08)	15.90 (35.05)

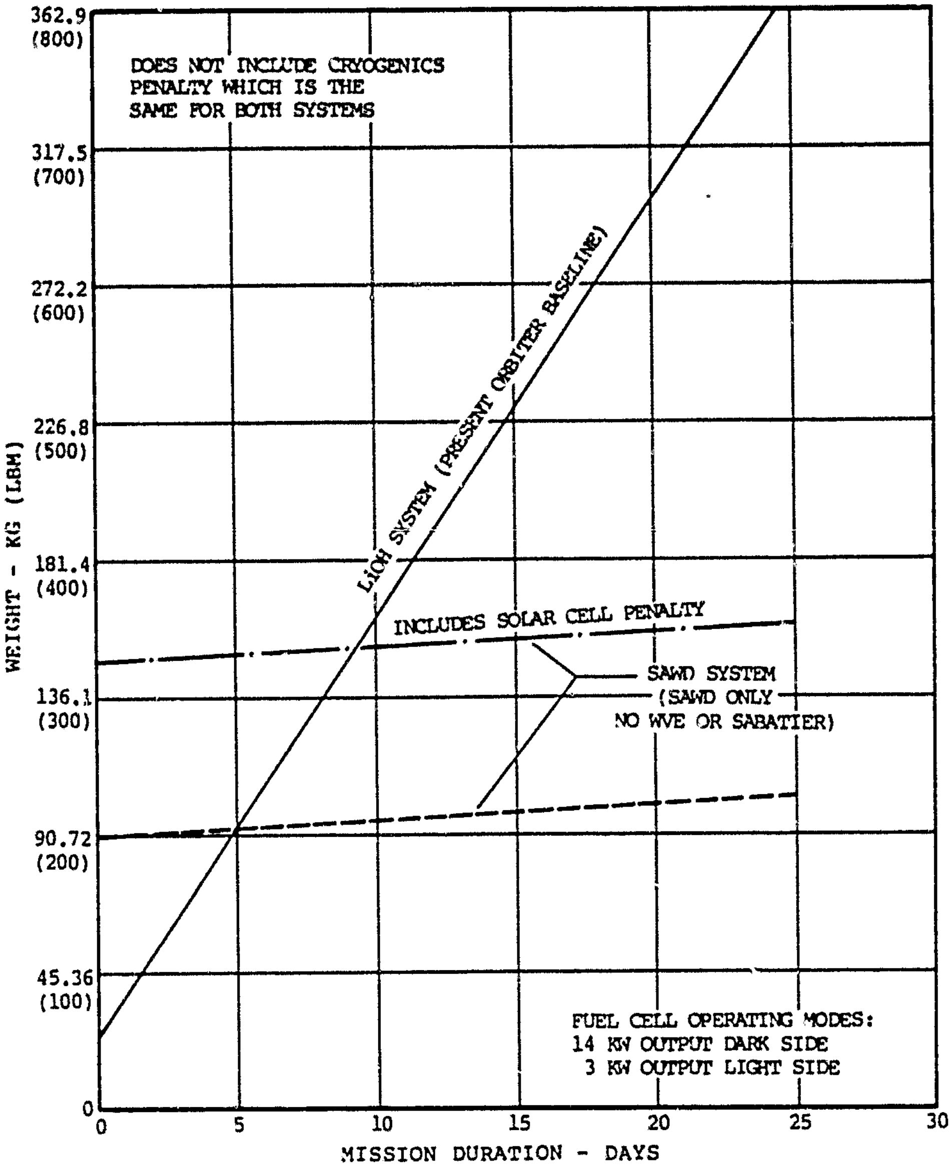

FIGURE 46

LiOH VS. SAWD
PEP MISSION
ORBIT 57° INCLINATION

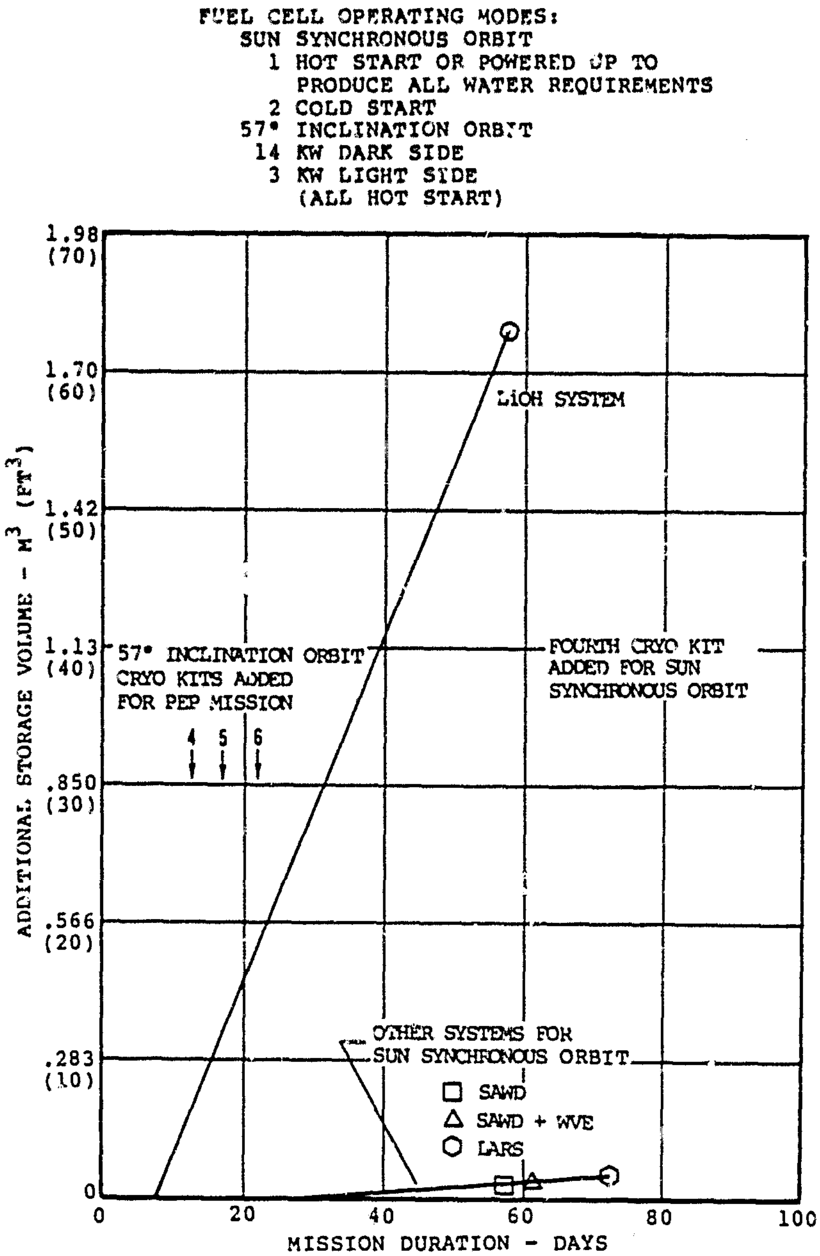

FIGURE 47

LiOH VS. LARS
PEP MISSION

Table 4

POWER SYSTEM MISSION (NO ADDITIONAL WATER STORAGE)
WATER BALANCE KG/DAY (LBM/DAY)

	SYSTEM			
	LiOH	SAWD	SAWD + WVE	LARS
Water Usage				
Potable	15.51 (34.20)	15.51 (34.20)	15.51 (34.20)	15.51 (34.20)
Non-potable				
Wash	6.94 (15.30)	6.94 (15.30)	6.94 (15.30)	6.94 (15.30)
EVA	1.24 (2.74)	1.24 (2.74)	1.24 (2.74)	1.24 (2.74)
WVE	---	---	6.37 (14.04)	6.37 (14.04)
Total	8.18 (18.04)	8.18 (18.04)	14.55 (32.08)	14.55 (32.08)
Water Produced				
Potable				
Fuel Cell	16.54 (36.47)	16.54 (36.47)	20.57 (45.34)	17.54 (38.67)
(kw)*	(1.67)	(1.67)	(2.08)	(1.77)
Condensate				
Metabolic	9.50 (20.94)	9.50 (20.94)	9.50 (20.94)	9.50 (20.94)
LiOH	2.34 (5.16)	---	---	---
Sabatier	---	---	---	3.03 (16,67)
Total	11.84 (26.10)	9.50 (20.94)	9.50 (20.94)	12.52 (27.61)

* Two fuel cells are in cold start mode (0.333 kw each), and one is in hot start mode (1.0 kw) or at a power output sufficient to supply all water needs.

Hydrogen Fuel cells	1.82 (4.01)	2.26 (4.99)	1.93 (4.25)

The times for adding crogenics kits, depending on the system installed, are given below:

	Duration--days		
	LiOH or SAWD System	SAWD and WVE System	LARS
Time for 3 baseline kits (O_2 or H_2 limited)	41.9 (O_2)	44.6 (H_2)	52.4 (H_2)
Time for each additional kit (O_2 or H_2 limited)	15.5 (O_2)	16.5 (H_2)	19.4 (H_2)
Total time for 4 kits	57.4	61.1	71.8

- Hardware

  The fixed weights for hardware and cryogenics are the same as those for the previous PEP mission trade study.

- LiOH and charcoal time dependent weights are the same as those for the previous PEP mission trade study.

Figure 48 shows a weight comparison between the four systems versus mission duration. A solar cell penalty was not included for power system missions, since the power system is not launched each time. For PEP missions a solar cell penalty of 57.61 kg (127 lbm) for the SAWD system and 226.8 kg (500 lbm) for the WVE systems must be added to the curves of Figure 48. The steps in the curves indicate when the fourth cryogenics kit is added for the power system mission. The curves show that all three increments of the LARS hardware addition compare favorably to the baseline LiOH system in less than eight days. Adding just the SAWD subsystem does not increase mission length, but results in a 699 kg (1541 lbm) weight savings at the end of the fourth cryogenics kit. The addition of the WVE and Sabatier subsystems does not significantly change the weight, but does increase the mission length. Addition of the WVE subsystem increases mission length by 3.7 days, and addition of the Sabatier subsystem increases the mission by another 10.7 days.

Figure 47 shows a volume penalty of 1.78 cubic meters (63 cubic feet) for the baseline LiOH system over any of the other three systems.

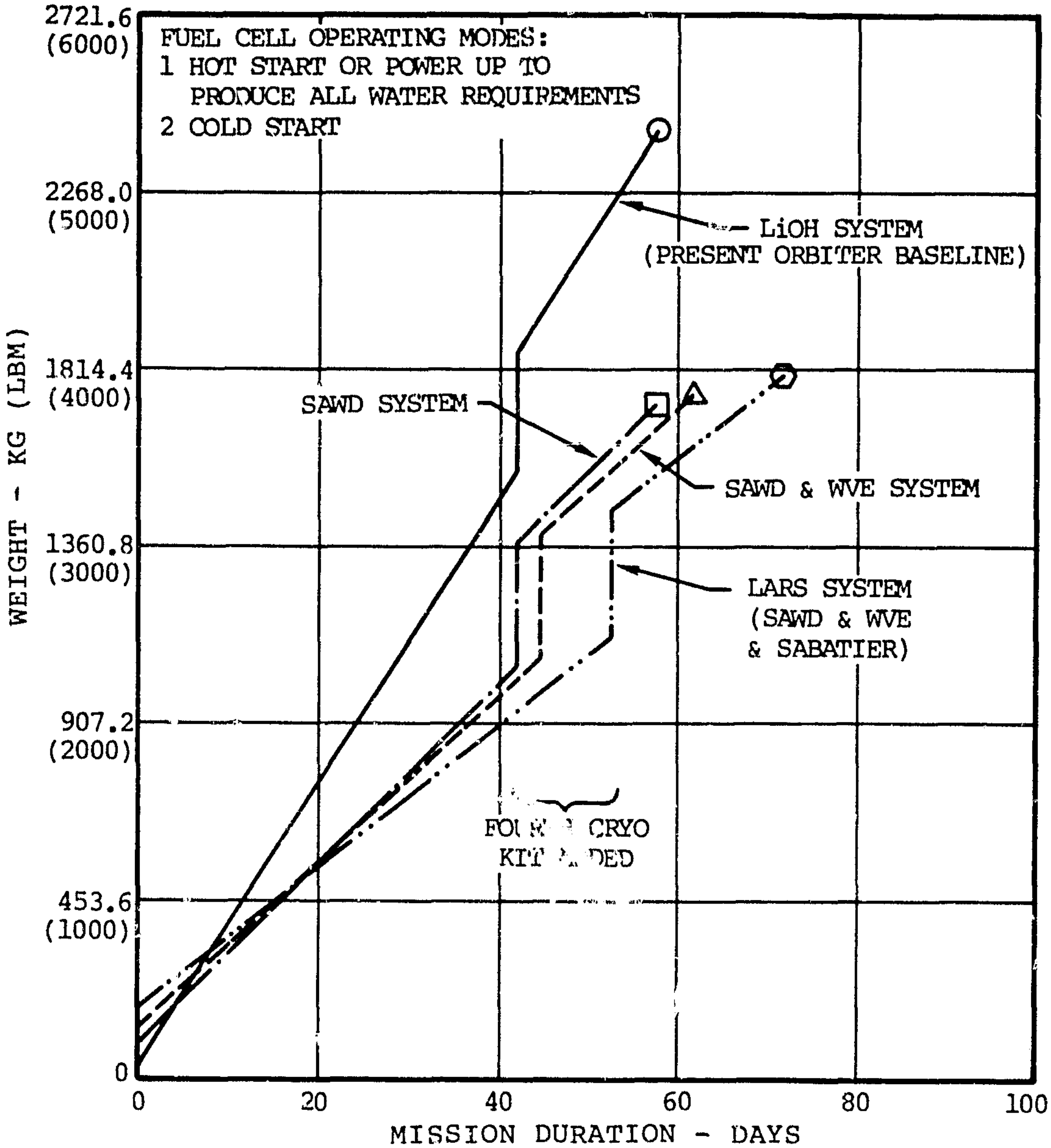

FIGURE 48

LiOH VS. LARS
SUN SYNCHRONOUS ORBIT
PEP MISSION

Power System Trade Study (all fuel cells at cold start)

The consumable requirements for each of the systems are described below:

- Water requirements

  A summary of the water requirements for the four systems is given in Table 5. All fuel cells are run at a cold start level, and additional water storage must be included to supply water needs.

- Cryogenics usage

	Consumption--kg/day (lbm/day) LiOH or SAWD System	LARS or SAWD and WVE System
Oxygen		
Metabolic	4.79 (10.56)	---
Leakage	0.87 (1.92)	---
Fuel cell	8.82 (19.44)	8.82 (19.44)
EVA	0.29 (0.64)	0.29 (0.64)
Total	14.77 (32.56)	9.11 (20.08)
Hydrogen		
Fuel cell	1.09 (2.40)	1.09 (2.40)

The times for adding additional cryogenics kits are given below:

	Duration--days LiOH or SAWD System	LARS or SAWD and WVE System
Time for 3 baseline kits (O_2 or H_2 limited)	58.7 (O_2)	92.8 (H_2)
Time for each additional kit (O_2 or H_2 limited)	21.7 (O_2)	34.4 (H_2)

- Fixed weights for hardware and cryogenics are the same as those for the missions discussed previously.

- LiOH and charcoal time dependent weights are the same as those for the previous mission trade studies.

Table 5

POWER SYSTEM MISSION (ALL FUEL CELLS AT COLD START)
WATER BALANCE KG/DAY (LBM/DAY)

	SYSTEM			
	LiOH	SAWD	SAWD + WVE	LARS
Water Usage				
Potable	15.51 (34.20)	15.51 (34.20)	15.51 (34.20)	15.51 (34.20)
Non-potable				
Wash	6.94 (15.30)	6.94 (15.30)	6.94 (15.30)	6.94 (15.30)
EVA	1.24 (2.74)	1.24 (2.74)	1.24 (2.74)	1.24 (2.74)
WVE	---	---	6.37 (14.04)	6.37 (14.04)
Total	8.18 (18.04)	8.18 (18.04)	14.55 (32.08)	14.55 (32.08)
Water Produced				
Potable				
Fuel Cell	9.91 (21.84)	9.91 (21.84)	9.91 (21.84)	9.91 (21.84)
Condensate				
Metabolic	9.50 (20.94)	9.50 (20.94)	9.50 (20.94)	9.50 (20.94)
LiOH	2.34 (5.16)	---	---	---
Sabatier	---	---	---	3.03 (6.67)
Total	11.84 (26.10)	9.50 (20.94)	9.50 (20.94)	12.52 (27.61)
Supplemental Water Storage Required	5.61 (12.36)	5.61 (12.36)	10.66 (23.50)	7.63 (16.83)
	Make-up For Potable Only		Make-up For Potable And Non-potable	

Figure 49 shows a weight comparison between the four systems versus mission duration. A solar cell penalty is not included for power system missions. The step in each curve indicates when the fourth cryogenics kit must be added. The curves show that all three increments of LARS hardware addition compare favorably to the baseline LiOH system in less than nine days. Adding only the SAWD subsystem does not increase the mission length, but does result in a 1005 kg (2217 lbm) weight savings at the end of the fourth cryogenics kit. The complete LARS installation also shows a weight advantage, and increases mission length by 47 days.

Figure 50 shows the volume penalty associated with the four systems. For all increments of the LARS system, the volume penalty is primarily for water storage. All LARS systems show a significant advantage over the baseline LiOH system.

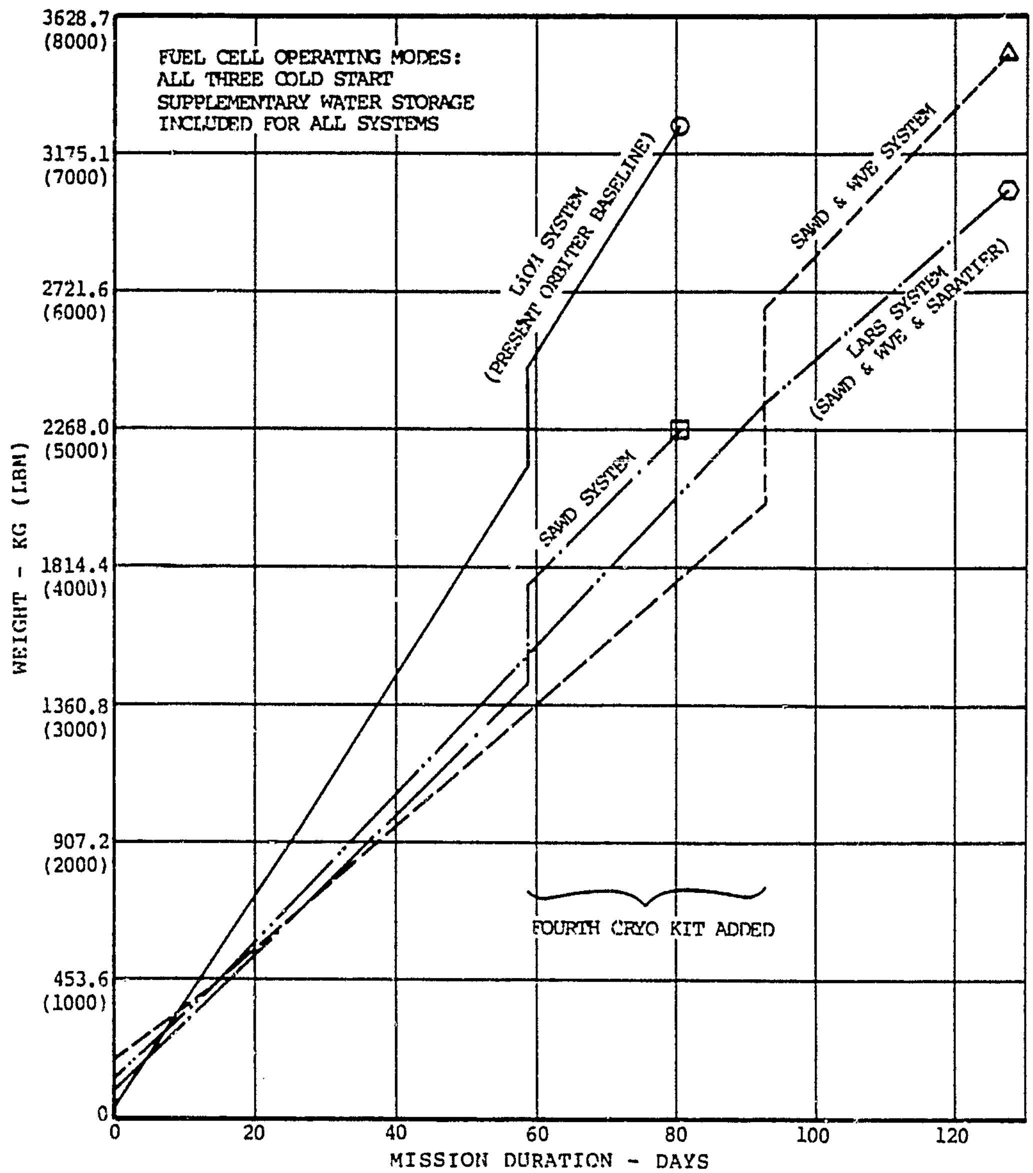

FIGURE 49

LiOH VS. LARS
POWER SYSTEM MISSION

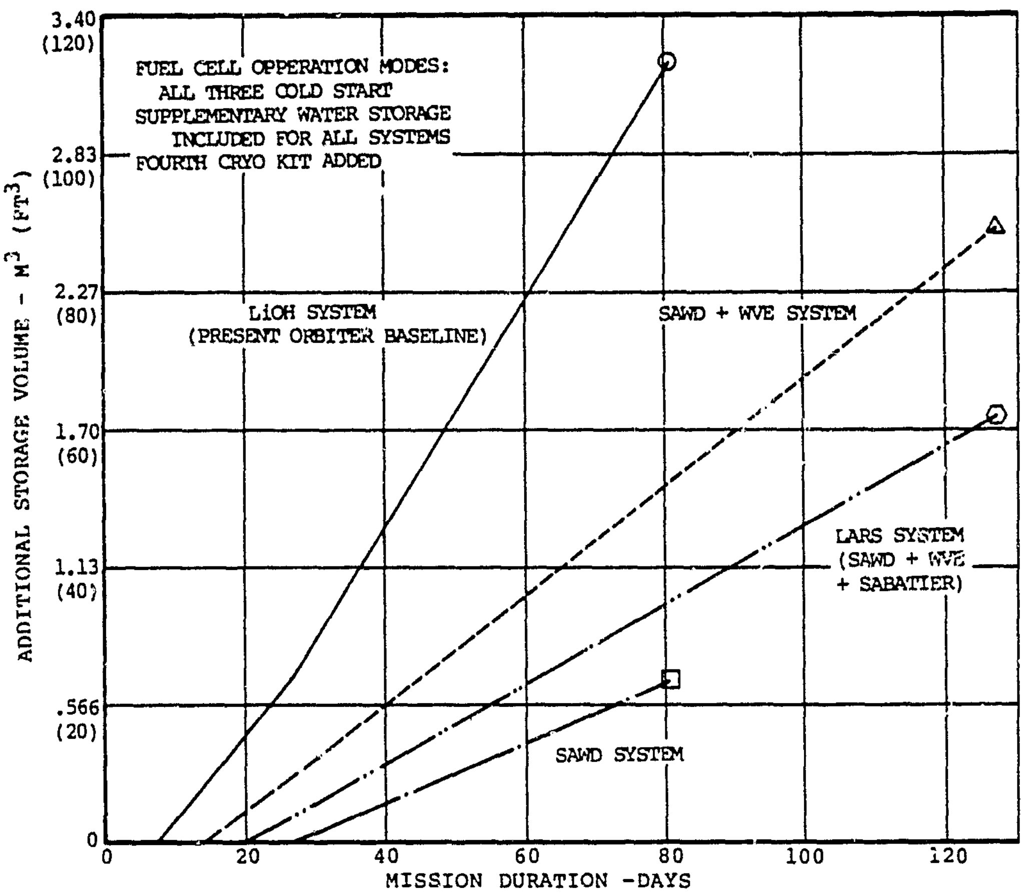

FIGURE 50

LiOH VS. LARS
POWER SYSTEM MISSION

TOPIC V
System Effectiveness Studies

System Safety

Nearly all of the components and materials associated with the Lightside Atmospheric Revitalization System are of a passive, non-hazardous nature. The two exceptions are the hydrogen product gas and sulfuric acid electrolyte of the water vapor electrolysis subsystem. The only two high temperature components are the Sabatier reactor and the SAWD subsystem water evaporator. Both of these items are designed to have touch temperatures of less than 45°C (113°F). There are no high pressure components in the system. The highest pressure at any point in the system is 455.05 kPa (66 psia) in the carbon dioxide accumulator for the 62.05 kPa (9.0 psia) cabin pressure case. For 101.35 kPa (14.7 psia) cabin pressure, the carbon dioxide accumulator pressure is 744.63 kPa (108 psia). All other system components operate at or near ambient cabin pressure. Since no part of the system operates at a vacuum, there is only a small interface with space vacuum at one point to dispose of methane produced in the Sabatier reactor and excess carbon dioxide.

The sulfuric acid electrolyte in the WVE cells is contained in the Tissuequartz cell matrix. During WVE testing electrolyte carry-over from the cells was never experienced under any test conditions. With proper reservoir sizing and the correct electrolyte charging procedure, the cells cannot be flooded. The cells are initially charged with excess electrolyte. Then, with no electrical power applied, they are subjected to moist air flow, such as 30.56°C (87°F) and 90% relative humidity. The electrolyte and water reach equilibrium in the cell matrix and reservoirs for this severe condition. Excess electrolyte is removed from the cells during this charging procedure. Now, the cells are compatible with any shuttle conditions including the severe 30.56°C (87°F) and 90% relative humidity, non-operating case.

The Hamilton Standard Space Systems Department Technical Standard SV-0264 sets specific guidelines for treatment of the hydrogen which is produced by the WVE and used in the Sabatier reactor.

According to these guidelines, the following precautions must be implemented:

1) The volume of the hydrogen carrying lines is to be kept to a minimum. This would allow for a minimum of hydrogen concentration build-up in the event of a leak in a line which had been isolated and had emptied into its environment. The cabin volume being large compared to hydrogen line volumes helps minimize the potential for concentration build-up.

2) Combustible gas detectors must be used to give a shutdown signal at 0.5% hydrogen concentration. Shutdown of hydrogen containing subsystems must be completed including a nitrogen purge, before the detectable concentration reaches 2.0%.

3) All hydrogen containing lines and equipment must be at least 6.89 kPa (1.0 psi) above ambient at all times to maintain a preferred direction of leakage. This prevents the possibility of air leaking into a hydrogen rich area, causing a potentially highly combustible mixture.

The design of the LARS conforms with the above requirements to ensure that the hydrogen produced by the WVE is safely handled.

System Maintainability

The Lightside Atmospheric Revitalization System requires no in-flight maintenance other than periodic replacement of the activated charcoal canister (every 10 days), and is designed for minimum ground turn-around time. The primary components of the three subsystems are the SAWD canisters with integrated water evaporators, the water vapor electrolysis cell pair stack, and the Sabatier reactor. These components are supported by ancillary items, such as water pumps, fans, accumulators, valves, and controllers. All of the primary and ancillary components can be maintained using a modular replacement concept. For example, a failure of a WVE cell pair would be corrected by replacing the WVE cell pair stack with a refurbished and tested unit. The individual cell pair would then be replaced in the ground support facility, and the entire cell pair stack would be tested and prepared for installation in another vehicle.

TOPIC VI
Subsystem Sizing and Operating Characteristics

SAWD Sizing

For the solid amine water desorbed carbon dioxide removal system a two bed system is the selected approach. The system schematic of Figure 51, shows the integration of the SAWD subsystem with the other components of the ARS. The desorb/adsorb schedules for the selected approach and for the alternate one bed approach are shown in Figure 52.

The selected approach utilizes a 72 minute adsorption cycle for each of the two solid amine beds. Each bed is desorbed for 24 minutes once during each 96 minute orbit. During desorption, steam is injected into the bed, desorbing the CO_2, which is pumped to approximately 455.05 kPa (66 psia) and stored in the CO_2 accumulator for subsequent processing in the Sabatier reactor. The steam generators are built as integral parts of the canister inlet headers to prevent condensation on the canister by preheating the metal.

The two bed SAWD system consists of two 5.90 kg (13 pound) dry weight beds of solid amine adsorbent. Bed sizing is based on the cyclic SAWD testing in which solid amine was continuously cycled through 96 minute adsorb/desorb periods. Each test run began with steam desorption, followed by an approximately 52 minute adsorption to give a 96 minute cycle. During the adsorption period, air at .991 m^3/min (35 CFM) was drawn through the 9.53 kg (21 lbm) dry weight solid amine bed exhausting to a 29.31 m^3 (1035 ft^3) sealed chamber. Carbon dioxide was continuously introduced to the chamber at a four man rate of 0.160 kg/hour (0.352 lbm/hour). The weight of the bed could be accurately measured at any time during a run. Instrumentation recorded air flow, bed pressure drop, bed inlet conditions of temperature and dewpoint, and several thermocouples measured the bed axial temperature profile.

As a basis for sizing calculations, a typical test cycle was chosen. Chamber inlet and outlet CO_2 partial pressures are shown in Figure 53 in the characteristic breakthrough curve. Absolute bed loadings are 0.259 kg (0.570 lbm) of CO_2 for a 52 minute cycle time and 0.279 kg (0.615 lbm) of CO_2 for a 72 minute cycle time. These loadings translate into loadings of 0.02714 kg CO_2/kg (lbm CO_2/lbm) dry bed at the 52 minute cycle time, and 0.02929 kg CO_2/kg (lbm CO_2/lbm) dry bed at a 72 minute cycle time.

Table 6 shows bed capacities at two cycle times, two total pressures, and two CO_2 partial pressures. Data from SAWD cyclic tests was extrapolated to 62.05 kPa (9 psi) and 5 mmHg pCO_2 through the use of Figures 53 and 54, which were also developed from SAWD test data.

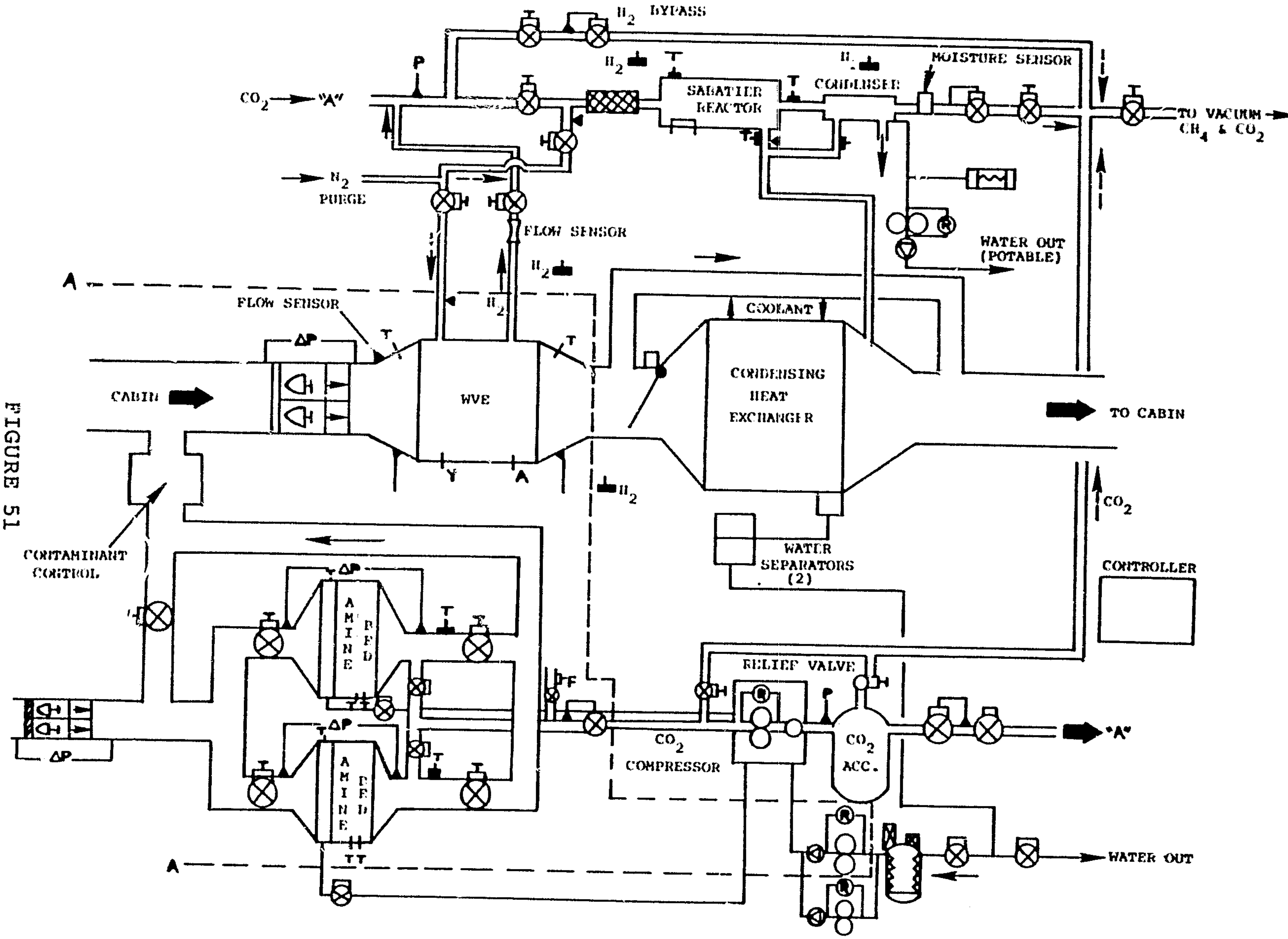

FIGURE 51
LARS SCHEMATIC

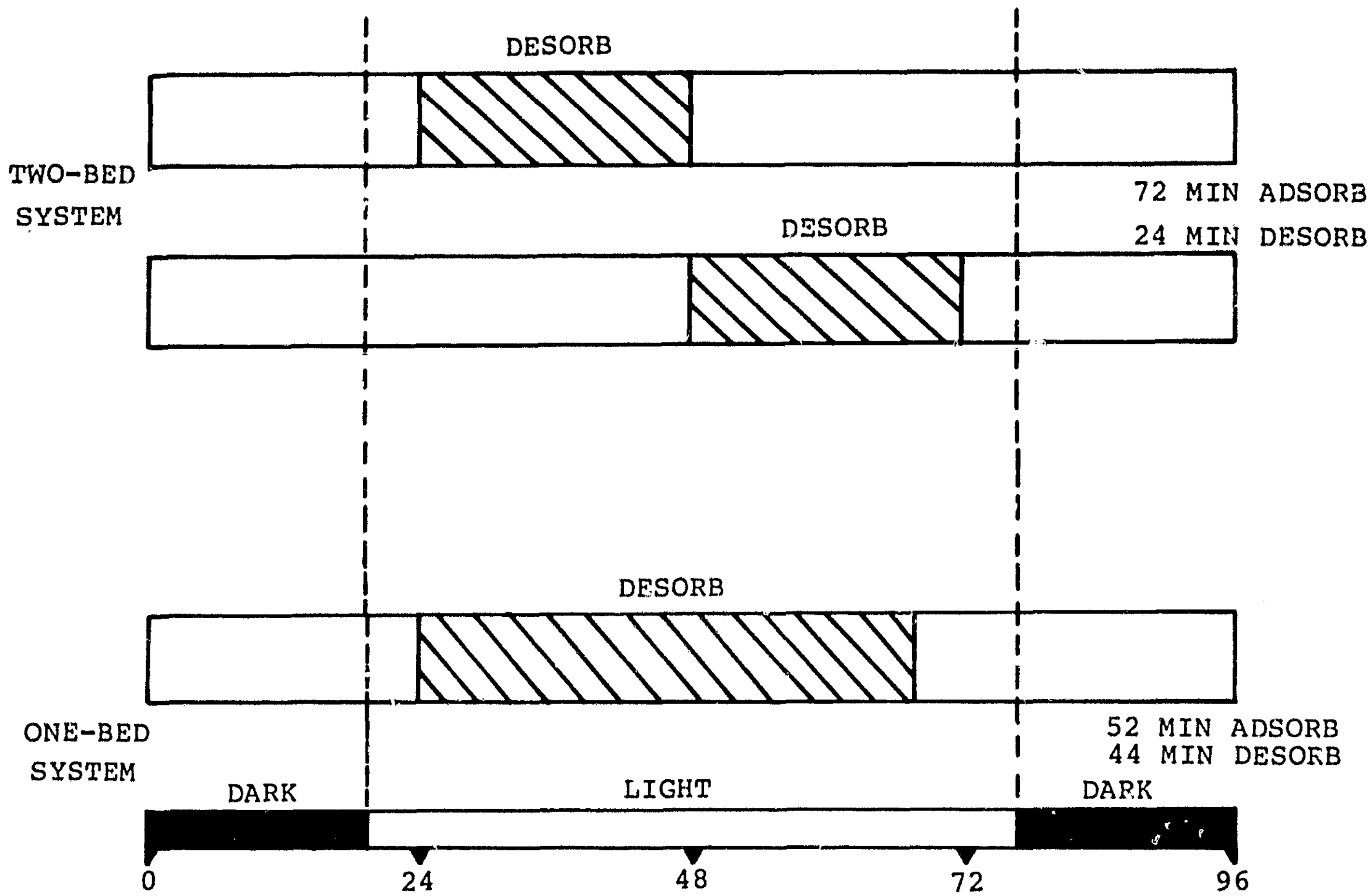

FIGURE 52

ADSORB/DESORB SCHEDULES FOR
SINGLE AND DUAL BED SAWD SYSTEMS

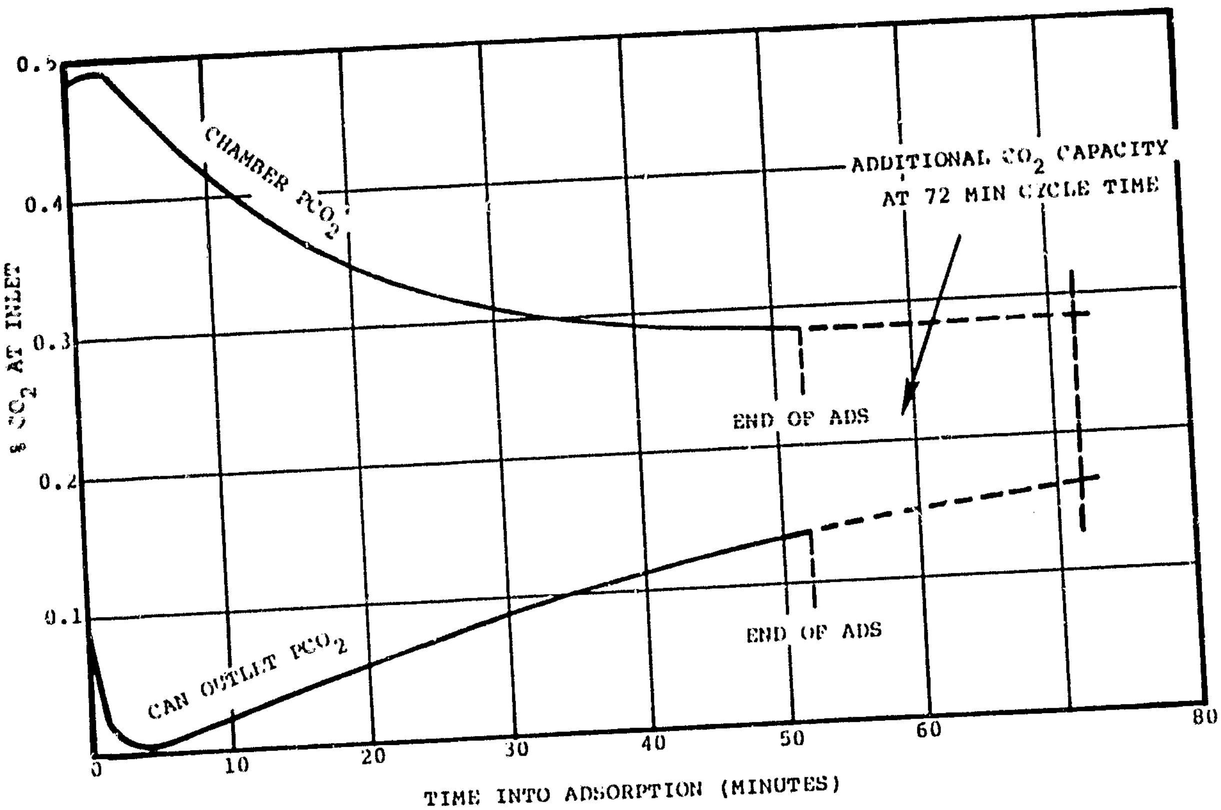

FIGURE 53

TYPICAL SAWD TEST BREAKTHROUGH CURVE

Table 6
SAWD BED LOADING

SAWD BED LOADING $\frac{\text{lbm } CO_2}{\text{lbm dry solid amine}}$ or $\frac{\text{kg } CO_2}{\text{kg dry solid amine}}$

52 MIN ADSORB				72 MIN ADSORB			
62.05 kPa (9 psia)		101.35 kPa (14.7 psia)		62.05 kPa (9 psia)		101.35 kPa (14.7 psia)	
3 mmHg	5 mmHg	3 mmHg	5 mmHg	3 mmHg	5 mmHg	3 mmHg	5 mmHg
.02714	.02978	.02929	.03213	.02937	.03587	.03169	.03870

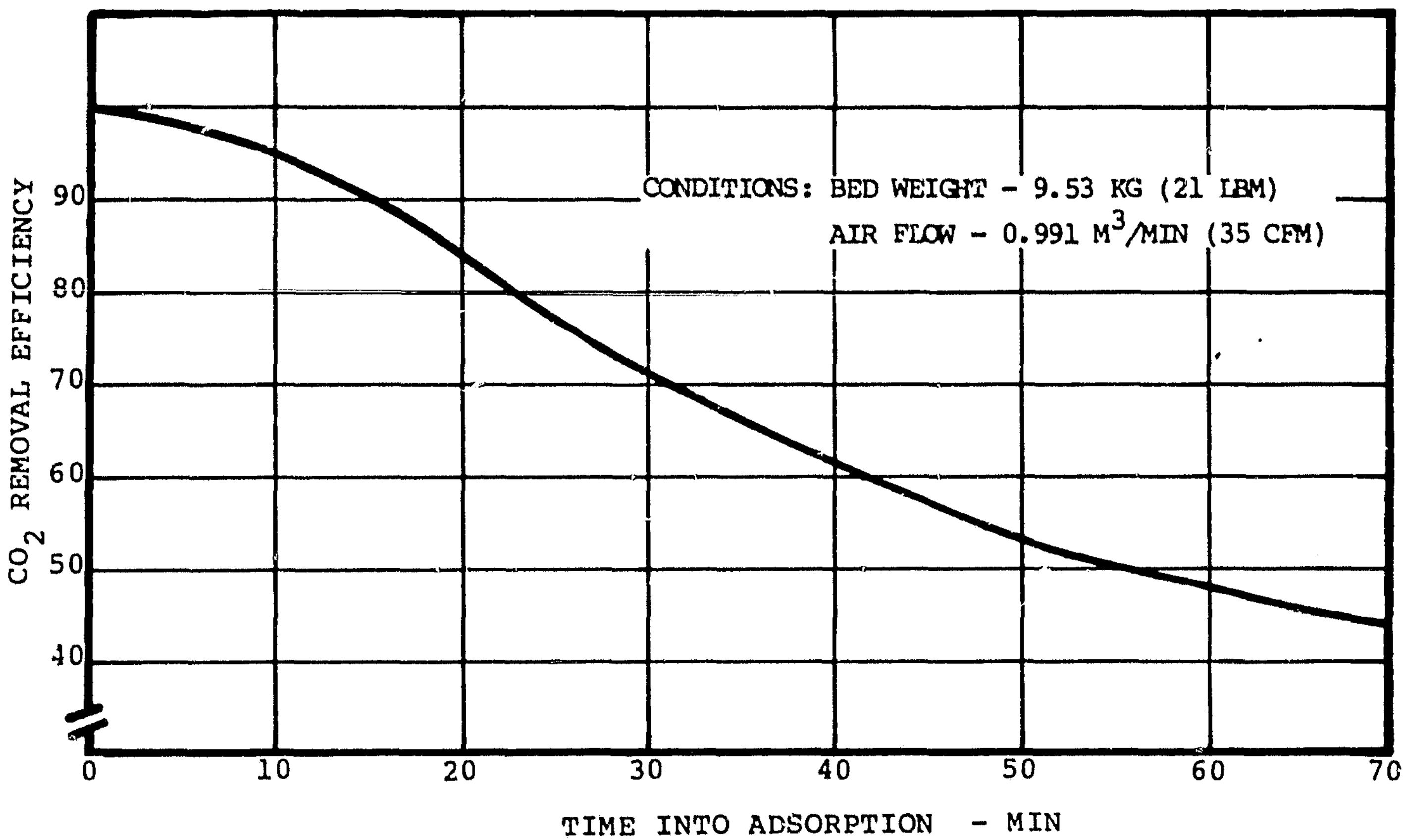

FIGURE 54

CO_2 REMOVAL EFFICIENCY VS. TIME

Parametric Sizing Characteristics

The results of the SAWD testing were used to size a total of six solid amine systems. The results of this sizing effort are presented in Table 7. The table shows the similarity between a 6 man 5 mmHg CO_2 partial pressure (baseline) SAWD design, and a 4 man 3 mmHg CO_2 partial pressure system. While the 6 man system must adsorb 50% more carbon dioxide, bed weight is only 20% more than the 4 man system due to the increased bed capacity at 5 mmHg CO_2 partial pressure.

Operation at 62.05 kPa (9 psia) total system pressure causes a loss in bed capacity as shown in Figure 55. Lower temperature desorption with 62.05 kPa (9 psia) steam is not as effective in regenerating the solid amine bed material. Residual CO_2 on the bed at the 87.22°C (189°F) desorption temperature results in a 7.3% decrease in adsorption capacity.

Solid Amine Moisture Control And Cyclic Moisture Equilibrium

From the SAWD test program it was found that if the moisture content of the amine is maintained between 20% and 35% of dry bed weight, then CO_2 adsorption performance is only a function of bed inlet CO_2 partial pressure and cycle time as shown in Figure 56. Below and above the acceptable moisture range, performance degrades. To adsorb CO_2, the amine groups must be hydrated. Only hydrated amine groups undergo the reversible reaction with CO_2 to form bicarbonate ions, and with less than 20% water on the bed, performance degrades as non-hydrated amine groups lose their ability to adsorb CO_2. Above 35% moisture loading, there is an inhibiting layer of water on the amine beads, which reduces the ability of CO_2 to diffuse to the active amine sites.

With continuous air flow at a given relative humidity, solid amine attains an equilibrium moisture content. This is shown in Figure 57. It is apparent that at inlet relative humidities below 70%, equilibrium moisture loadings are below the 20% by weight required for adequate CO_2 removal performance. Fortunately, the cyclic nature of the SAWD system and the drying characteristics of the bed do not allow bed moisture levels to reach these low equilibrium levels.

The drying of a solid amine bed during adsorption occurs in three phases. Just after a bed is desorbed and returned to adsorption, the hot, wet bed dries rapidly with the outlet air nearly saturated with water vapor at the average bed temperature. Solid Amine has a heat transfer area of approximately 6890 m^2/m^3 (2100 ft^2/ft^3) of material, and it operates as a very effective heat exchanger during the initial phase of drying. Cooling is especially rapid in the front of the bed where CO_2 adsorption begins immediately. During this phase of drying, sensible heat for evaporation comes from the thermal mass of the solid bed material and supporting structure.

Table 7

SAWD SUBSYSTEM SIZING SUMMARY

	kg (lbs) CO_2 / Orbit	Total Bed Weight 101.35 kPa (14.7 psia) kg (lbm)	Total Bed Weight 62.05 kPa (9.0 psia) kg (lbm)	CO_2 ads. Rate Required kg/hr (lbm/hr)	Minimum Air Flow Required m^3/min(CFM)	Required Air Flow Based On CO_2 m^3/min(CFM)	Specific Air Flow $\frac{m^3/min}{kg\ bed}$ $\frac{CFM}{lb\ Bed}$
4 Men (3 mmHg) 72 min ads.	0.2552 (0.5626)	8.85 (19.5)	9.53 (21.0)	0.2126 (0.4688)	0.498 (17.6)	0.750 (26.5)	0.0787 (1.26)
6 Men (5 mmHg) 72 min ads.	0.3828 (0.8440)	10.89 (24.0)	11.75 25.9)	0.3190 (0.7033)	0.447 (15.8)	0.674 (23.8)	0.0574 (0.92)
6 Men (5 mmHg) 52 min ads.	0.3828 (0.8440)	13.11 (28.9)	14.15 (31.2)	0.4418 (0.9740)	0.620 (21.9)	0.804 (28.4)	0.0568 (0.91)

Pressure Drop cm H_2O (inch H_2O)

	Pressure Drop cm H_2O (inch H_2O) 101.35 kPa (14.7 psia)	Pressure Drop cm H_2O (inch H_2O) 62.05 kPa (9.0 psia)	Plumbing* P cm H_2O (inch H_2O)	Required Fan P cm H_2O (inch H_2O)
4 Men (3 mmHg) 72 min ads.	11.18 (4.4)	11.18 (4.4)	-2.54 (-1.0)	8.64 (3.4)
6 Men (5 mmHg) 72 min ads.	11.18 (4.4)	11.18 (4.4)	-2.54 (-1.0)	8.64 (3.4)
6 Men (5 mmHg) 52 min ads.	17.78 (7.0)	17.78 (7.0)	-2.54 (-1.0)	15.24 (6.0)

* Net gain from cabin fan

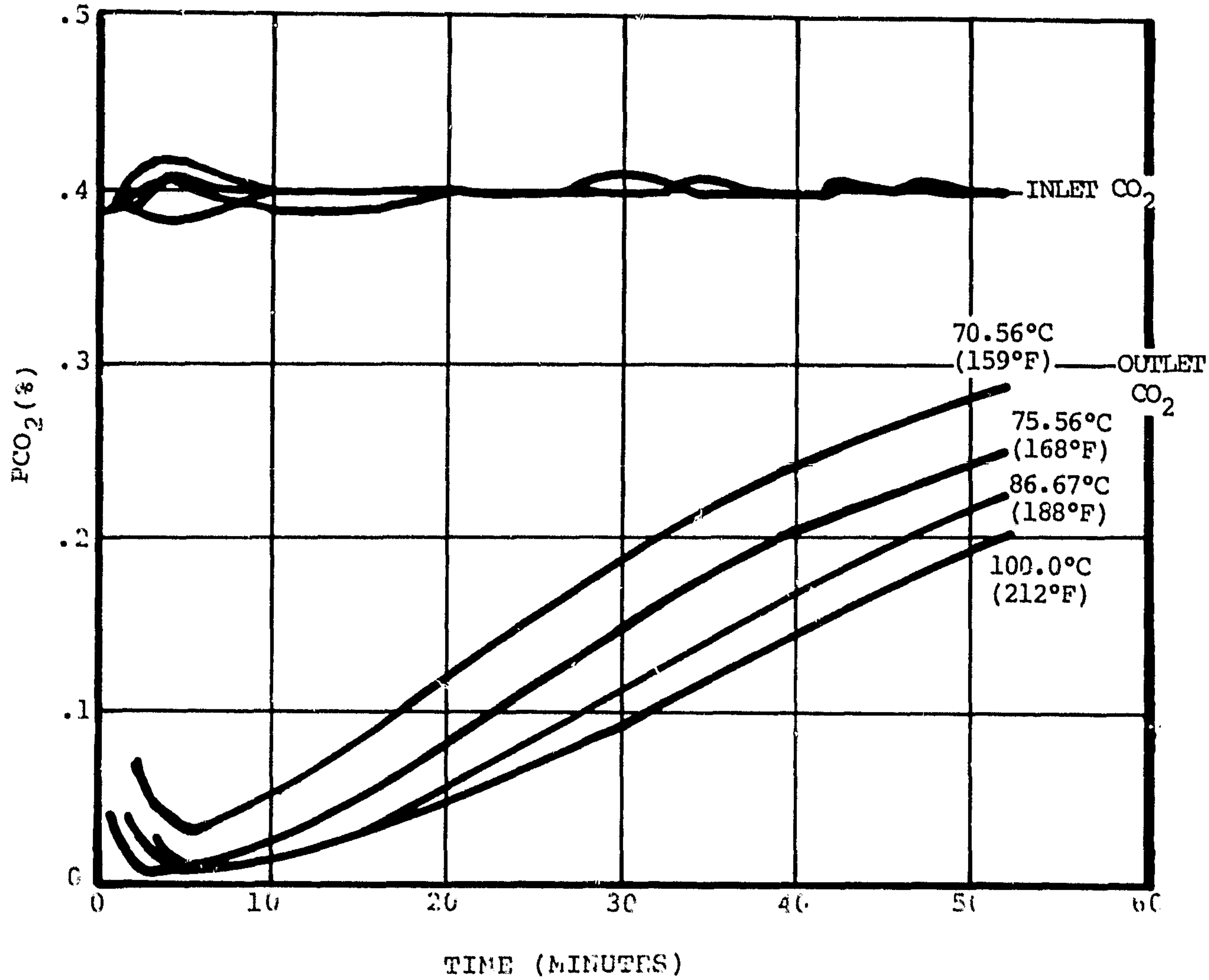

FIGURE 55

EFFECT OF DESORB TEMPERATURE
ON ADSORPTION BREAKTHROUGH

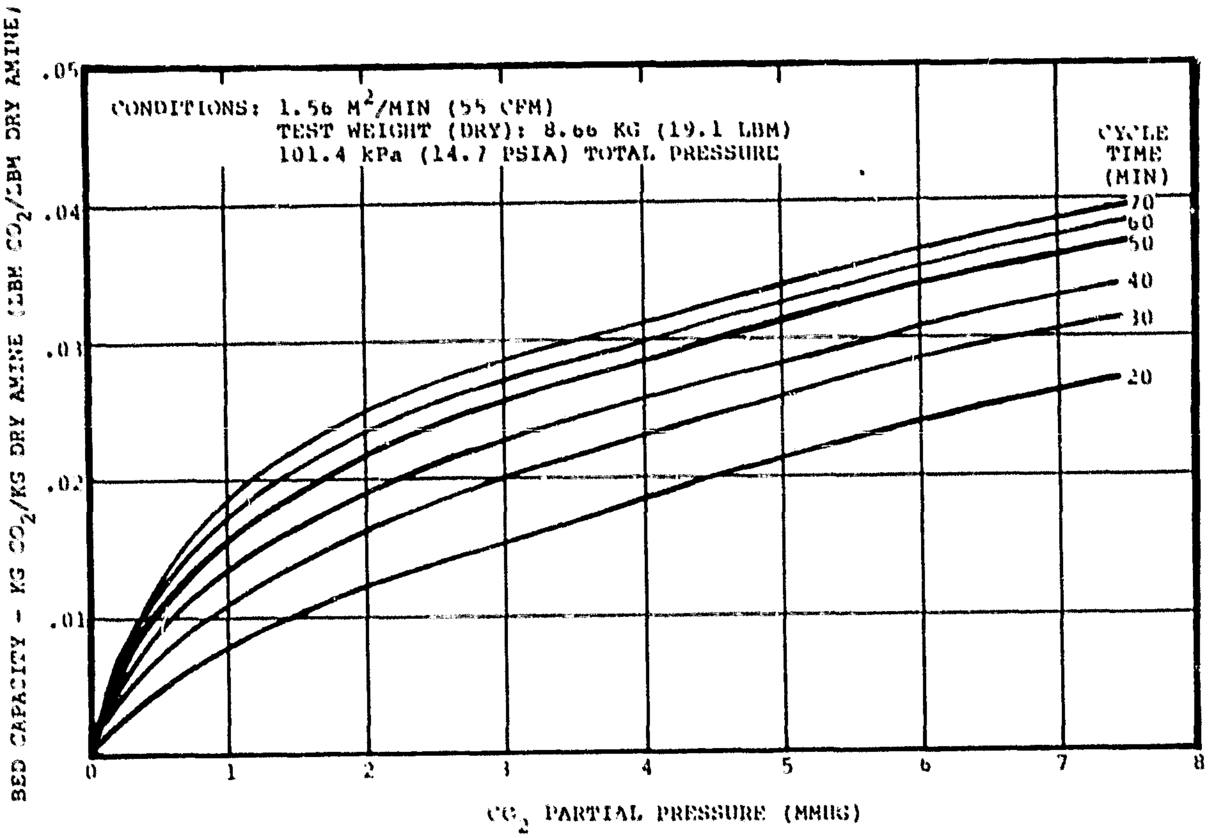

FIGURE 56

SOLID AMINE BED CAPACITY AS A FUNCTION OF CO_2 PARTIAL PRESSURE AND CYCLE TIME

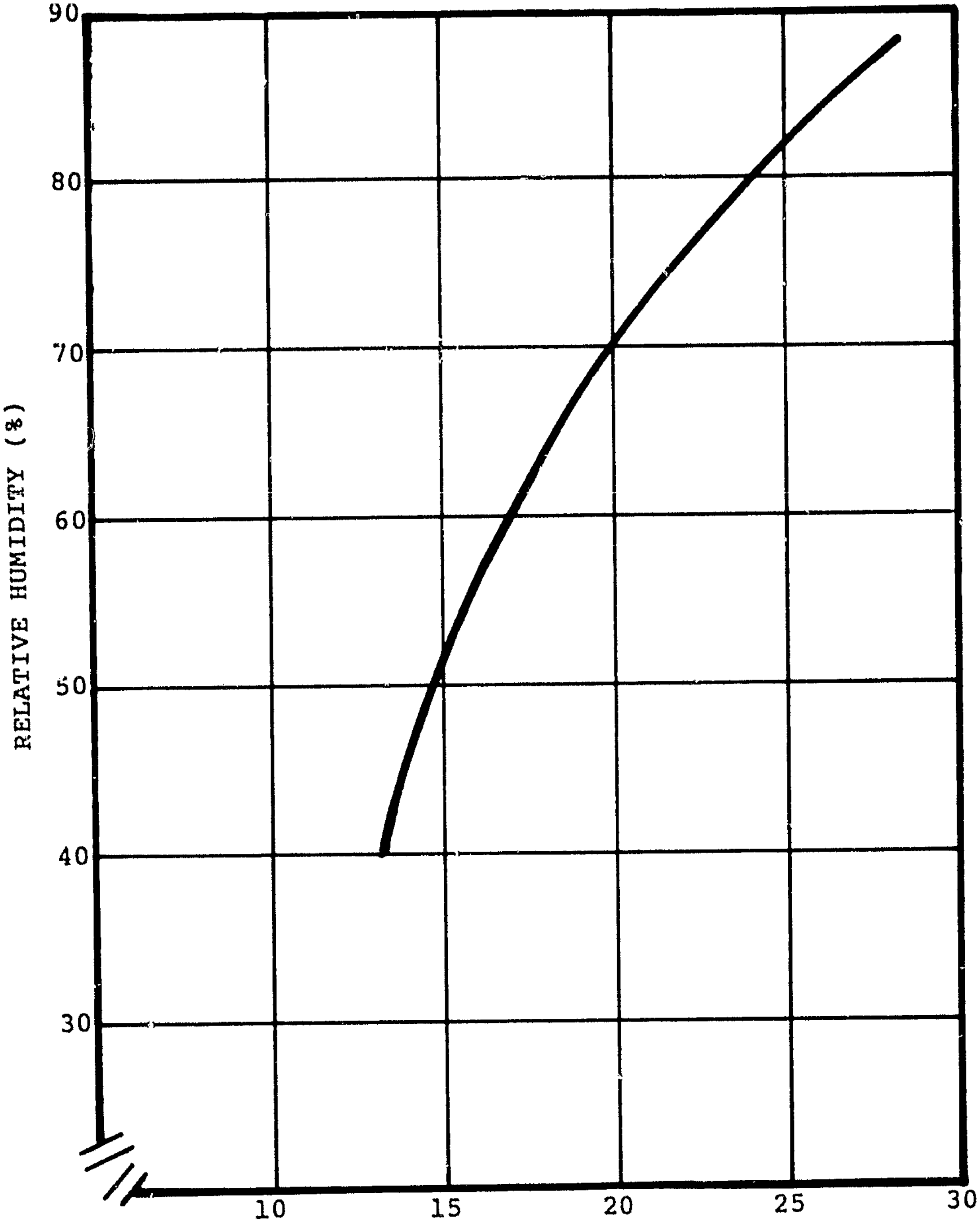

FIGURE 57

MOISTURE EQUILIBRIUM LOADING
FOR SOLID AMINE

The second phase of drying is at a constant rate, which depends on inlet relative humidity and the rate of CO_2 adsorption. During this phase sensible heat transfer from the incoming air to the bed is balanced by latent heat transfer to the air stream. In the absence of CO_2 adsorption with its heat release, the bed attains the adiabatic saturation (wet bulb) temperature of the inlet air. Test data indicates that the effect of CO_2 adsorption is to elevate the average bed temperature above the wet bulb temperature.

The third phase of drying is the longest part of the drying cycle and is called the falling rate phase. In this phase of the drying process intraparticle diffusion of water becomes important, as the bed material approaches its equilibrium moisture loading for the prevailing relative humidity.

During a 96 minute orbit each bed is desorbed with steam and dried with process air flow. Bed drying rates are most dependent on relative humidity of the inlet air and the bed moisture content. Figure 58 shows bed drying rates with various percentages of initial bed moisture. This figure is a computer simulation of the first two stages of bed drying. The figure was prepared for a 5.90 kg (13 lbm) solid amine bed with .340 m^3/min (12 CFM) of air flow.

Bed drying rates can be expressed in another manner as shown in Figure 59. At a given bed moisture content and process air relative humidity the minimum cycle time necessary to dry the bed to its initial moisture loading can be calculated. Such calculations were performed using the drying rate theories of phases I and II described earlier. These calculations resulted in Figure 59, which adequately defines equilibrium conditions at higher moisture levels. With higher moisture loadings, drying rates are entirely described by phase I and II conditions, and the bed does not approach the third phase or falling rate period. This method predicts that the bed approaches zero percent moisture loading, which is known to be incorrect. Figure 59, however, does reveal the vertical asymptotes at various relative humidities. The rates of evaporation decrease as bed moisture content approaches the equilibrium value at a given relative humidity. The phases of the curves in Figure 60, which include the effect of the falling rate period, depend on the rates of drying during the final phase of the process, and the shapes of the curves presented are consistent with the SAWD test data.

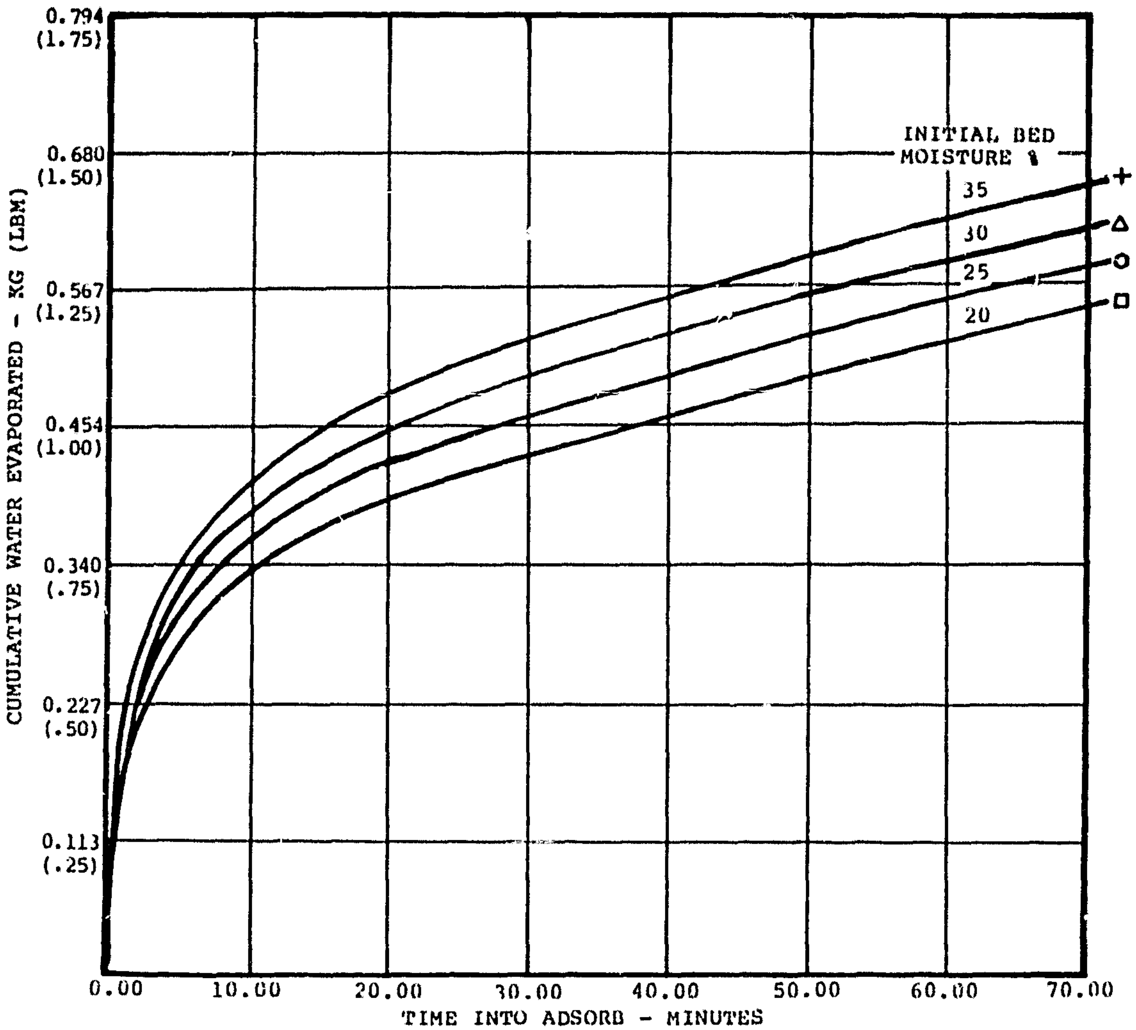

FIGURE 58

DRYING RATES WITH 50% RELATIVE HUMIDITY

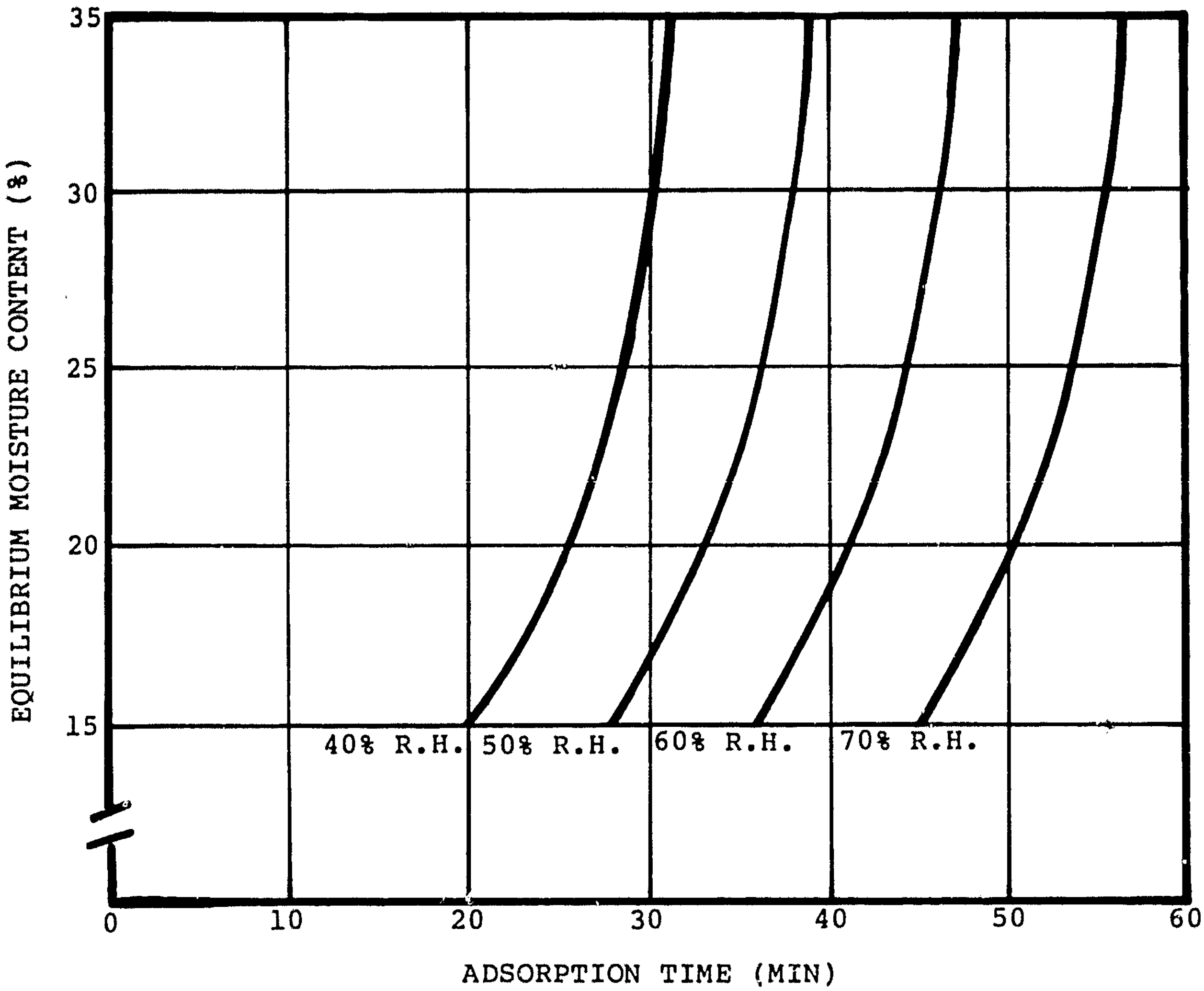

FIGURE 59

EQUILIBRIUM MOISTURE CONTENT VERSES
ADSORPTION TIME (DRYING PHASE I & II)

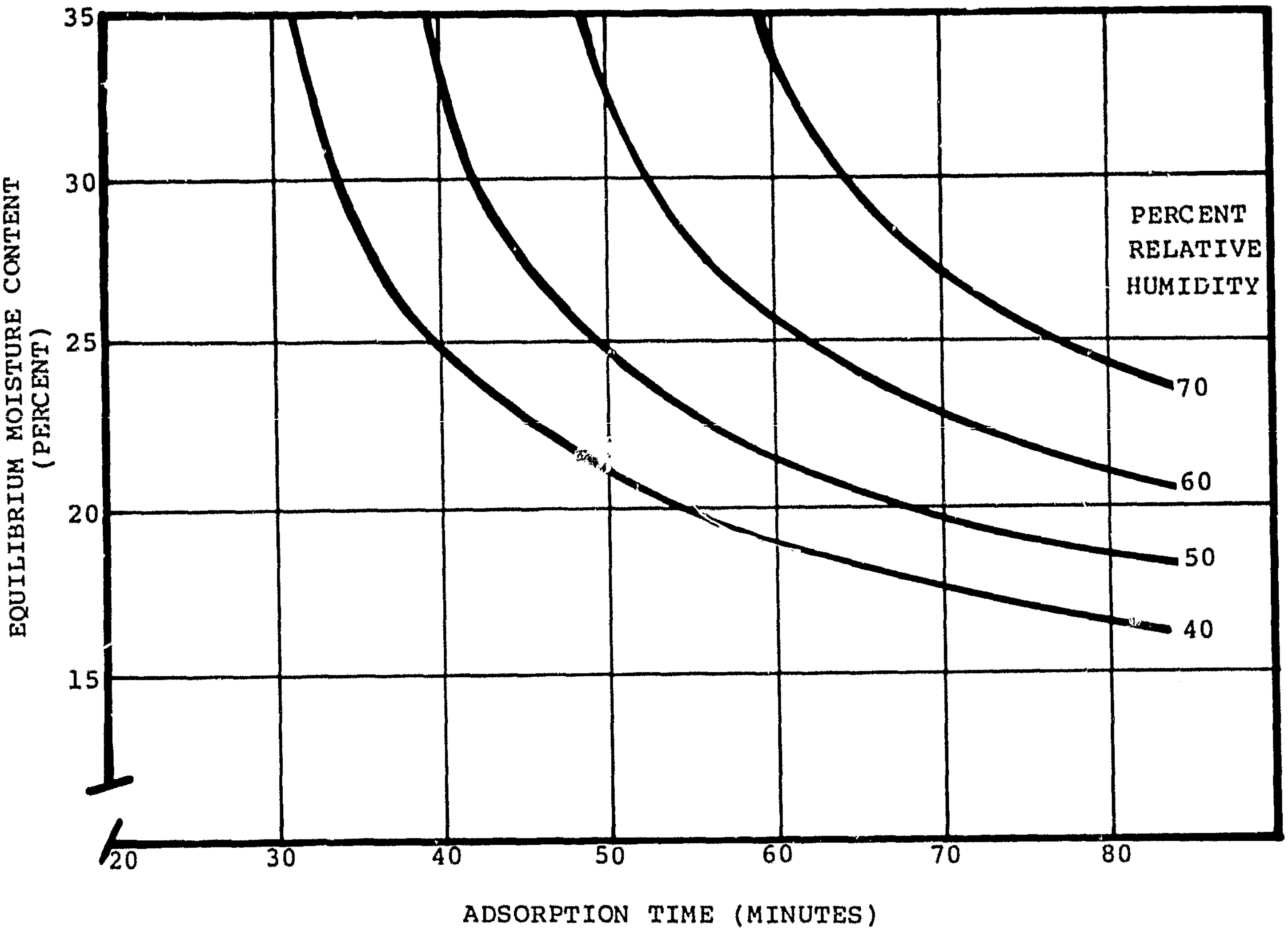

FIGURE 60

EQUILIBRIUM MOISTURE CONTENT
AS A FUNCTION OF ADSORPTION TIME

The performance map shown in Figure 60 was determined from the SAWD testing. During the testing an air flow of 0.106 m^3/min/kg (1.7 CFM/lbm) of dry solid amine was used. The SAWD subsystem of LARS operates at about 0.0624 m^3/min/kg (1.0 CFM/lbm) of solid amine due to the higher allowable CO_2 partial pressure of 5 mmHg. This lower air flow reduces drying potential by 38%, but sensible heat loss to the process air is also less. With more heat available for latent heat transfer, the result is a net 26% decrease in drying potential during a given cycle. This means that all curves in Figure 60 must be moved right such that a given point has a 26% longer cycle time than previously. Figure 61 shows the moisture performance map projected for the 72 minute adsorb/24 minute desorb cycle. However, the performance map presented in Figure 61 is extrapolated from the 52 minute adsorption SAWD testing, and testing of solid amine under the two bed operating conditions of 72 minute adsorption, 24 minute desorption is necessary to verify these predictions.

Cabin dewpoint predictions from the transient computer program indicate that cabin dewpoint will vary between 9.44°C (49°F), 21.11°C (70°C) dry bulb temperature, and 16.11°C (61°F), 26.67°C (80°F) dry bulb temperature. This represents a relative humidity swing in the cabin from 47 to 52%, and indicates that bed moisture content will remain above the minimum requirement of 20% under typical cabin operating conditions.

Bed Steaming Requirements

To desorb the weakly held CO_2, steam at 62.05 kPa (9 psia) and 87.22°C (189°F) is generated within the steam generator. The steam enters the cool solid amine beads and condenses, driving off the adsorbed CO_2. Since the steam progresses through the bed in a well defined wave, the CO_2 which is desorbed is readsorbed in the cool portion of the bed. As steaming continues, and CO_2 is progressively concentrated, the CO_2 eventually is eluted from the solid amine bed. The detailed CO_2 desorption process is described more fully later in this section.

Steam requirements for desorption are largely a function of desorption time and bed moisture content. It is obvious from Figure 62 that the total water to desorb the 9.53 kg (21 lbm) SAWD test bed was a strong function of the initial water loading. This is not surprising due to the high heat capacity of liquid water and the low heat capacity of dry solid amine of 249.82 Joules/kg°C (0.29 BTU/lbm °F). With a constant steam generation rate, desorption time is quite predictable as shown in Figure 63. This may be extended to give a plot of bed moisture content as a function of desorption time as shown in Figure 64. This dependency is a valuable aid in determining bed moisture loading.

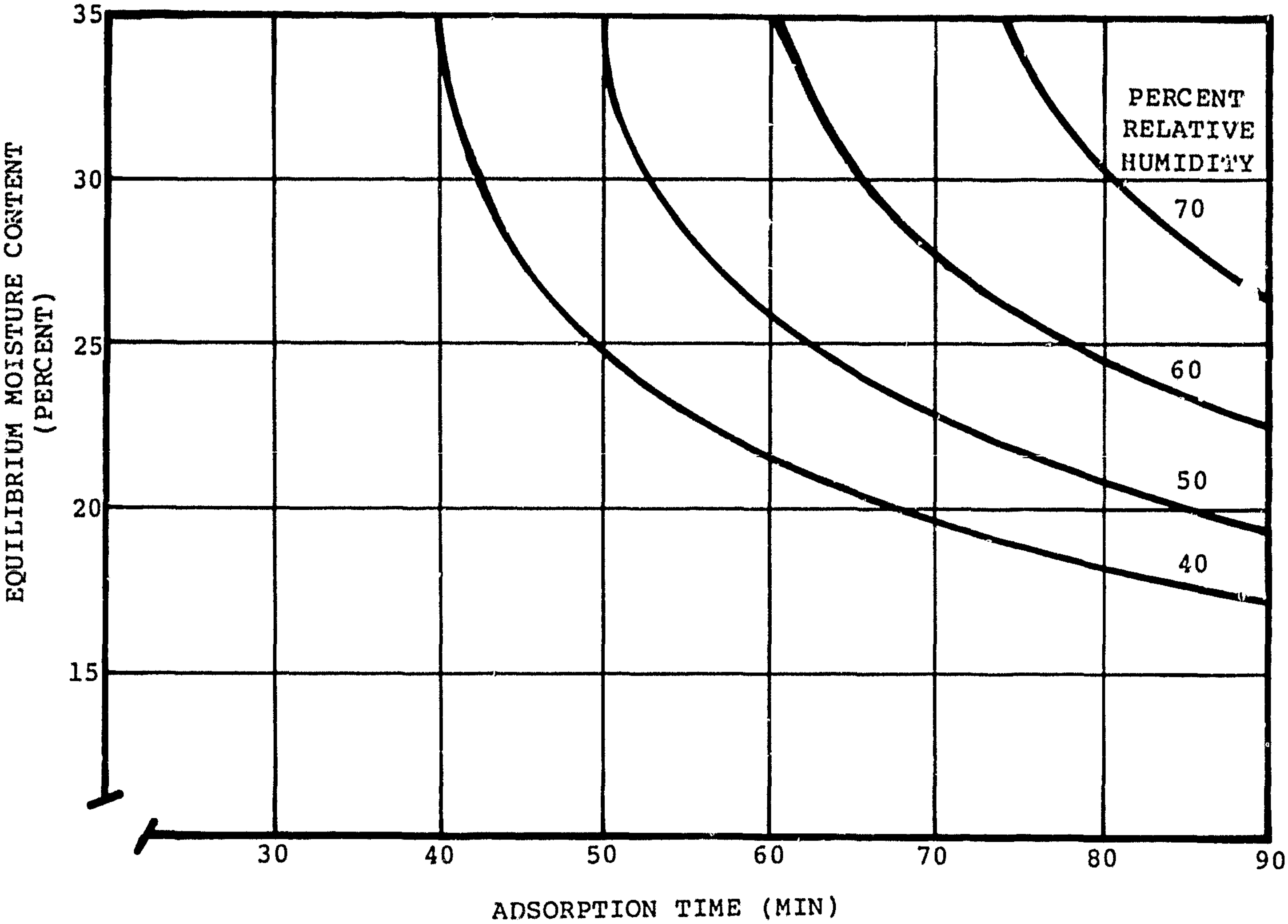

FIGURE 61

LARS PREDICTED MOISTURE CONTENT
AS A FUNCTION OF ADSORPTION TIME

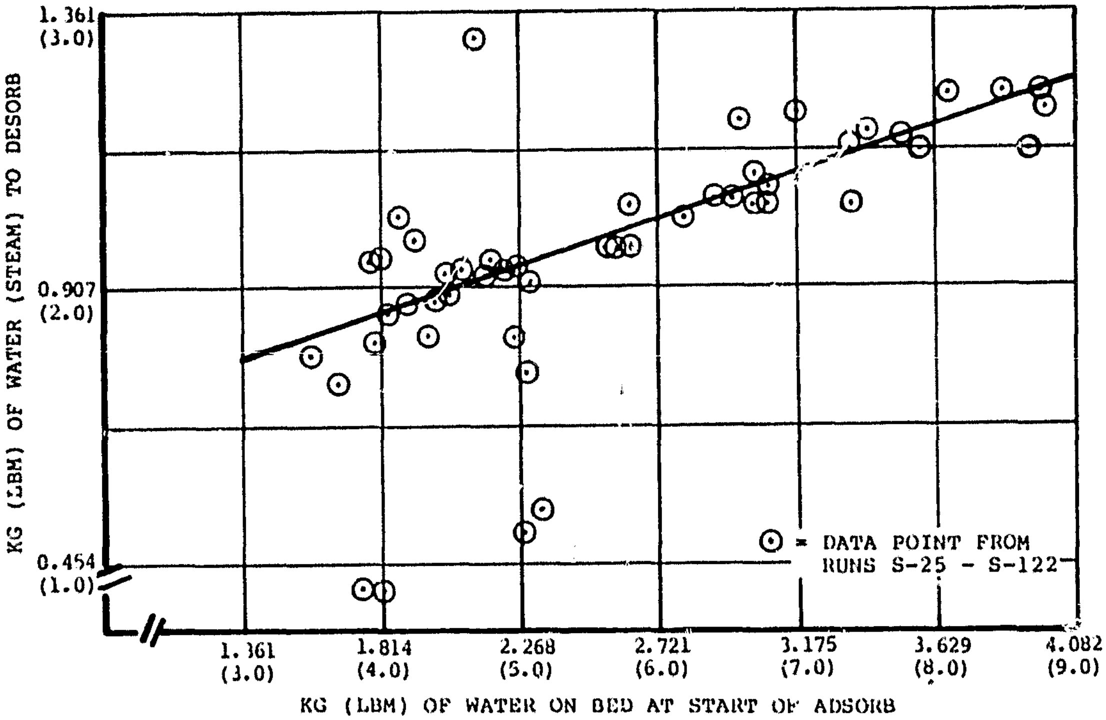

FIGURE 62

DESORPTION STEAM REQUIREMENTS AS A FUNCTION
OF BED MOISTURE LEVEL

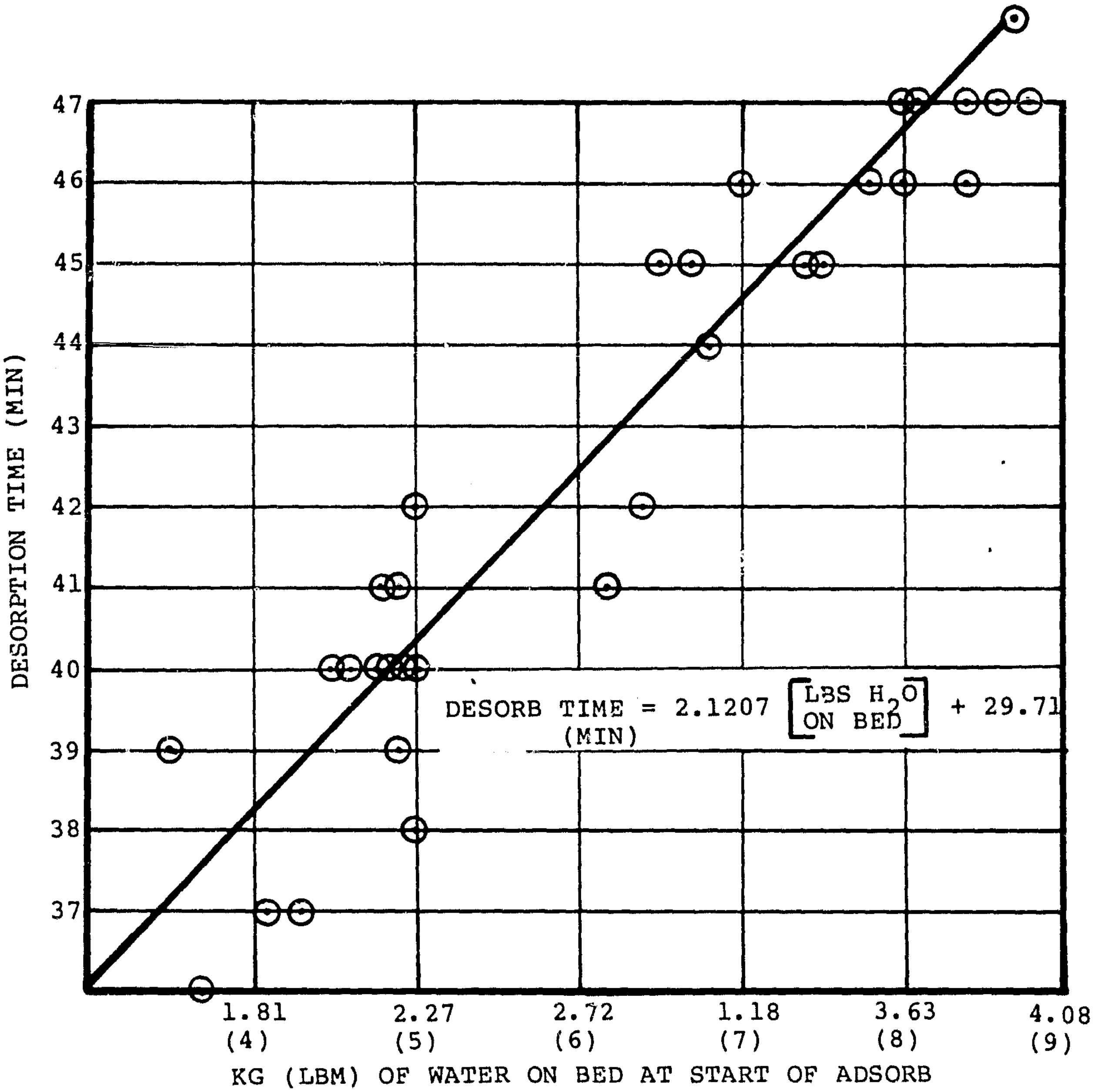

FIGURE 63

DESORPTION TIME AS DEPENDENT
UPON BED WATER LOADING

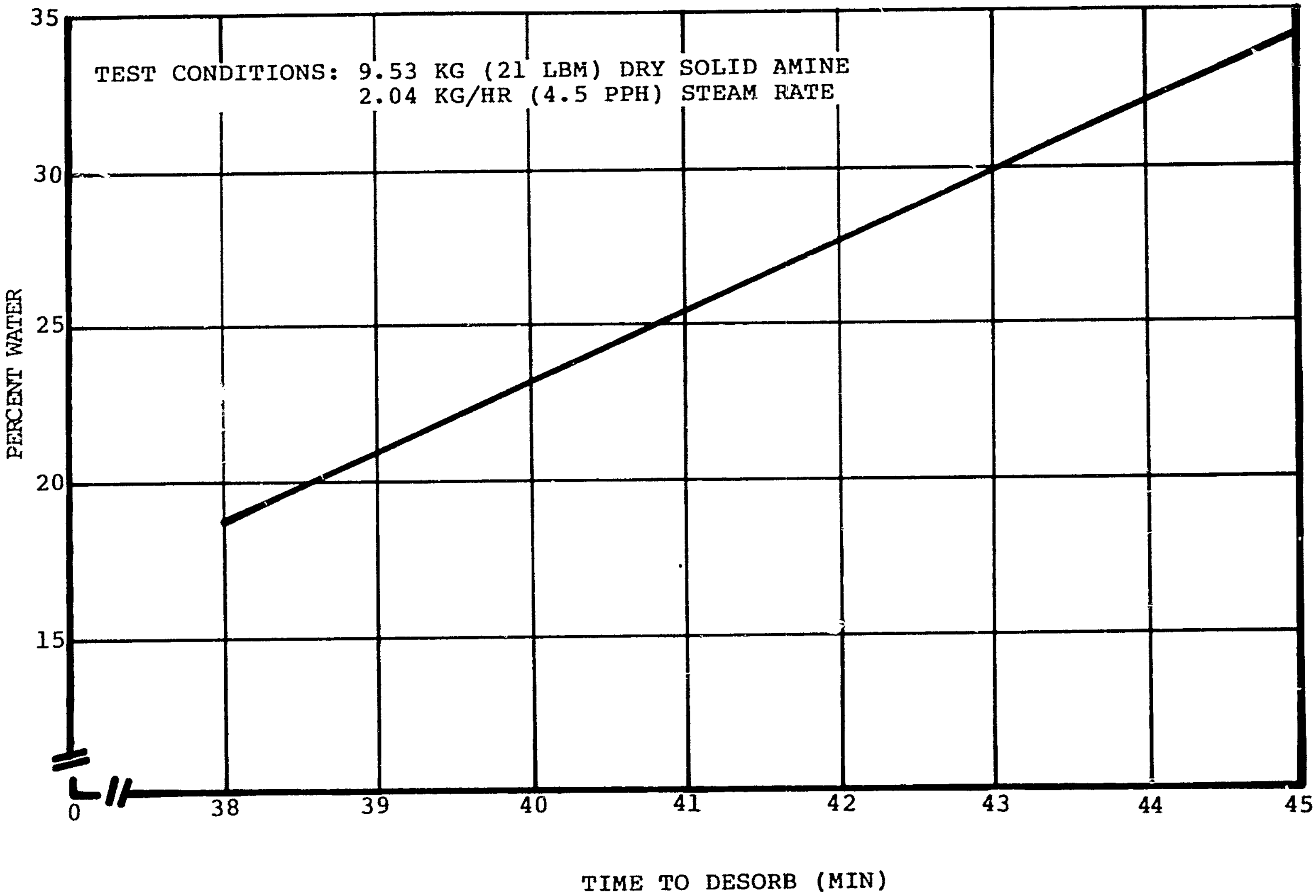

FIGURE 64
PERCENT MOISTURE VERSES DESORPTION TIME

Considerably less steam is required to desorb the solid amine bed material at 62.05 kPa (9 psia) compared to 101.35 kPa (14.7 psia). This is illustrated in Figures 65 through 67. Note that even the increased bed weight requirement at 62.05 kPa (9.0 psia) does not result in a greater steam requirement.

SAWD System Operating Characteristics

Air flow enters the system through one of two redundant IMU fans with flow split between an orificing valve and the two parallel SAWD beds. The flow split is such that .680 m^3/min (24 CFM) enters the SAWD beds and .510 m^3/min (18 CFM) bypasses the beds through the orificing valve. Flow from the parallel beds mixes with the bypass flow and enters the contaminant control canister before mixing with the main cabin flow upstream of the cabin fans.

Total subsystem pressure drop is composed of bed pressure drop, ducting losses, and the contaminant canister/LiOH canister pressure drop. For the SAWD beds pressure drop is a weak function of bed moisture loading, as shown in Figure 68. After one bed is desorbed, for a short time it has approximately 10 percent more moisture than the other bed. However, as can be seen from Figure 68, a 10 percent swing in moisture content in a bed causes little change in bed pressure loss, since bed particles swell as moisture is adsorbed. The small increase in pressure drop in a regenerated bed reduces the cabin humidity/temperature spikes due to the slight reduction in flow during the first minute of an adsorption cycle.

Each IMU fan has the performance characteristics shown in Figure 69. The system resistance line also shown in Figure 69 passes through the vertical scale at -6.35 cm (-2.1 inches) of water, since it discharges upstream of the cabin fans leading to the WVE. Solid amine bed pressure drop for a 15.24 cm (6 inch) bed is 10.16 cm (4.0 inches) of H_2O and contaminant canister/duct losses are 3.81 cm (1.5 inches) of H_2O for a total of 13.97 cm (5.5 inches) of H_2O. The 5.33 cm (2.1 inch) credit results in an IMU fan net pressure rise requirement of 8.64 cm (3.4 inches) of H_2O. The radial flow contaminant control canister has a pressure drop which varies linearly with flow, and therefore, assuming a contaminant canister/duct work pressure drop of 3.81 cm (1.5 inch) of H_2O at .680 m^3/min (24 CFM), and linear variation of this pressure drop with flow, the IMU fan operates at 1.19 m^3/min (42 CFM) with a pressure rise of 11.43 cm (4.5 inches) of H_2O.

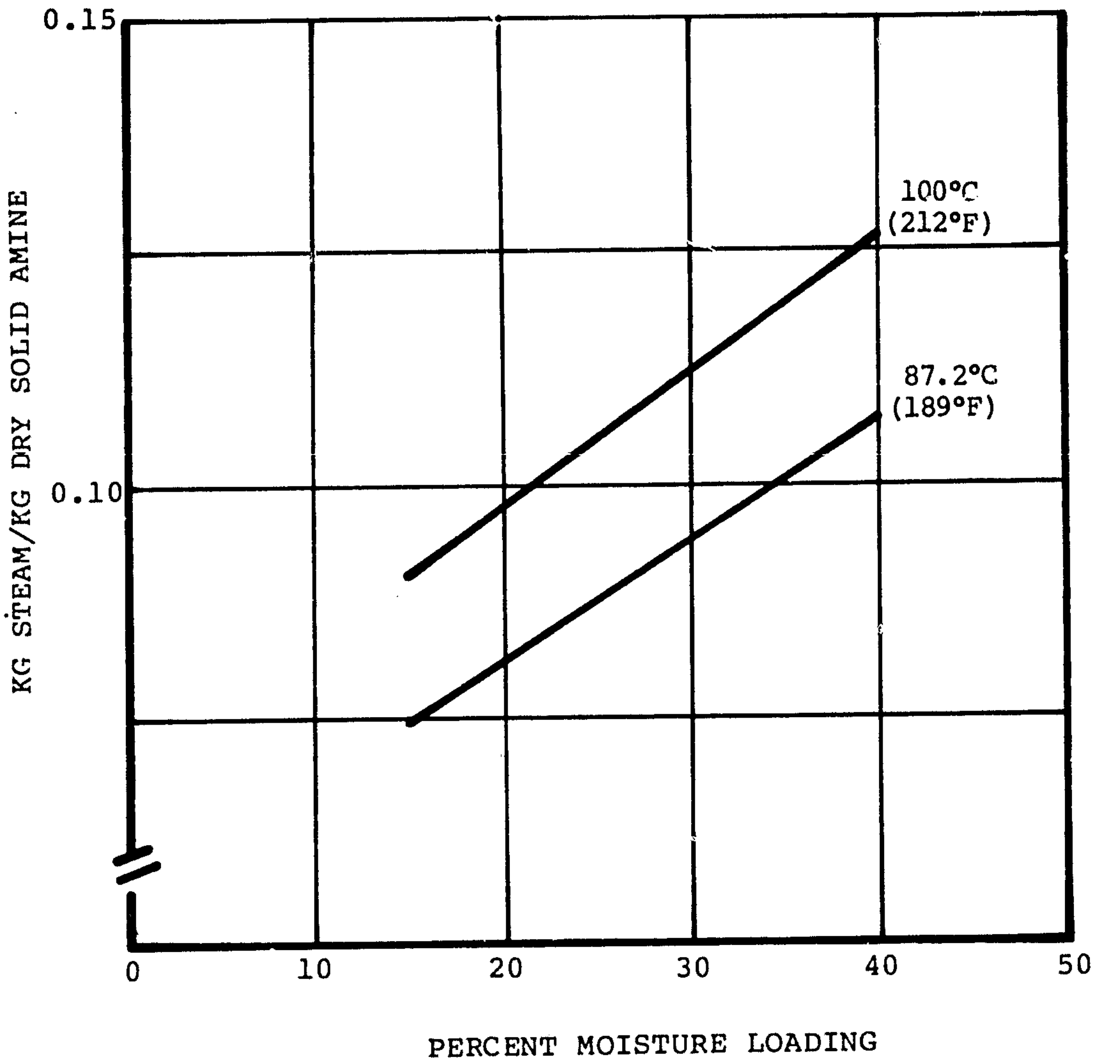

FIGURE 65

SOLID AMINE DESORPTION STEAMING REQUIREMENTS
AS A FUNCTION OF DESORPTION TEMPERATURE
(24 MIN DESORPTION)

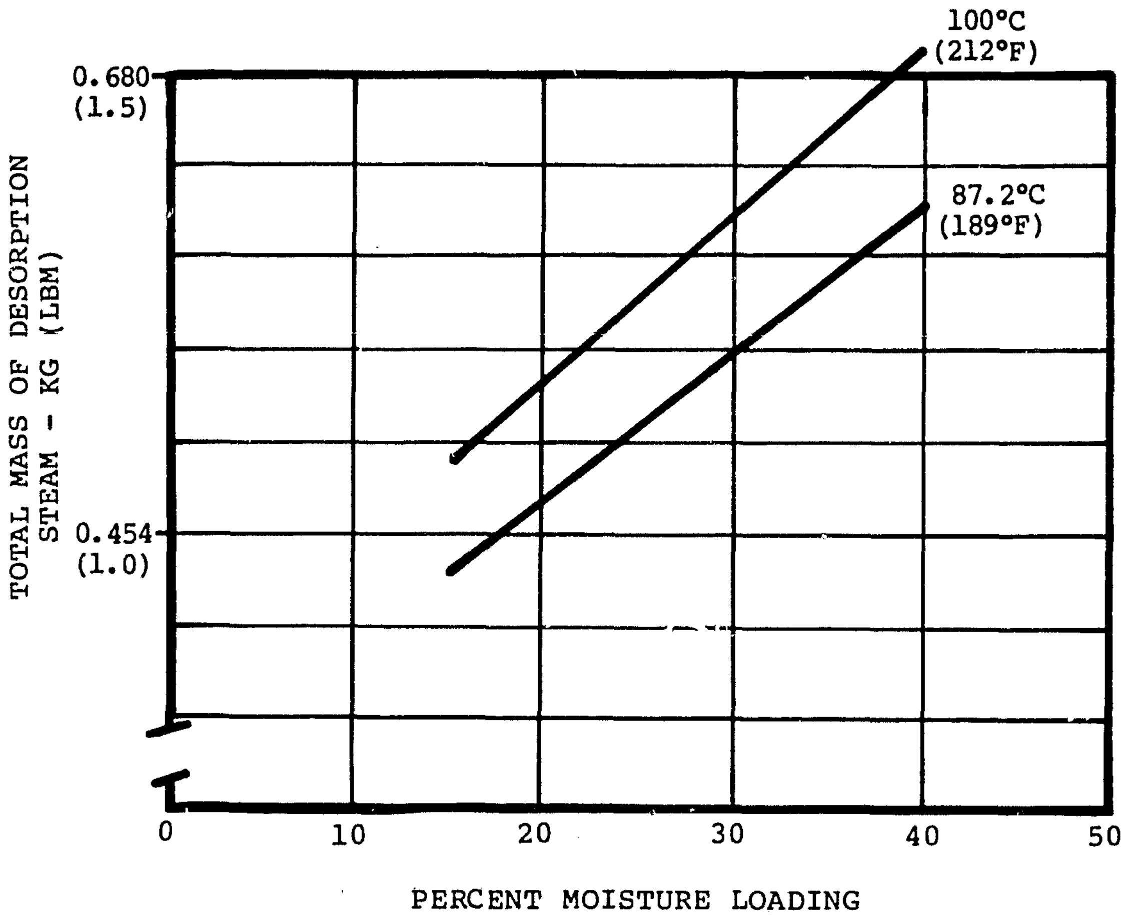

FIGURE 66

SOLID AMINE DESORPTION STEAM
REQUIREMENTS FOR BASELINE CASE

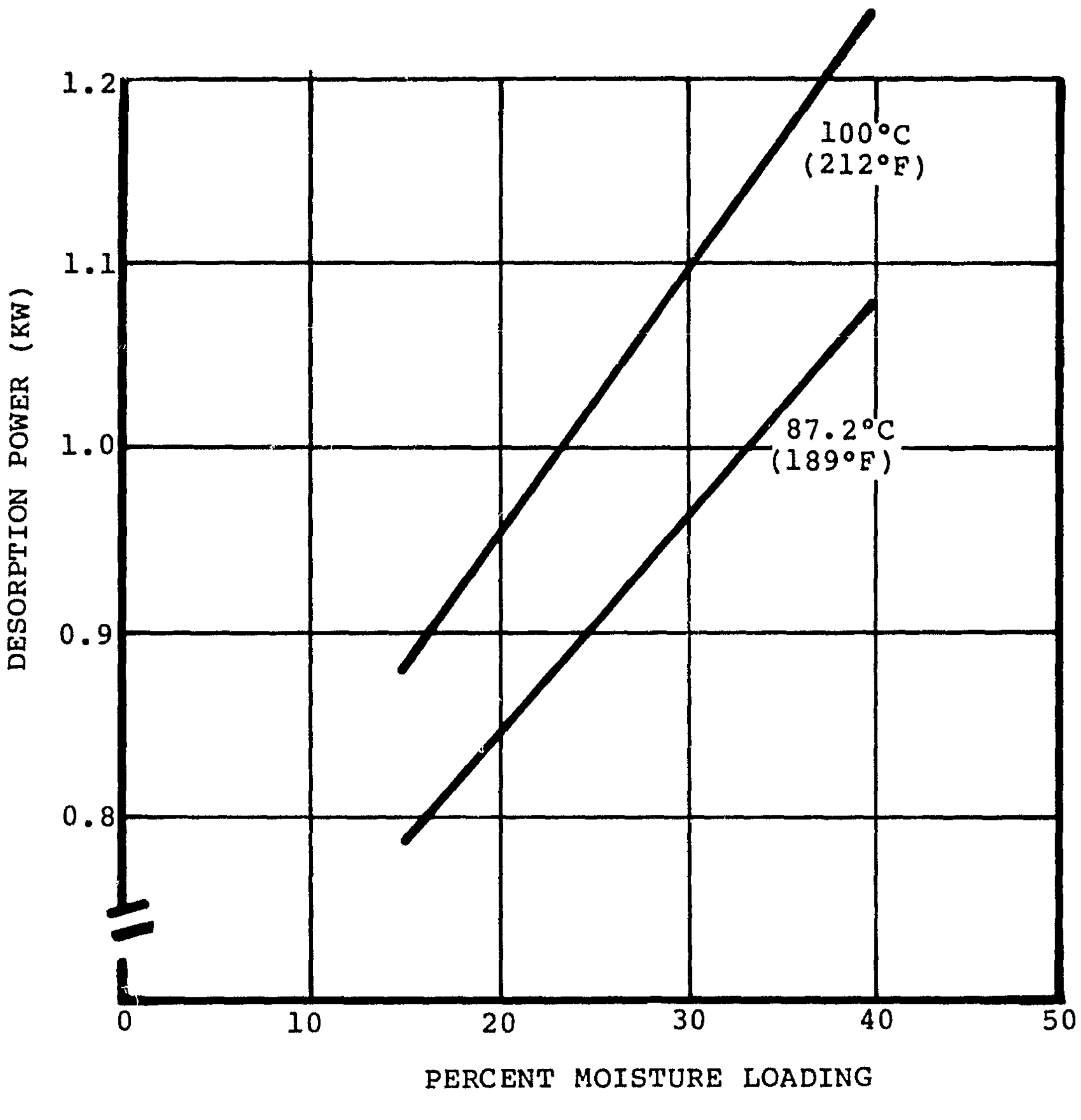

FIGURE 67

STEAM GENERATOR POWER
REQUIREMENTS FOR BASELINE CASE

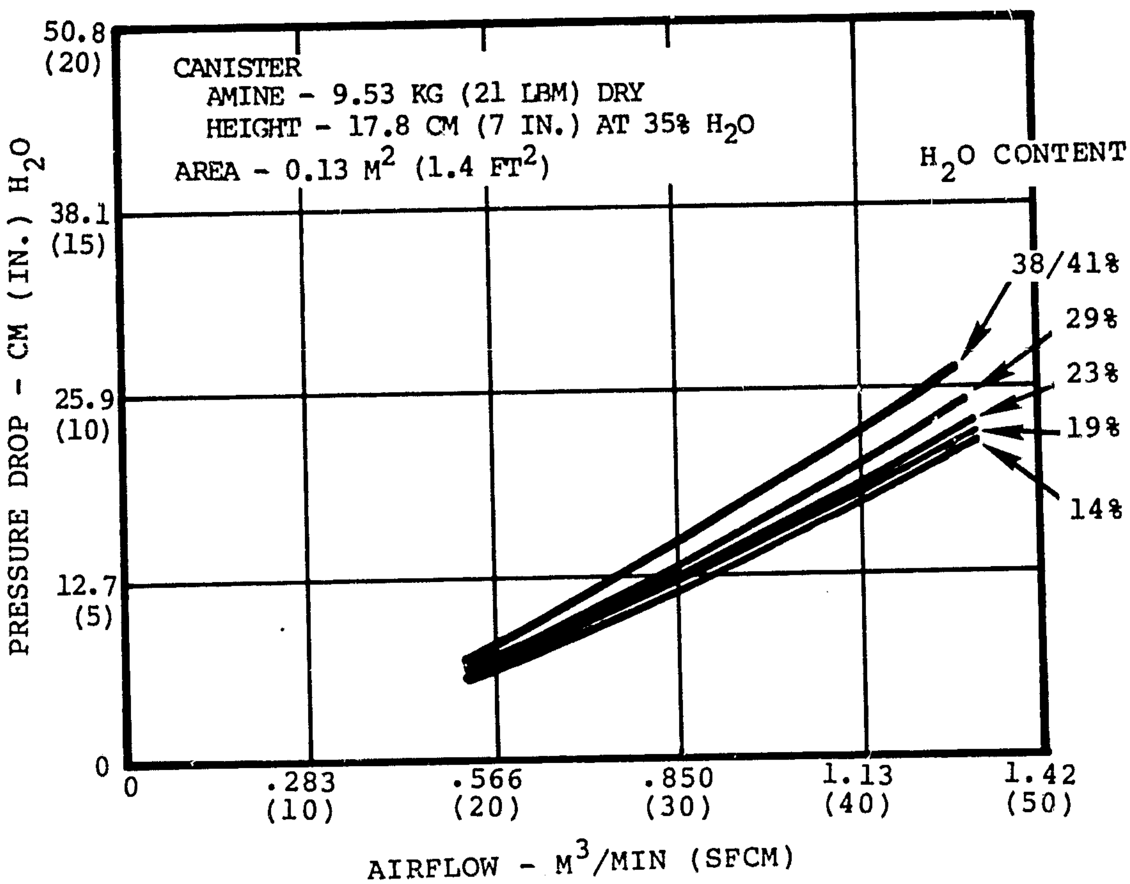

FIGURE 68
SOLID AMINE BED PRESSURE DROP

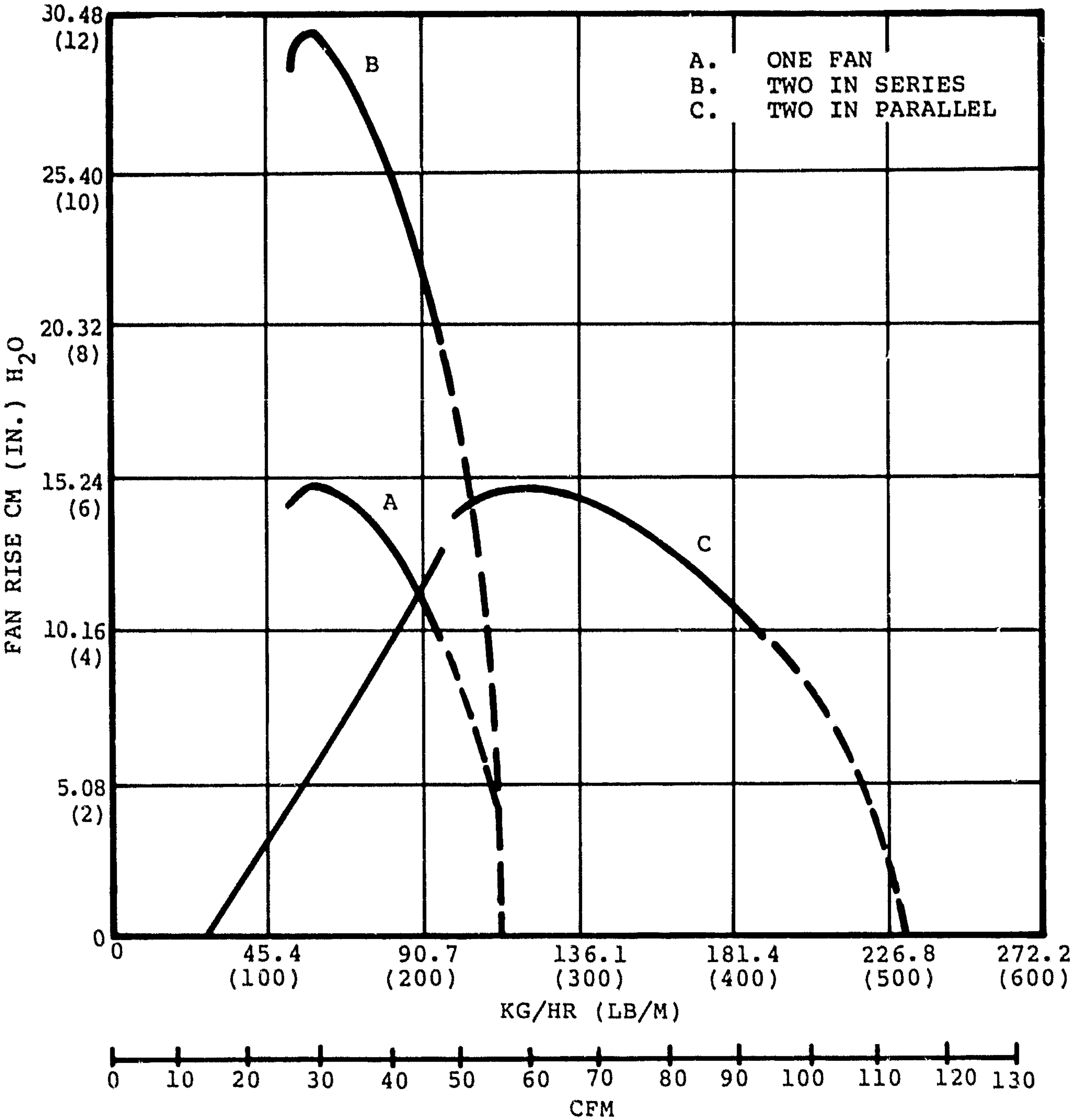

FIGURE 69

IMU FAN PERFORMANCE CURVES

When a canister is returned to adsorption after regeneration, flow enters the contaminant canister with a temperature versus time as shown in Figure 70. Moist flow from the desorbed bed is mixed with bypass air flow limiting maximum temperatures into the charcoal. Initially there was some concern that the hot moist air flow into the contaminant canister would desorb the contaminants. While it is true that elevated temperature, greater than 100°C (212°F), is capable of desorbing some contaminants from charcoal, the air temperature entering the contaminant canister just after returning a regenerated bed to service is elevated for only a short time. When one bed is being desorbed, the orificing valve indexes to limit flow through the single adsorbing bed to .340 m^3/min (12 CFM). Thus, the hot bed effluent flow is mixed with approximately .850 m^3/min (30 CFM) of bypass flow to reduce contaminant canister inlet temperature to that shown in Figure 70. The temperature/humidity spike entering the contaminant canister is considered to be insufficient to desorb significant quantities of contaminants. Literature indicates that time periods on the order of hours at temperatures above 100°C (212°F) with hard vacuum are required to desorb an activated charcoal bed.

Desorption Cycle Operating Characteristics

When a bed is to be desorbed, the bed is first isolated by closing the inlet and outlet poppet valves. Simultaneously the variable bypass orifice is indexed to provide proper flow distribution while one of the beds is temporarily out of service. This valve does not index again until both beds have completed desorption. With the spent bed isolated, the outlet valve in the line to the CO_2 compressor and the ullage air valve are opened, and the water evaporator is started to begin steaming the bed. Initially ullage air is pushed from the bed, followed some time later by pure carbon dioxide. The ullage air line is equipped with a flow sensor downstream of the valve, which senses the sudden change in flow rate as CO_2 begins to be eluted from the bed. The flow sensor provides a signal to close the ullage valve and start the CO_2 compressor. A typical desorption profile predicted from data obtained during the SAWD test program is shown in Figure 71.

Steam for the 62.05 kPa (9 psia) desorption is generated in the steam generator, which is fed with water by a positive displacement pump. Approximately .544 kg (1.2 lbm) of water are required for the desorption of CO_2 from one of the 5.90 kg (13 lbm) dry weight SAWD beds at 87.22°C (189°F). Water is pumped from an accumulator to the evaporator through the water jacketed CO_2 compressor as shown in the LARS schematic, Figure 51. The water

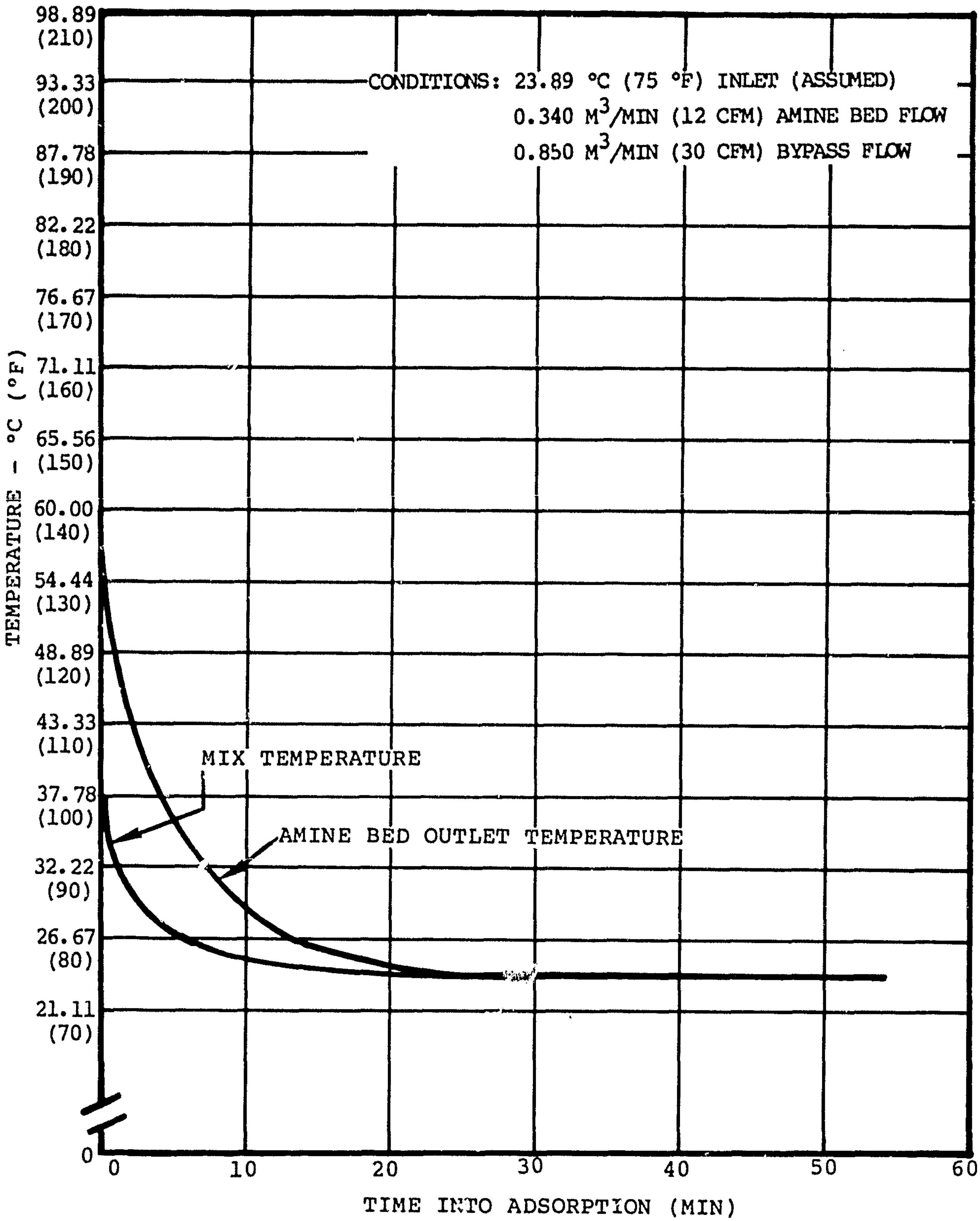

FIGURE 70
CONTAMINANT CONTROL CANISTER INLET TEMPERATURE

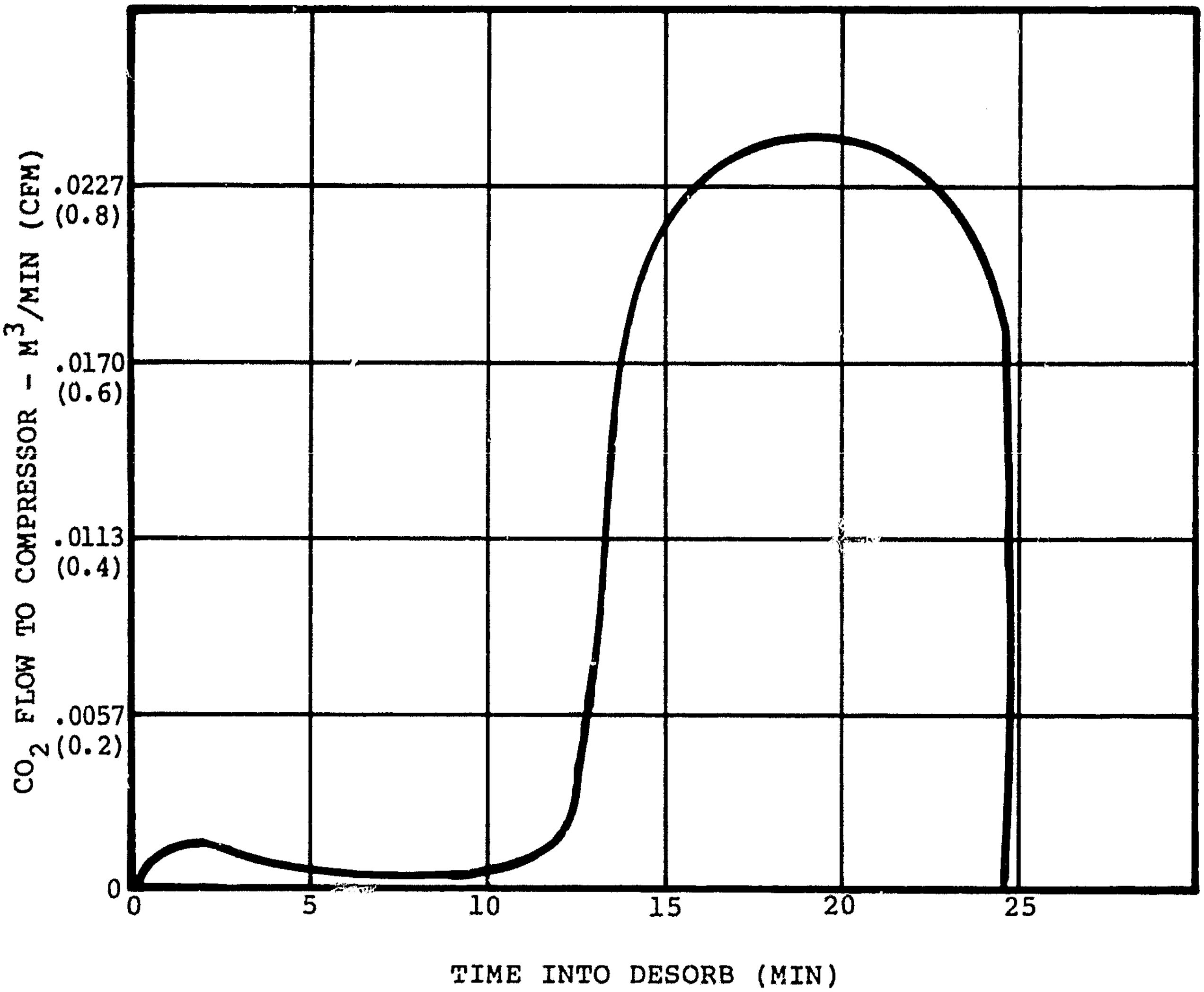

FIGURE 71

ESTIMATED CO_2 FLOW RATE DURING DESORPTION accumulator holds .862 kg (1.9 lbm) of water, which is more than adequate to provide capacitance for the SAWD system regeneration. The simplified schematic shown in Figure 72 depicts the system material balance for one complete orbital cycle. Approximately 2.89 kg (6.36 lbm) of water are available from the condensing heat exchanger output while only about 1.09 kg (2.4 lbm) of steam are required for desorption.

The CO_2 accumulator is sized to contain the desorbed CO_2 from one of the amine beds, 0.191 kg (0.42 lbm). The CO_2 compressor pumps the effluent CO_2 from the desorption pressure of 62.05 kPa (9 psia) to 455.05 kPa (66 psia) in the accumulator. The Sabatier reactor requires a feed pressure of 20.68 kPa gage (3 psig), and therefore, the operating pressures for the accumulator are 82.74 kPa (12 psia) to 455.05 kPa (66 psia). For the storage of 0.191 kg (0.42 lbm) of CO_2, the accumulator size is .0283 m^3 (1.0 ft^3). The compressor, which consumes 250 watts while operating (duty cycle is 20 percent), is water jacketed to conserve steam generator power input. The feed water for the steam generator is preheated by passing it through the compressor jacket.

Selected Approach as Applied to Polar Orbit Mission

For a polar orbit mission where power availability is continuous, utilizing a two bed system with a 48 minute adsorption/48 minute desorption reduces system peak power requirements by 50%. For the baseline air flow and bed weight an increase in cabin CO_2 partial pressure occurs and the bed moisture equilibrium is affected. By closing the bypass valve, shown in the LARS schematic Figure 51, sufficient flow, 0.906 m^3/min (32 CFM), is directed through the SAWD beds to compensate in drying potential for the decrease in adsorption time from 72 minutes to 48 minutes. This also maintains average cabin CO_2 partial pressure at or below the 5 mmHg design value with a 6 member crew.

Conditioning of Solid Amine Prior to Launch And Upon Reentry

The SAWD beds are pre-conditioned to provide an average bed moisture content of 25 percent at time of launch. This ensures adequate CO_2 adsorption performance upon start-up. With a cold bed at start-up, the low bed drying rates keep the bed above 20 percent moisture during the initial adsorption.

The SAWD subsystem can be operated during launch and reentry. However, cabin accumulation with 6 men in the shuttle vehicle provides CO_2 capacitance for 2.8 hours after launch, provided that the cabin air is initially free of CO_2. The SAWD system will provide at least 72 minutes of additional CO_2 capacitance without desorption for a total of 168 plus 72 or 240 minutes. This is approximately 2.5 orbits, and provides sufficient time needed prior to the SAWD subsystem start-up, LiOH is available.

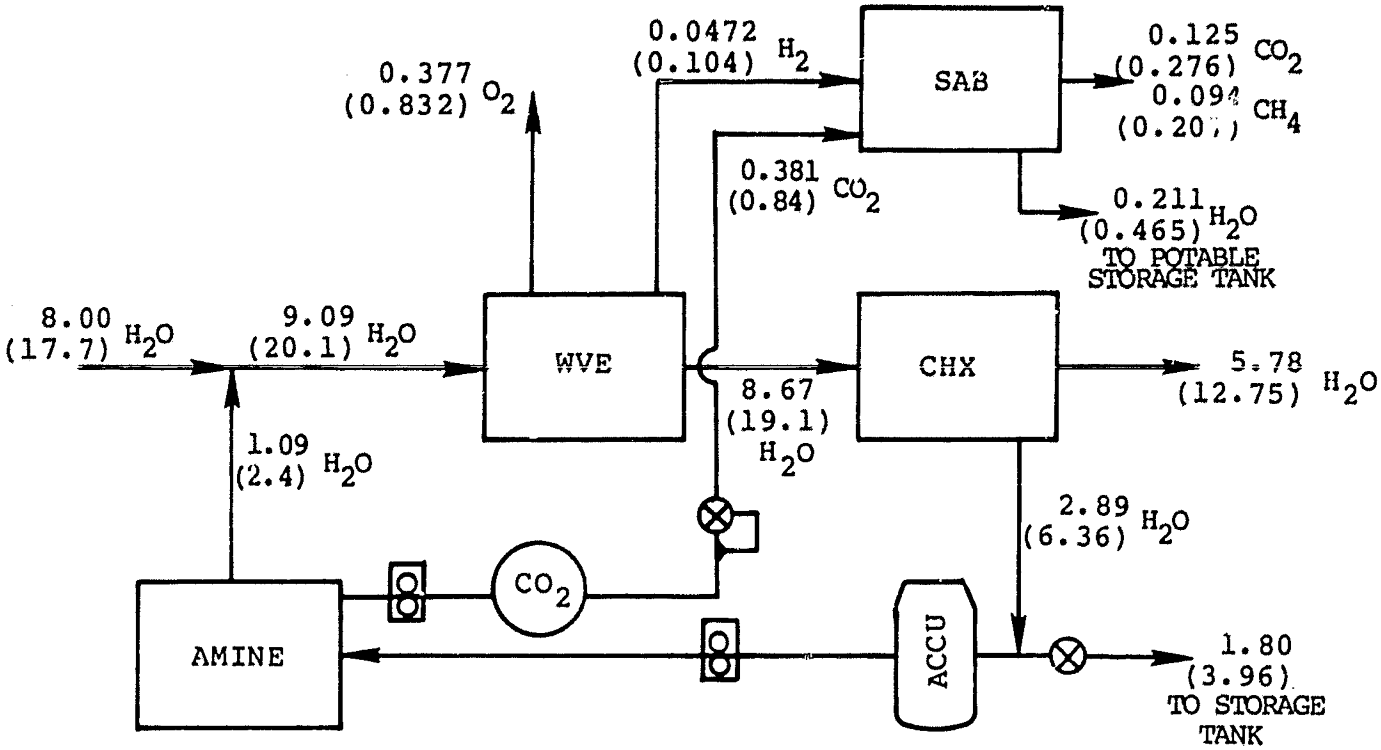

FIGURE 72

LARS MASS BALANCE FOR ONE ORBIT
KG (LBM)

In preparation for reentry, upon shutdown of the SAWD, one of the four contingency LiOH cartridges can be installed in the contaminant control cartridge location. One LiOH canister provides CO_2 control for more than 7 hours with a six man crew.

WVE Sizing

The purpose of the water vapor electrolysis subsystem is to replace, by the dissociation of water, the oxygen required for metabolic consumption by crew members and that lost via all types of cabin leakage.

The electrolysis process is accomplished by imposing an electrical potential across two electrodes, between which is a matrix material impregnated with a strong electrolytic solution. Water from the acid solution is dissociated at the WVE anode to produce oxygen and hydrogen ions. The hydrogen ions migrate, by diffusion and migration in the electric field, to the cathode, where they receive their missing electrons and are combined to produce hydrogen gas.

Water necessary to maintain the reaction is replenished by absorption of water vapor from the air, as shown in the reaction sequence below:

$$2\,[H_2O \text{ air} \rightarrow H_2O \text{ electrolyte}]$$
$$2\,H_2O \text{ electrolyte} \rightarrow O_2 + 4H^+ + 4e \qquad \text{anode}$$

$$4H^+ + 4e \rightarrow 2H_2 \qquad \text{cathode}$$

The hydrogen produced by the WVE is fed into the inlet of the Sabatier reactor where it is mixed with a regulated flow of carbon dioxide to produce water and methane.

To eliminate the potential of a fire in the hydrogen line, the hydrogen system is maintained at least 6.89 kPa (1.0 psi) above ambient at all times. This overpressure ensures that any leakage is from the hydrogen rich stream into the larger cabin volume, thus diluting the hydrogen mixture, rather than air leakage into the hydrogen rich space.

Combustible gas detectors are used to detect leakage by indicating if hydrogen concentration reaches 0.5% in the vacinity of the WVE and Sabatier subsystems.

WVE Sizing Procedure

WVE sizing is based on performance data obtained during extensive cell pair testing performed by Hamilton Standard under Contract No. NAS 9-11830. All testing under this contract was done with the cells fitted with an external electrolyte reservoir composed of non-compressed layers of Tissuequartz. Subsequent testing, employing porous titanium reservoirs internal to the cell pair, showed that at 39 amps and a 5.83°C (42.5°F) dewpoint required cell voltage was reduced from 1.73 volts for the external reservoir cells to 1.70 volts for the internal reservoir design. At 1.70 volts and 5.83°C (42.5°F) dewpoint, for the external reservoir design, only 32 amps of current is produced. Hence the internal reservoir design, because it is more efficient in transporting electrolyte to the electrodes, shows a 21.9% (39 amps/32 amps) increase in performance.

All WVE test data was ratioed to reflect this increase in performance. The results, as used in the WVE portion of the integrated thermal model, are shown in Figure 73.

The WVE design point for a six-man system operating at 62.05 kPa (9 psia) has the following oxygen requirements:

Metabolic: (6 men)(0.798 kg O_2/man day) = 4.79 kg/day
(6 men)(1.76 lbm O_2/man day) = 10.56 lbm/day

Leakage: Air leakage rate kg/day (lbm/day)

Cabin	1.666 (3.673)	
Air Lock	.278 (.612)	
Tunnel Adapter	.278 (.612)	
Waste Management	.680 (1.500)	
	2.902 (6.397)	(.30 kg O_2/kg air) = .871 kg/day (1.92 lbm/day)

Total = 5.66 kg O_2day (12.48 lbm O_2/day)

Assuming an average WVE inlet dewpoint of 10°C (50°F), using 15 cells would necessitate an average cell voltage of between 1.85 and 1.875 volts per cell. Laboratory tests have shown that cell voltage should be kept below 1.90 volts for sustained operation, to avoid electrolyte degredation and the possibility of matrix dry-out, which could lead to gas cross-over. Examination of cell performance shows that, for a sustained WVE inlet dewpoint of less than 46°F, individual cell voltages must exceed 1.9 volts to produce sufficient oxygen for a six man crew plus leakage make-up with a cabin pressure of 62.05 kPa (9.0 psia). Analysis has shown that sufficient reservoir volume exists, so

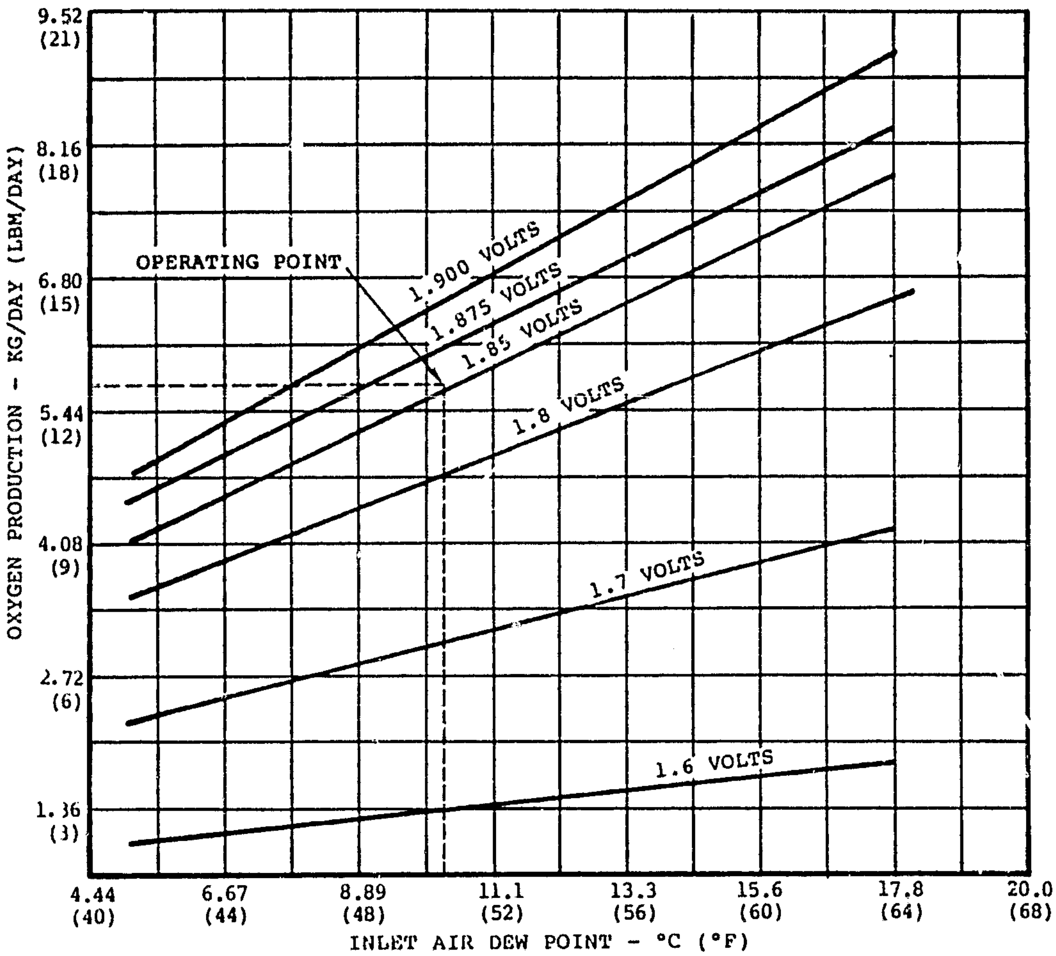

FIGURE 73

WVE 15 CELL PERFORMANCE

that the WVE cell configuration is capable of enduring, without flooding, an emergency condition in which the inlet air stream is at 30.56°C (87°F) with a 90% relative humidity, while the cells are not in operation.

The WVE, in the Lightside Atmospheric Revitalization System, follows an operating schedule of 53 minutes on and 43 minutes off, during a 96 minute orbit. The WVE is operational during the light side of the orbit when solar cell power is available and off during the dark side of the orbit when solar power is unobtainable.

During the operational portion of the orbit, the WVE cells absorb water vapor from the incoming air stream at a rate proportional to the partial pressure in the stream minus the partial pressure of water in the cells. The rate of absorption is, however, not as great as the rate at which water is consumed in the electrolysis process. This results in a net drying of the cells and an increase in electrolyte concentration. Cell moisture is recovered during the off period by water vapor absorption from the circulating air stream. Release of moisture from the SAWD system into the cabin air circulation system enhances the ability of the WVE cells to absorb moisture and to maintain an acceptable concentration of electrolyte.

A Hamilton Standard water vapor cell pair, shown in Figure 74, consists of the following components:

- Titanium outer housings
- Titanium center housing
- Electrodes
- Matrix
- 65% Void volume titanium reservoirs

The cell pair peripheral housing configuration has been flight optimized for weight and volume, while providing sufficient reservoir volume for intrinsic reliability.

The electrodes are a teflon-bonded, catalyzed, tantalum screen type.

The WVE electrolyte, sulfuric acid, has an infinite theoretical relative humidity tolerance and negligible vapor pressure. Of the suitable acid electrolytes, it has the smallest electrical resistance and gives the least electrode polarization. These properties cause it to require the minimum over-voltage for oxygen production.

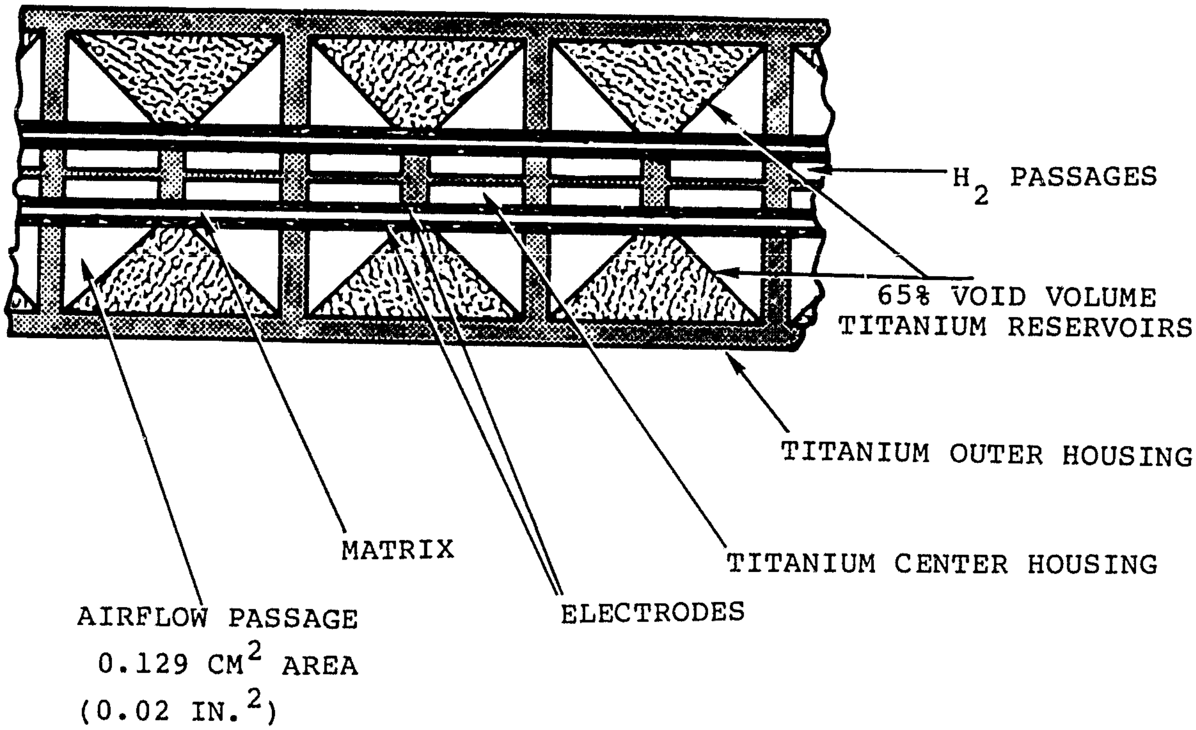

FIGURE 74

WVE CELL PAIR

The cell matrix consists of one layer of Tissuequartz.

The outer titanium housings are platinum plated to minimize electrical contact resistance. The center housings are gold plated for the same reason, and in addition, gold is used to preclude hydrogen diffusion into the titanium base metal, which could cause hydrogen embrittlement.

Sabatier Subsystem

The Sabatier carbon dioxide reduction subsystem receives the hydrogen from the WVE subsystem and the carbon dioxide from the SAWD subsystem, and converts them to water vapor and methane. The water vapor is condensed and stored for potable usage, and the methane and any excess reactant gases are vented overboard. A successful program to design, build, and test a preprototype Sabatier carbon dioxide reduction subsystem has recently been completed.

The Sabatier subsystem schematic is shown in Figure 51. The carbon dioxide and hydrogen mixture enters the subsystem through a charcoal filter, which protects the reactor from any trace contaminant carryover from the upstream carbon dioxide concentrator or the electrolysis subsystem. The mixture then passes to the reactor, where it is converted to water vapor and methane. The water vapor, methane, and excess CO_2 then flow to the air cooled condenser/separator, where the water vapor is condensed, separated from the gas stream and pumped out. The gases (methane, excess reactant, and uncondensed water vapor) are then vented overboard to space vacuum through a pressure regulator, which also serves to regulate CO_2 and H_2 supply pressure. A bypass function for CO_2 and H_2 is provided for emergency shutdown and to permit maintenance on the Sabatier subsystem without interruption of the CO_2 removal and O_2 generation processes. The water is pumped out of the water separator by the pressure differential between the reactant pressure and a spring loaded accumulator which maintains a constant pressure drop across the porous plate separator. A positive displacement pump empties the accumulator, when it is full. A fixed air cooling flow is supplied to the Sabatier reactor and the condenser/separator by a bleed flow from downstream of the condensing heat exchanger. A controller is provided to control system operation, to monitor system status, activate bypass operating modes in response to out of tolerance conditions, and provide warnings to the operator. For all operating conditions and modes other than failure modes, the controller is not required to drive any thermal controls, because the Sabatier reactor requires no cooling modulation or heater operation (except at start-up) to meet the full range of performance requirements. The subsystem functions, capabilities, interface definition, schematic and operation are consistent with the RLSE system requirements.

The design of the Sabatier carbon dioxide reduction system is based on an extensive background of both experimental and analytical data with the high activity catalyst, developed and fabricated by Hamilton Standard and designated as UASC-151G. This catalyst, ruthenium on a 14-18 mesh granular alumina substrate, permits a simple straight-through plug flow reactor design without complicated heat exchangers. More than one thousand hours of operating time have been accumulated on the catalyst.

The preprototype Sabatier subsystem is designed to meet the requirements of Table 8. The main features of the design are flexibility of operation and simplicity of control. The Hamilton Standard developed catalyst permits operation over a wide range of temperatures, molar ratios, and loads with no active control, while maintaining over 99% process efficiency. The Sabatier reaction is temperature selflimiting at about 593°C (1100°F). Therefore, there is no danger of overheating it under any load or molar ratio. Since the catalyst has a high reactivity, the reaction starts at under 177°C (350°F) and maintains itself at low loads without heaters. Cooling flow is set for the maximum load conditions and does not need to be changed for any lower load condition. Electric heaters are required for less than 5 minutes only for the initial startup after a shuttle launch. The compact size and insulating of the Sabatier reactor minimize heat loss, so startup during the light side of each orbit is accomplished without heaters. Two temperature measurements are sufficient to indicate reactor performance status and provide overtemperature protection. The only active controls in the Sabatier subsystem are the limits in the water accumulator to control its pump down.

Performance of the Sabatier subsystem was demonstrated by over seven hundred hours of testing on the preprototype system. Process efficiencies of over 99% were observed for a range of H_2/CO_2 molar ratios of 1.8 to 5.0 for a crew of one person with steady state operation to 3 persons under cyclical operation with a simulated 55 minute light side/39 minute dark side orbital cycle. Tables 9 and 10 show the performance data. An off design 10 person case at a molar ratio of 2.6 with the same cooling flow had a conversion efficiency of 97.1%. As can be noted in Table 10, testing after a catalyst treatment to remove additional residual chlorides resulted in improved performance.

The effects of varying the dewpoint of the reactant gases and of adding some air to the reactant gases were also tested. Variations in reactant gas dewpoint from dry conditions to 21.1°C (70°F) showed conversion efficiency variations of less than 0.1%. A test conducted with 5.1% air (1% oxygen) in the inlet reactants showed no catalyst damage as a result of oxygen exposure.

Table 8

DESIGN SPECIFICATION

CO_2 FLOW RATE		
NOMINAL	3.0 kg/day	(6.6 lb/day)
MINIMUM	0.9 kg/day	(2.0 lb/day)
MAXIMUM	3.6 kg/day	(7.92 lb/day)
H_2/CO_2 MOLAR RATIO		
MINIMUM	1.8	1.8
MAXIMUM	5.0	5.0
REACTOR EFFICIENCY	99%	99%
REACTANT SUPPLY PRESSURE	1.24 ATM	(3.5 PSIG)
REACTANT SUPPLY TEMPERATURE	18-24°C	(65-75°F)
REACTANT DEW POINT	SATURATED	SATURATED
TOUCH TEMPERATURE MAXIMUM	45°C	(113°F)
WATER DELIVERY PRESSURE	2 ATM	(30 PSIA)
START-UP TIME MAXIMUM	5 MIN	5 MIN
GRAVITY	0 TO ± 1G	0 TO ± 1G
SUBSYSTEM DUTY CYCLE	CONTINUOUS OR CYCLIC	

Table 9

PREPROTOTYPE SABATIER SUBSYSTEM PERFORMANCE
CONVERSION EFFICIENCY DURING STEADYSTATE TESTING

CO_2 Flow	H_2/CO_2 Molar Ratio				
	1.8	2.6	3.5	4.0	5.0
1 Man Continuous	99.8	99.8	99.6	99.1	100
1 Man Cyclic	99.7	99.7	99.2	98.2	100
2 Man Cyclic	----	99.7	----	----	----
3 Man Continuous	99.3	99.6	99.3	99.0	100
3 Man Cyclic	99.4	99.6	99.3	98.4	100
10 Man Continuous (off design)	----	97.2	----	----	----

Table 10

PREPROTOTYPE SABATIER SUBSYSTEM PERFORMANCE
AVERAGE CONVERSION EFFICIENCY DURING CYCLIC TESTING
(55 MINUTES ON--39 MINUTES OFF)

CO_2 Flow	H_2/CO_2 Molar Ratio				
	1.8	2.6	3.5	4.0	5.0
1 Man	99.6	99.6	99.4	98.6	100
2 Man	----	99.6	----	----	----
3 Man	99.6	98.8 (99.4)	98.1	97.4 (98.8)	100

( ) - Test results after completion of test program and catalyst treatment

TOPIC VII
System Integration Studies

The Lightside Atmospheric Revitalization System utilizes the existing ECLS shuttle orbiter volume now used for carbon dioxide control and LiOH storage. Since it may be desirable to install LARS aboard the shuttle in phases, two installation drawings have been prepared. Figures 75, 76, and 77 show the installation of only the SAWD regenerable CO_2 removal system. Figures 78, 79, and 80 show the installation of the entire LARS. The general packaging concept is to locate the WVE cell stack directly down stream of the shuttle cabin fans in place of the two LiOH canisters. The SAWD and Sabatier subsystems are located in the volume presently used for LiOH storage.

As can be seen in Figure 51, there are five mechanical interfaces between the present shuttle systems and LARS. None of these has a significant impact on the associated system. The line for carrying the methane and excess CO_2 to space vacuum can be joined with the present waste management and air lock vacuum line. Other required interfaces are: a nitrogen supply for purging the WVE cells and the Sabatier reactor and condenser; connections between the pure water storage tanks and the Sabatier and SAWD water accumulators; the WVE cell stack interfaces with the cabin fan discharge and the heat exchanger bypass valve; and the SAWD subsystem discharge connection into the cabin fan suction.

The WVE cell stack is oriented, so no change in flow direction is required as the air passes from the cabin fan through the WVE to the heat exchanger. Additionally, the orientation prevents the launch acceleration loads from acting along the longitudinal axis of the cells, limiting the possibility of electrolyte migration to one end of the cells. The SAWD canisters are arranged to prevent the launch and reentry acceleration loads from potentially causing channelling in the bed material. Therefore, although operation of the SAWD subsystem is not necessary during launch and reentry, its operation is not prohibited.

Major Component Descriptions

The three subsystems that comprise the LARS have, at minimum, been designed through the preprototype stage. In the case of Sabatier, a preprototype system has been successfully built and tested by Hamilton Standard under Contract NAS 9-15470. Prototype WVE cells were built and tested in the One Man ARS Program under Contract NAS 9-13679. This system was approximately one-quarter sized in relation to the LARS oxygen generation requirement. A

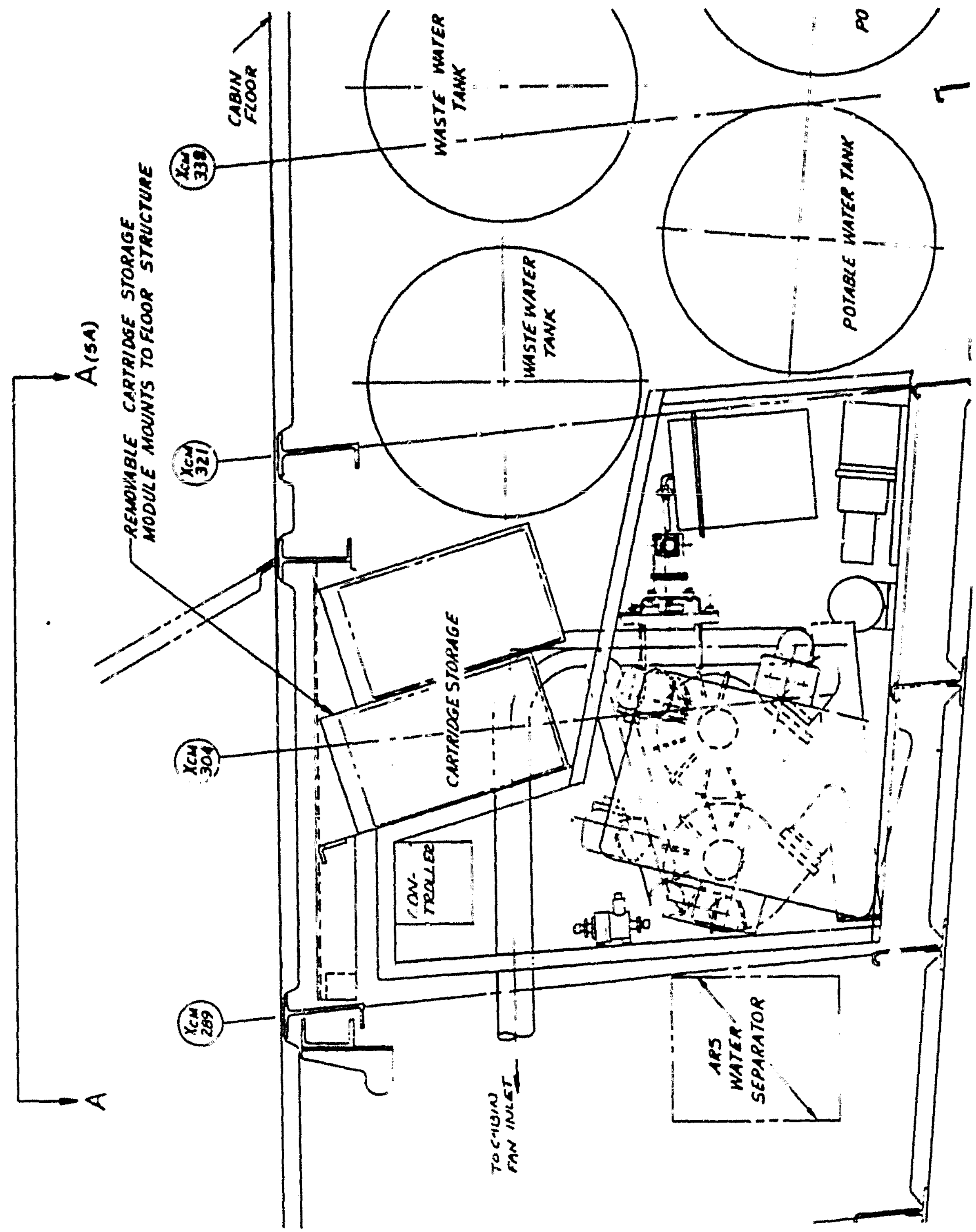

FIGURE 75
SAWD INSTALLATION DRAWING (SHEET 1)

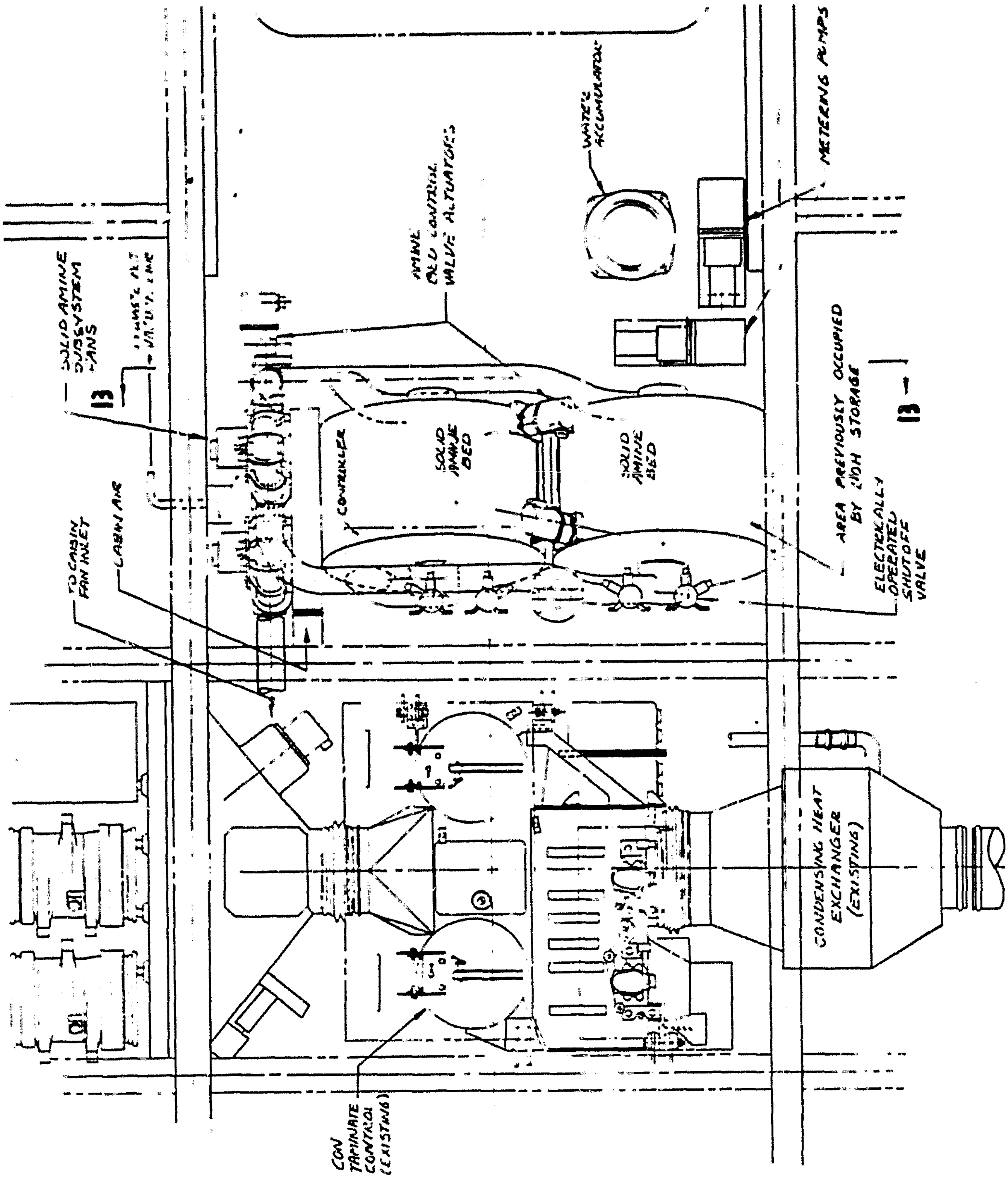

FIGURE 76
SAWD INSTALLATION DRAWING (SHEET 2)

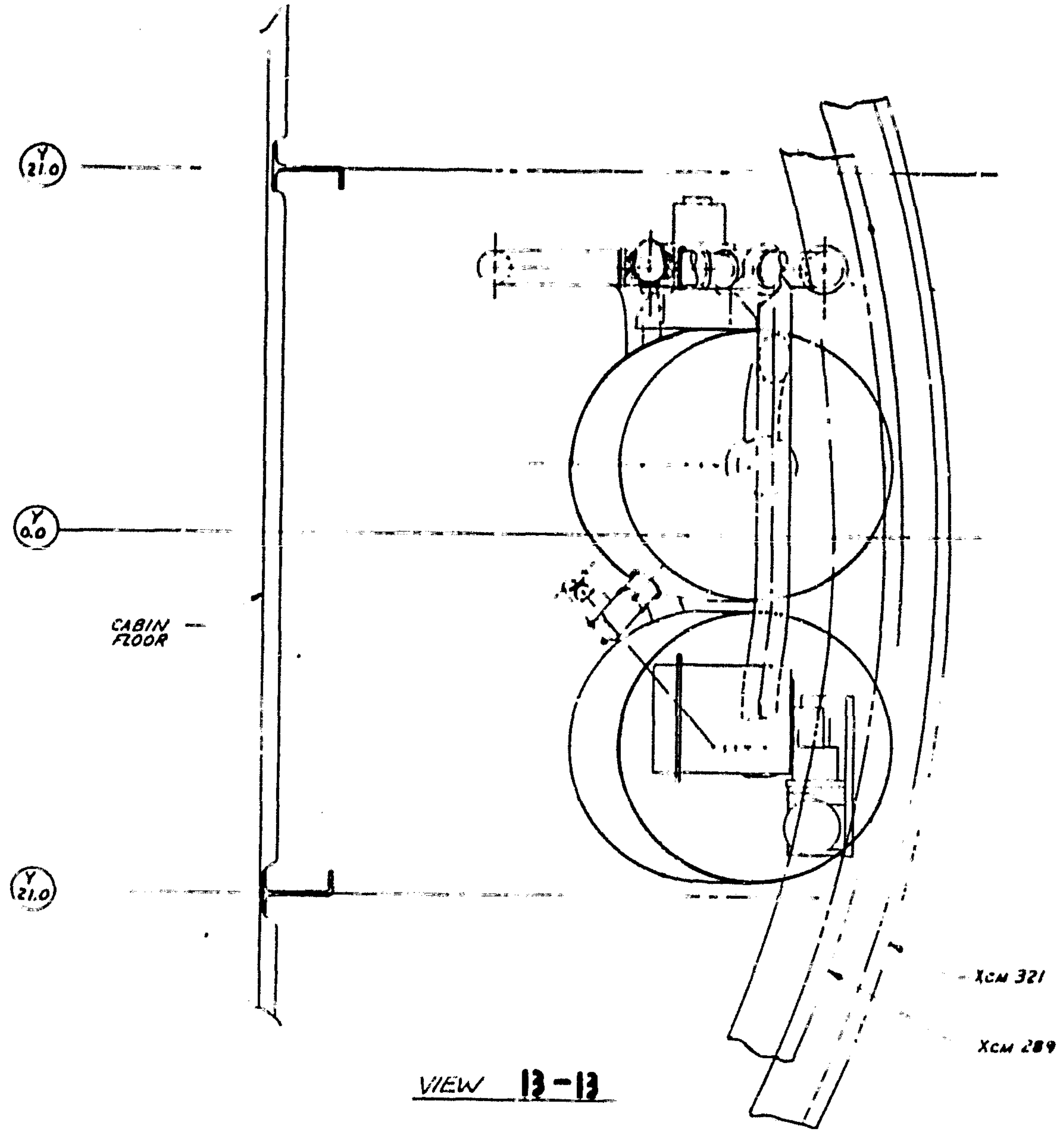

FIGURE 77

SAWD INSTALLATION DRAWING (SHEET 3)

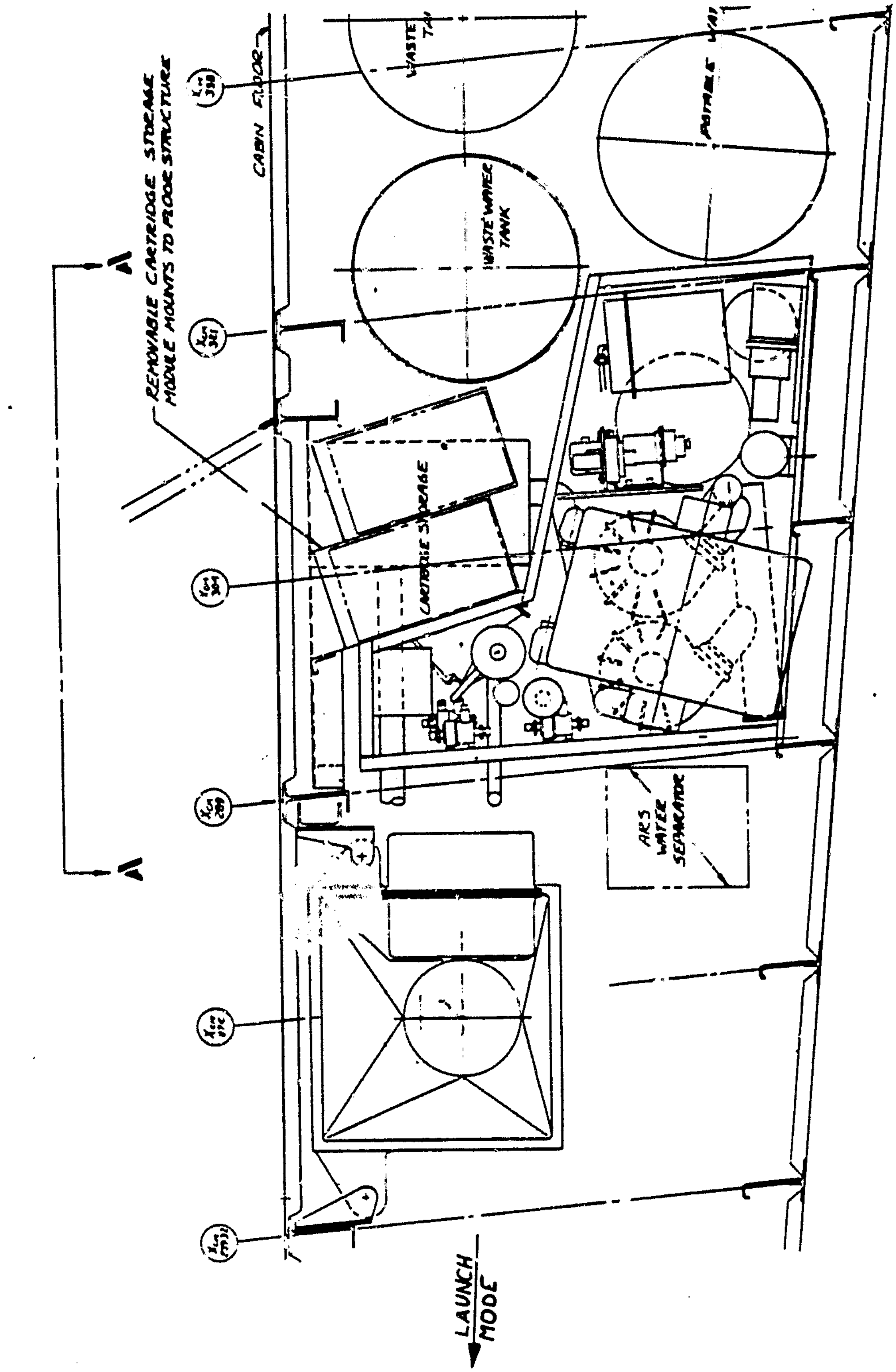

FIGURE 78

LARS INSTALLATION DRAWING (SHEET 1)

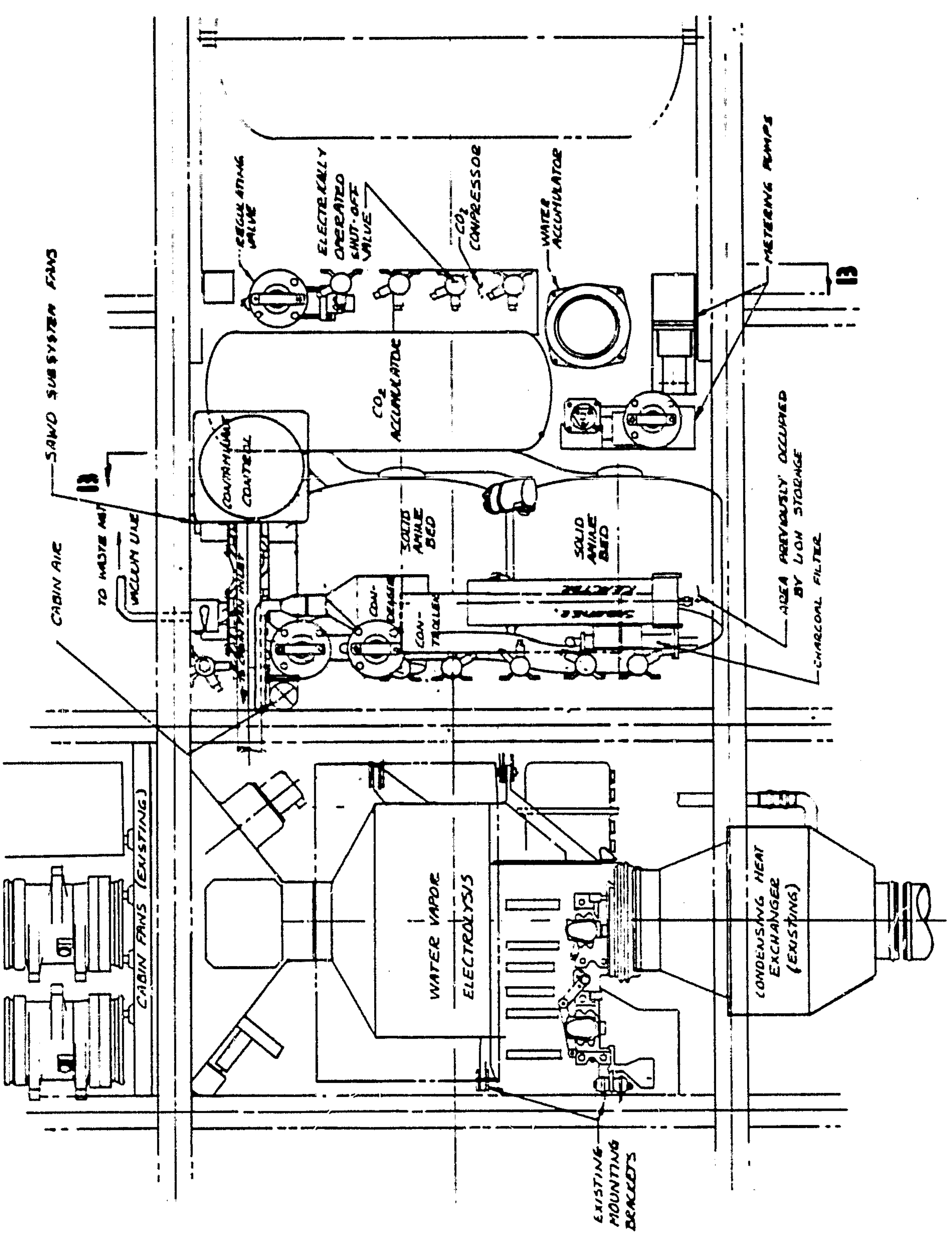

FIGURE 79
LARS INSTALLATION DRAWING (SHEET 2)

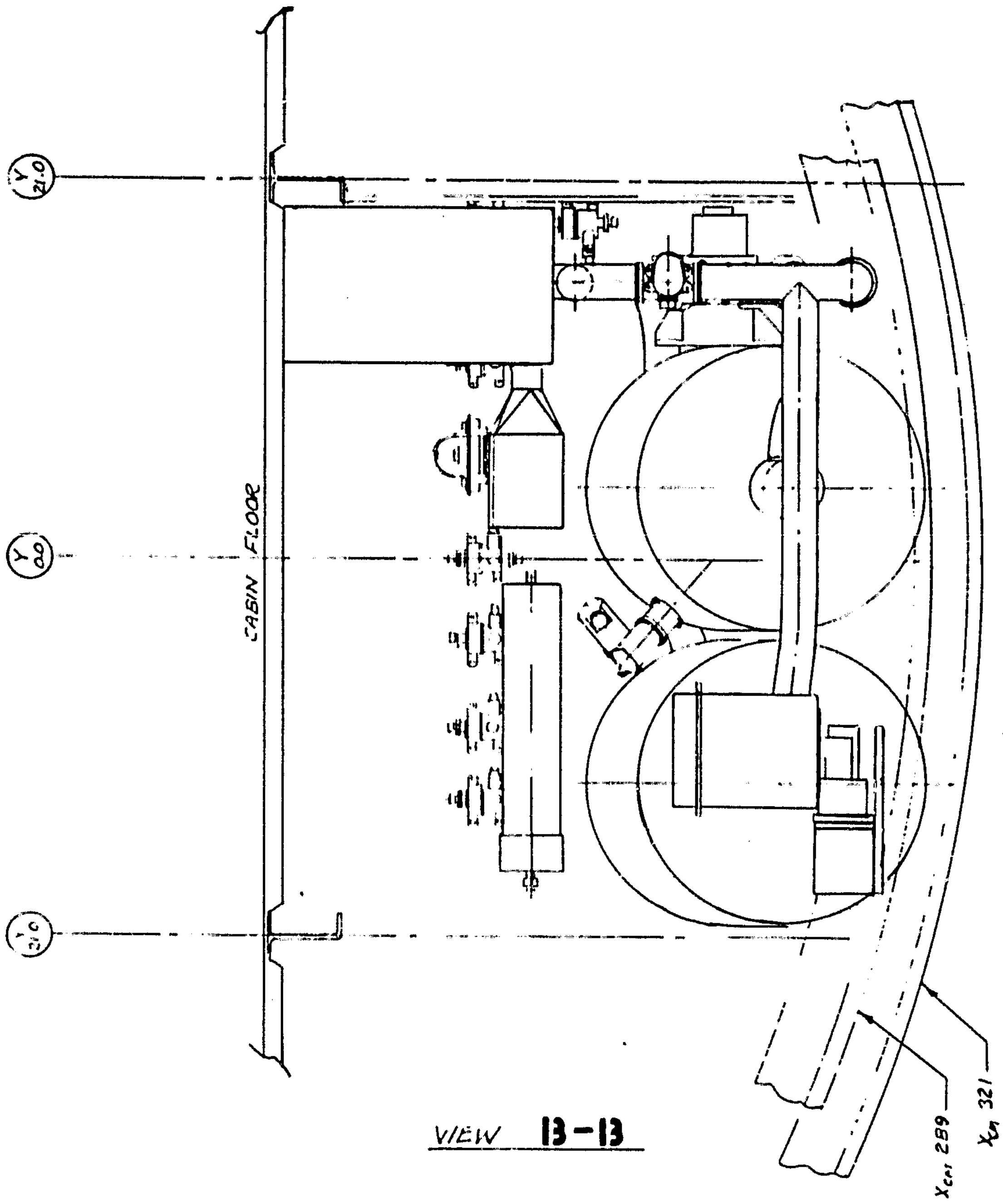

FIGURE 80

LARS INSTALLATION DRAWING (SHEET 3)

full scale SAWD subsystem has been built and tested in a breadboard configuration. However, preprototype designs of the SAWD canister and water evaporator are completed. The discussion given below of the major LARS components describes the preprototype designs. However, the weights and volumes of the major components accurately reflect those of flight hardware.

The major components of the SAWD subsystem are the IR-45 canisters, the zero gravity steam generators, the CO_2 accumulator, the steam generator water accumulator, the CO_2 compressor, the steam generator water pumps, and the fans.

The SAWD subsystem has two canisters. The preprototype design is shown schematically in Figure 81. Each contains 5.90 kg (13 lbm) of dry solid amine material. The canisters have double walls of stainless steel with 2.54 cm (1.0 inch) of insulation between the walls. The bed depth is 15.24 cm (6 inches), and the bed material is retained on the inlet and outlet by layers of stainless steel feltmetal and perforated plate. Threaded rods hold the bed in place in the canister. The zero gravity steam generator is attached to the inlet header to preheat it during desorption and minimize condensation inside the canister.

The zero gravity steam generator consists of a stainless steel tube with an electric tubular heating element inside. The diametral clearance between the heater and tube is between .254 and .635 mm (.010 and .025 inch). Once the heater is inserted into the tube, the assembly can be bent to any convenient shape. In the case of the SAWD subsystem, a flat spiral is convenient for attaching the steam generator to the canister inlet header. Water is fed to the steam generator by a positive displacement metering pump. The pump used in the breadboard system was a variable stroke piston pump. A similar design is feasible for the flight unit. Since the two steam generators operate at different times, one water pump can service both. Two pumps are provided for redundancy.

The water accumulator for the SAWD steam generators is the same accumulator that has been developed for the shuttle water pump package. It is a Metal Bellows Corporation accumulator with a minimum fluid volume of 819.35 cubic centimeters (50 cubic inches). The shell is aluminum alloy 6061. The bellows are inconel alloy 718, and the headers are inconel alloy 625.

Two shuttle IMU fans were selected to provide the air flow for the SAWD canisters. Since one fan supplies the required air flow, one is an installed spare. The IMU fan is a centrifugal type, driven by a 3 phase, 400 hertz, 115 volt induction motor. It has a minimum design requirement of 65.32 kg/hr (144 lbm/hr) flow at 1.12 kPa (4.5 inches of water) pressure rise with inlet conditions of 101.35 kPa (14.7 psia) and 54.44°C (130°F).

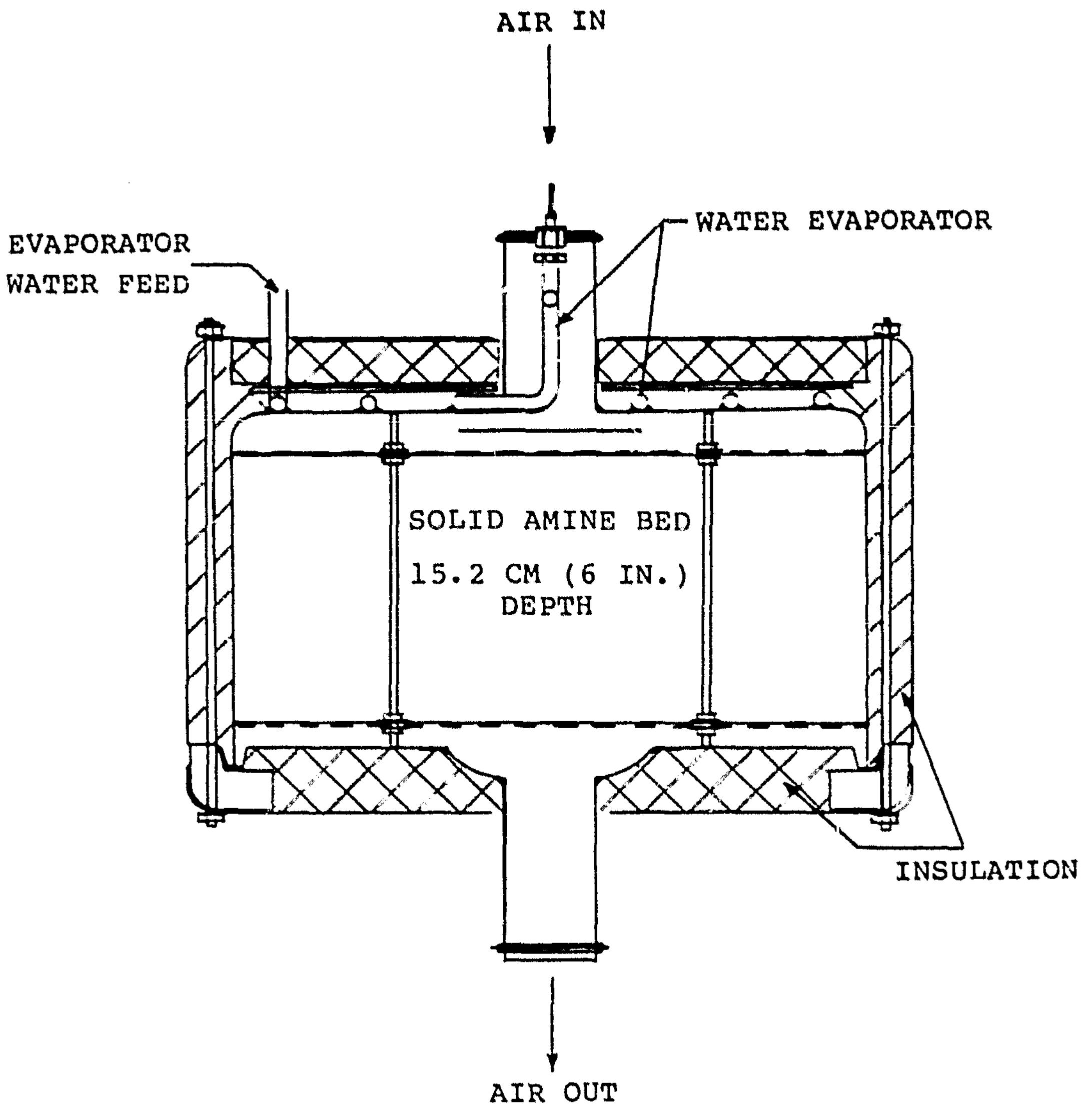

FIGURE 81

PREPROTOTYPE SAWD CANISTER

Specific component selections have not been made for the carbon dioxide accumulator and compressor. However, the requirements for these components have been determined to provide the necessary information for the packaging study and system analysis. The CO_2 accumulator is a flask with a .028 m^3 (1.0 ft^3) volume and a maximum normal operating pressure of 744.63 kPa (108 psia). It has a common inlet and outlet connection to receive CO_2 from the compressor and supply CO_2 to the Sabatier subsystem. A relief valve is provide to discharge excess CO_2 overboard. The CO_2 compressor must have a capacity of .028 m^3/min (1.0 CFM) at a suction pressure of 101.35 kPa (14.7 psia) and a discharge pressure of 744.63 kPa (108 psia).

The primary components of the Sabatier subsystem include the reactor, the water condenser/separator, the accumulator and the water pump. These items were developed for the preprototype system to the standards of space flight hardware, and will not require major modifications for flight use.

The Sabatier reactor has a catalyst bed weighing 460 gms (1.01 lbm), and is contained in a cylindrical tube, 34 cm (13.5 in) long and 3.6 cm (1.43 in) in diameter, separated into two zones: the high temperature primary reaction zone; and the cooling or secondary reaction zone. Two heaters for redundancy are used to initially heat the catalyst to start the reaction. The heaters are not required during normal cyclic operating modes, as there is sufficient thermal storage to restart the reaction. The first or primary reaction zone is insulated to prevent heat loss to the cabin and to retain the heat of reaction during the "down" cycle of operation, eliminating power and time requirements for reheating of the catalyst. Two cooling jackets with a fixed rate of cabin air flow surround the secondary zone. A platinum resistance temperature (PRT) sensor is located below the heater rod to indicate when the catalyst and reaction has reached a high or low temperature. Another PRT sensor, located on the outside of the reactor underneath the insulation, is used to monitor the temperature in the event that the bed temperature becomes too high due to failure to turn off the heaters.

The unit is of all stainless steel construction, welded and bolted together with an aluminum perforated sheet outside shell for handling and touch temperature protection. The catalyst bed is enclosed in a stainless steel tube with a welded cap on the inlet end with an opening for the reactant gas and the heater elements. The heater elements are enclosed in a close fitting sheath for good heat transfer into the primary zone of the catalyst bed. The heaters can be removed and/or replaced without disturbing the bed. The exit end is flanged and bolted with provision for preloading the catalyst bed. The primary zone is insulated with a High Temperature Min K (F 182) blanket. The cooling jacket consists of stainless steel serrated fins wrapped around the bed cylinder for good air flow and heat conduction, covered with a shell of stainless steel.

The condenser/separator is a stainless steel plate and fin heat exchanger. The unit comprises three adjacent layers. The first layer is a single pass 0.51 cm (0.200 in) high plate and fin construction with a header on one end for avionics or cabin air flow. The water collection pass is a pin-fin plate, that is the cold plate of the system, and is on one side of the cold air pass. The top layer or hot pass consists of a stainless steel porous plate, that is in contact on one side with the pin-fin plate on the other side with a 4 pass configuration of stainless steel serrated fins, separated with stainless steel pass separators. The top plate is a solid stainless steel plate, that is brazed to the top unit. The water accumulator is sized to hold 45 gms (0.1 lb). For 3-man operation at an H_2/CO_2 molar ratio of 2.6 it cycles approximately every 41 minutes during continuous operation and about every 24 minutes during the on phase of cyclic operation. The pump delivers water to the water management system at 2 atm (30 psia), which is the upper pressure limit defined by RLSE.

The only major components in the water vapor electrolysis subsystem are the WVE cell pairs. The internal details of the cells were described in the Subsystem Sizing and Operating Characteristics section of this report. The fifteen cells are arranged in a stack with a gasket seal between the cells to prevent bypass air flow. The cell stack is built into a section of ducting with inlet and outlet headers to mate with the present ARS.

A weight summary for the LARS is given in Table 11. The weights are listed to show the effect of adding the subsystems to the shuttle orbiter in phases. Therefore, as an example, the CO_2 compressor and accumulator are listed as weights in the Sabatier subsystem, since they are not necessary if only a SAWD subsystem is installed.

LARS Instrumentation Requirements

The instrumentation requirements for LARS are listed in Table 12. They are divided into lists for the three subsystems. The requirements include indications for both monitoring and control. Since it is feasible that the three subsystems would be installed in the shuttle vehicle in distinct phases, the instrumentation requirements are listed under the subsystem with which they would be included. For example, the CO_2 compressor and accumulator would be installed with the Sabatier subsystem. Therefore, a CO_2 compressor indicating light and a CO_2 accumulator pressure indication are necessary only when the Sabatier subsystem is installed.

Table 11

LARS WEIGHT SUMMARY

SAWD Subsystem

Items	Weight kg.	(lbm)
Canister assemblies (2)	22.68	(50)
Fan assemblies (2)	8.16	(18)
Metering pumps (2)	4.54	(10)
Water accumulator	2.27	(5)
Controller	2.27	(5)
Regulating valve	2.27	(5)
Solenoid shutoff valves (8)	6.35	(14)
Support framing	9.07	(20)
Ducting	0.82	(1.8)
Tubing	1.36	(3)
Subsystem Total	59.80	(131.8)

WVE Subsystem

WVE cell assembly	36.29	(80)
Contaminant control canister	4.08	(9)
Controller	2.27	(5)
Regulating valve	2.27	(5)
Solenoid shutoff valves (2)	1.59	(3.5)
Tubing	0.68	(1.5)
Subsystem Total	47.20	(104)

Table 11

LARS WEIGHT SUMMARY (Continued)

Sabatier Subsystem

Items	Weight kg.	(lbm)
Sabatier reactor	3.40	(7.5)
Sabatier condenser	1.32	(2.9)
Charcoal canister	0.64	(1.4)
Flow sensor	0.23	(0.5)
Misc. sensors (H_2, temp., Pressure)	0.59	(1.3)
Water pump	4.54	(10)
Water accumulator	1.13	(2.5)
Controller	2.27	(5)
CO_2 compressor	4.54	(10)
CO_2 accumulator	7.71	(17)
Regulating valves (2)	4.54	(10)
Solenoid shutoff valves (6)	4.65	(10.25)
Relief valves	0.23	(0.5)
Support framing	7.71	(17)
Tubing	2.04	(4.5)
Subsystem Total	45.50	(100.35)
LARS Total	152.50	(336.15)

Table 12

LARS INSTRUMENTATION REQUIREMENTS

Indication	Purpose
SAWD Subsystem	
Canister isolate valve position	monitor
Fan energized	monitor
Solenoid valves energized	monitor
Steam generator energized	monitor
Water pump energized	monitor
Water accumulator level	monitor
Bed outlet temperature	steam generator control
Steam generator outlet temperature	steam generator control
CO_2 flow	ullage valve/CO_2 compressor control
WVE Subsystem	
Cell and total voltage	monitor
Oxygen partial pressure	monitor/WVE voltage control
Hydrogen line pressure	monitor
Combustible gas detector	alarm/emergency shutdown and purge control
Solenoid valves energized	monitor
Sabatier Subsystem	
Reactor temperature	monitor/overtemperature shutdown control
Hydrogen flow sensor	CO_2 flow control
Water pump energized	monitor
Water accumulator level	monitor
CO_2 accumulator pressure	monitor
Reactor heater energized	monitor
Solenoid valves energized	monitor

Power Distribution To LARS

A summary of the power requirements for the three LARS subsystems is given in Table 13. Peak values are given. For the SAWD and Sabatier subsystems the peak power requirements are independent of crew size. For the WVE subsystem the peak level given is for a crew of six.

The Sabatier and WVE subsystems would be operated only on missions using solar power. With the exception of control power, all of the power required by these subsystems is drawn during the light side of an orbit. The SAWD subsystem would be operated during either fuel cell or solar powered missions. During solar powered missions, only the fan and controller are operated during the dark side of an orbit. During fuel cell powered missions, since power availability is independent of phase in orbit, the peak power requirement can be significantly reduced by increasing desorption time.

The power requirements of the LARS can be supplied by the existing shuttle orbiter power distribution system. Therefore, no major modifications are required in the electrical system with the installation of the LARS.

Table 13

LARS POWER SUMMARY

SAWD Subsystem	
Steam generator (including water pump)	1300 watts
Fan	45 watts
Control power	130 watts
WVE Subsystem	
Electrolysis power	2570 watts
Control power	250 watts
Sabatier Subsystem	
Heater (initial startup only)	100 watts
CO_2 compressor	250 watts
Controller	15 watts

APPENDIX A

Lightside Atmospheric Revitalization System Computer Program Listings

As part of the LARS study, computer programs were developed as analysis aids for the following areas:

- WVE system performance
- SAWD system CO_2 performance
- Cabin temperature and humidity with LARS installed

The SAWD system CO_2 performance program (PROF2) and the cabin temperature and humidity program (LARS-2) listings are included in this appendix. The WVE system performance program is included in the temperature and humidity program as a subroutine.

**** TSO FOREGROUND HARDCOPY ****
DSNAME=TSOG15T.PROF2.FORT

```
C     THIS PROGRAM CALCULATES IR45 BED PARAMETERS
      DOUBLE PRECISION CABC,PCO2C,GENC,ETA,CO2R
      TIME=0.
      READ(5,*)PCO2C,VCAB,TCAB,XM,TSTEP,CFM,LADS,LDSB,NC
      CALL HEAD
      DO 99 I=1,NC
      GENC=XM*2.11/24./60.*TSTEP
      J=LADS-LDSB
      K=LADS-1
      TTIM=J-1
      DO 10 M=J,K
      TTIM=TTIM +1.
      CALL ADS1(TTIM,CO2R1,PCO2C,CFM,ETA1,TSTEP,TCAB,QC1,QC2,GENC)
      CABC=PCO2C*44.*VCAB/(TCAB+460.)/760./0.7302
      CABC=CABC+GENC-CO2R1
      PCO2C=CABC*0.7302*760./44./VCAB*(TCAB+460.)
      CALL OUTPUT(PCO2C,TIME,QC1,QC2)
      TIME=TIME+TSTEP
      QC1=QC1+CO2R1
      QC2=0.
   10 CONTINUE
      TTTM=0.
      J=LDSB+1
      DO 20 II=1,J
      TTTM=II-1
      CALL ADS2(TTTM,CO2R2,PCO2C,CFM,ETA2,TSTEP,TCAB,QC1,QC2,GENC)
      CABC=PCO2C*44.*VCAB/(TCAB+460.)/760./0.7302
      CABC=CABC+GENC-CO2R2
      PCO2C=CABC*0.7302*760./44./VCAB*(TCAB+460.)
      CALL OUTPUT(PCO2C,TIME,QC1,QC2)
      TIME=TIME+TSTEP
      QC1=0.
      QC2=QC2+CO2R2
   20 CONTINUE
      XX1=0.
      XX2=LDSB+1.
      KL=LADS-LDSB-1
      DO 30 LL=1,KL
      CALL ADS1(XX1,CO2R1,PCO2C,CFM,ETA1,TSTEP,TCAB,QC1,QC2,GENC)
      CALL ADS2(XX2,CO2R2,PCO2C,CFM,ETA2,TSTEP,TCAB,QC1,QC2,GENC)
      CABC=PCO2C*44.*VCAB/(TCAB+460.)/760./0.7302
      CABC=CABC+GENC-CO2R2-CO2R1
      PCO2C=CABC*0.7302*760./44./VCAB*(TCAB+460.)
      TIME=TIME+TSTEP
      XX1=XX1+TSTEP
      XX2=XX2+TSTEP
      QC1=QC1+CO2R1
      QC2=QC2+CO2R2
      CALL OUTPUT(PCO2C,TIME,QC1,QC2)
   30 CONTINUE
C     ------------------------------------------------------------
   99 CONTINUE
      STOP
      END
      SUBROUTINE ADS1(X,CO2R1,PCO2C,CFM,ETA1,TSTEP,TCAB,
     1 QC1,QC2,GENC)
```

```
      IF(X.EQ.0.)GO TO 22
      ETA1=EXP(0.6557617*ALOG(X)-0.16287231*(ALOG(X)**2)
     1 -0.68969727)
   22 IF(X.LE.5.)ETA1=1.0
      CO2R1=PCO2C*CFM*44.*ETA1*TSTEP/760./0.7302/(TCAB+460.)
      RETURN
      END
C     ----------------------------------------------------------
      SUBROUTINE ADS2(Z,CO2R2,PCO2C,CFM,ETA2,TSTEP,TCAB,
     1 QC1,QC2,GENC)
      IF(Z.EQ.0.)GO TO 23
      ETA2=EXP(0.6557617*ALOG(Z)-0.16287231*(ALOG(Z)**2)
     1 -0.68969727)
   23 IF(Z.LE.5.)ETA2=1.0
      CO2R2=PCO2C*CFM*44.*ETA2*TSTEP/760./0.7302/(TCAB+460.)
      RETURN
      END
C     -----------------------------------------------------------
      SUBROUTINE OUTPUT(PCO2C,TIME,QC1,QC2)
      WRITE(7,50)PCO2C,TIME,QC1,QC2
   50 FORMAT(1X,4(F10.3,1X))
      RETURN
      END
      SUBROUTINE HEAD
C ----------------------------------------------------------------
      WRITE(7,51)
   51 FORMAT(
     A '00004',/,
     B 'CO2 PARTIAL PRESSURE-MMHG',/,
     C 'TIME INTO ADSORB-MIN',/,
     D 'TOTAL CO2 REMOVED IN BED 1-LBS',/,
     E 'TOTAL CO2 REMOVED IN BED 2-LBS',/,
     F '(1X,4(F10.2,1X))')
      RETURN
      END
```

SVHSER 7224

```
**** TSO FOREGROUND HARDCOPY ****
DSNAME=TSOG15K.LARS2.FORT

C  INTEGRATED SAWD-WVE-CONDENSOR FOR LARS
      DIMENSION VALVE(11)
      DATA VALVE/1.,4.,0.,0.,1.,2.,2.5,0.,.00286,.00571,.007143/
      REAL KK
C     INITIAL VALUES-TOTAL SENSIBLE HEAT LOAD
      ICOUNT=0
      TEND=96*60.*2.
      CABVOL=2000.
      NOBED=2
      TIME=0.0
      TSTEP=6.0
      QS4=0.0
      QL4=0.0
      QE1=1871.
      Q2=4353.
      Q3=1660.
      Q6=1.
      QS1=650.
      QL1=416.
      QIMU=154.
      TCI=40.3
      CFM3=340.
      CFMIMU=12.
      WC=600.
      PC=14.7
      TCAB=70.
      TDPCAB=46.96+460.
      CALL KANDK(PCABIN,TDPCAB,2)
      AHCAB=.622*PCABIN/(PC-PCABIN)
      QTSS=QE1+Q2+QS4+Q3+Q6
      QTS=QTSS+QS1
C     TOTAL LATENT LOAD
      QTL=QL1+QL4
C     HX TOTAL HEAT LOAD
      QT=QTS+QTL
C     COOLANT OUTLET TEMP
      TCI=TCI+459.6
      TCO=TCI+QT/WC
C     INITIAL FAN INLET DENSITY
      RHO2=PC*.005
      EMCAB=CABVOL*RHO2
C     INITIAL FLOW RATE
      WA=CFM3*RHO2*60.
C     INITIAL GUESS OF HX OUTLET DEW POINT
      CALL KANDK(PSXO,TCI+5.0,2)
      AHXO =.622 *PSXO/(PC-PSXO)
      T1=TCAB +459.6
      WHX=WA
C     AIR BYPASS KEY
      LL=1
C     AIR BYPASS-CABIN TEMP LOOP
    1 NN=3000
      TSTEP=6.0
      IF(TIME.GE.2940.0.AND.TIME.LT.3180.0.AND.NOBED.EQ.1)TSTEP=.5
      IF(TIME.GE.1740.0.AND.TIME.LT.1860.0.AND.NOBED.EQ.2)TSTEP=0.500
      IF(TIME.GE.3180.0.AND.TIME.LT.3300.0.AND.NOBED.EQ.2)TSTEP=0.500
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      IF(TIME.GE.7500.0.AND.TIME.LT.7620.0.AND.NOBED.EQ.2)TSTEP=0.500
      IF(TIME.GE.8700.0.AND.TIME.LT.8940.0.AND.NOBED.EQ.1)TSTEP=.5
      IF(TIME.GE.8940.0.AND.TIME.LT.9060.0.AND.NOBED.EQ.2)TSTEP=0.500
      IF(TIME.GT.0.0)NN=1
      DO 100 N=1,NN
C     LOOP ON FAN FLOW RATE
      DO 50 NA=1,5
C     CABIN OUTLET AH
      AHCO=AHXO +QL1/WA/(1067.)
      GBODY=QL1/WA/1067.
      DELTI=TSTEP/3600.
      IF(TIME.GT.0.)AHCO=AHCAB+QL1/1000./EMCAB*DELTI
C     AVIONICS OUTLET TEMP
      WI=(CFM3-50.)*RHO2*60.
      T2=T1+Q2/WI/.24/(1.+AHCO)
C     CABIN DEW POINT PRESS
      PDP=PC/(.622/AHCO+1.)
C     INLET FAN DENSITY
      RHO2=(PC-PDP)*2.699/T2
C     FAN FLOW RATE
      WAF=CFM3 *RHO2*60.
C   IS AIR FLOW IN TOLERENCE
      IF(ABS(WA/WAF-1.).LE.0.02) GO TO 60
C     NOT IN TOL -NEW AIR FLOW GUESS
 50   WA=0.3*WA +0.7*WAF
C     LOOP NOT CONVERGED-PRINT
      WRITE(11,501) N
      WRITE(6,501) N
      WRITE(11,502) WA,WAF,T2,PDP
      WRITE(6,502) WA,WAF,T2,PDP
C     LOOP CONVERGED -FAN OUTLET TEMP
 60   WA=WAF
      IF(TIME.EQ.0.0)AHCO=AHXO+QL1/WI/1067.
      T2=T1+Q2/WI/.24/(1.+AHCO)
      WCAB=WA*(1.+AHCO)
      IF(TIME.GT.0.AND.NOBED.EQ.1) CALL SAWD1(T1,TDPC,QS4,QL4,
     1TSTEP,PC,CFMIMU,QIMU,RHO2,AHCO,WSAWD,QUAN,TIME)
      IF(TIME.GT.0.0.AND.NOBED.EQ.2)CALL SAWD2(T1,TDPC,QS4,QL4,
     2TSTEP,PC,CFMIMU,QIMU,RHO2,AHCO,TIME,WSAWD,QUAN)
      T3=(T2*WI+T1*WSAWD+(QS4+QIMU)/.24/(1.+AHCO))/(WI+WSAWD)
      T4=T3+Q3/WA/.24/(1.+AHCO)
      CALL KANDK(PC,T4MAX,1)
      IF(T4.GT.T4MAX)T4=T4MAX
      DO 121 I=1,2
      QTS=QE1+Q2+QS4+Q3+Q6+QS1
      QTL=QL1+QL4
      QT=QTS+QTL
      IF(TIME.EQ.0.0)CALL CCHQUA(WCAB,QTS,QTL,WC,UAA)
C     SAWD OUTLET TEMP
C     SAWD HUMIDITY OUTLET
      IF(WSAWD.NE.0.0)QSAWD=QL4/WSAWD/1067.
      AHXI=AHCO +QSAWD
      IF(TIME.GT.0.0.AND.AHCAB.NE.0.0)AHXI=(AHCO*WI+(QSAWD+AHCO)*WSAWD)
     1/(WI+WSAWD)
C     IF(TIME.GE.0.0.AND.TIME.LT.6000.)WRITE(11,383)AHXI,AHCO
C 383 FORMAT(2X,2(4X,F8.4))
C    CALCULATING WATER LOADINGS FROM BED
C    QXTRA--ENERGY RELEASED WHEN SAWD H2O CONDENSES
      PXI=PC/(.622/AHXI+1.)
      IF(TIME.EQ.0.0.OR.I.EQ.2)GO TO 121
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      CALL KANDK(PXI,DPMIX,1)
      DELTAT=DPMIX-T4
      IF(DELTAT.GT.0.0)QXTRA=WA*.24*DELTAT
      IF(DELTAT.LE.0.0)QXTRA=0.0
      H2OXTA=QXTRA/1000.
      WATER=WATER+H2OXTA
      QL4=QL4-QXTRA
      QS4=QS4+QXTRA
C   QREHT--ENERGY ABSORBED WHEN SAND WATER RE-EVAPORATES
      IF(DELTAT.LT.0.0) QREHT=DELTAT*WA*.24
      IF(DELTAT.GE.0.0) QREHT=0.0
      IF(DELTAT.LT.0.0) WATER=WATER+QREHT/1000.
      IF(WATER.LT.0.0)WATER=0.0
      IF(WATER.EQ.0.0) QREHT=0.0
      IF(DELTAT.LT.0.0) QL4=QL4-QREHT
      IF(DELTAT.LT.0.0) QS4=QS4+QREHT
  121 CONTINUE
      NNN=0
      AHCABO=AHCAB
      IF(TIME.GT.0.0) GO TO 90
C     CABIN INLET TEMP
      T7=T1-(QS1+QE1)/WA/.24/(1.+AHXO)
C  HX OUTLET TEMP-ZERO BYPASS
      T5=T7-Q6/WA/.24/(1.+AHXO)
C   IS HX OUTLET TEMP TOO LOW
      IF((T5-TCI).GE.2.)GO TO 61
C   HX TOO SMALL-RAISE CABIN TEMP
      T1N=T1+TCI+2.-T5
C   SET KEY THAT TCAB HAS BEEN RAISED
      LL=2
      GO TO 81
C     FIND UAR FOR FULL FLOW CONDITION
C    CONDENSER INLET DEW POINT
 61   PXI=FDP
       CALL KANDK(PSXO,T5,2)
      AHXO=.622*PSXO/(PC-PSXO)
      AHXI=AHXO+QTL/WA/(1067.)
      PXI=PC/(.622/AHXI+1.)
      CALL KANDK(PXI,TDPI,1)
 68   DT=(T4-TCO-T5+TCI)/ALOG((T4-TCO)/(T5-TCI))
C        UA
      UAR=QT/DT
C     IS HX UA IN TOLERENCE
      IF(ABS(UAR/UAA-1.).LE.0.01) GO TO 75
C  NOT CONVERGED-IS HX TOO SMALL
      IF(UAR.LT.UAA) GO TO 70
C     HX TOO SMALL-RAISE CABIN TEMP
      LL=2
C     HOW MUCH SHOULD TEMP BE RAISED
      IF(UAA/UAR.GT.0.8) GO TO 80
C     RAISE TCAB 2 DEG F
      T1N=T1+2.
      GO TO 81
C     RAISE CABIN TEMP  1 DEG F
 80   T1N=T1+1.
C     NEW METABOLIC SPLIT
C     CALL QMET(T1N-459.6,QS1,QL1)
C     HX SENS LOAD
 81   QTS=QTSS+QS1
C     HX LATENT LOAD
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      QTL=QL1+QL4
C     SET UP FOR NEXT ITERATION -NEW OUTLET DEW PT
      T5=T5+T1N-T1
      CALL KANDK(PSXO,T5,2)
      AHXO=.622*PSXO/(PC-PSXO)
      GO TO 100
C     HX WAS TOO LARGE-SHOULD AIR BE BYPASSED
 70   GO TO(90,91),LL
C     LOWER CABIN TEMP
 91   T1N=T1-.030
      GO TO 81
C     END LOOP
 100  T1=T1N
C     CABIN TEMP LOOP NOT CONVERGED
      WRITE(11,503) T1,WA,AHXO,UAR,TDPI,T5,T4,QT,QS1
      WRITE(6,503) T1,WA,AHXO,UAR,TDPI,T5,T4,QT,QS1
      WRITE(11,923)N
      WRITE(6,923)N
 923  FORMAT(1X,'NO. OF ITERATIONS =',I4, ' ******'/)
      TCI=TCI-459.6
      TCO=TCO-459.6
C     RETURN
      GO TO 999
C   BYPASS AX-CAN MEET TCAB -LOOP TO FIND BYPASS FLOW
   90 DO 200 NC=1,120
C     NEW GUESS OF AIR OUTLET TEMP
      IF(TIME.EQ.0.0)T5=TCI+(T5-TCI)*UAR/UAA
      IF(NOBED.EQ.1.AND.TIME.EQ.TSTEP.AND.NC.EQ.1)T5=T4
      IF(NOBED.EQ.2.AND.TIME.EQ.1740.0.AND.NC.EQ.1)T5=T4
      IF(NOBED.EQ.2.AND.TIME.EQ.7500.0.AND.NC.EQ.1)T5=T4
      IF(NOBED.EQ.2.AND.TIME.EQ.3180.0.AND.NC.EQ.1)T5=T4
      IF(NOBED.EQ.2.AND.TIME.EQ.8940.0.AND.NC.EQ.1)T5=T4
      IF(TIME.EQ.0.0) TSET=T7
      IF(TIME.EQ.5760.)TSET=T7
      IF(TIME.GT.0.0) GO TO 111
C    IS OUTLET TEMP LESS THAN MIN
      IF((T5-TCI).LT.2.) T5=TCI+2.
C     HX FLOW RATE
      WHX=QTS/(T4-T5)/.24/(1.+AHXI)
  111 IF(TIME.EQ.0.0)GO TO 112
      GO TO 898
  899 ERROR=T7-TSET
      IF(ERROR.GT.2.5)ERROR=2.5
      IF(ERROR.LT.-2.5)ERROR=-2.5
      CALL BIQUAD(VALVE,1,ABS(ERROR),0.,FLOWK,K)
      IF(ERROR.NE.0.0)WHX=WHX+(ERROR/ABS(ERROR))*FLOWK*WHX*TSTEP
      IF(WHX.GT.WA)WHX=WA
      GO TO 889
  898 CONTINUE
C     OUTLET DEW POINT
  112 CALL KANDK(PSXO,T5,2)
      AHXO=.622*PSXO/(PC-PSXO)
C     WVE INLET HUMIDITY
      IF(TIME.EQ.0.0)AHXI=AHXO +QTL/WHX/(1067.)
C     WVE INLET DEW POINT
      PXI=PC/(.622/AHXI+1.)
      CALL KANDK(PXI22,T4,2)
      IF(PXI.GT.PXI22)PXI=PXI22
      IF(TIME.EQ.0.0) GO TO 889
      GO TO 883
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  889 CALL WVE(TSTEP,T4,PXI,PC,TDPI,T22,CFM3,EV,TIME,POWER,DP,AWVEX)
      QLWVE=(WI+WSAWD)*(AHXI-AWVEX)
      IF(TIME.NE.0.0) GO TO 72
  888 CONTINUE
C   INLET DEW POINT
      WHXI=WHX*(1.+AHXI)
      QSENSI=WHX*.24*(T4-T5)
      QLAT=(AHXI-AHXO)*WHX*1000.
C     CALL CONDUA(WHXI,QSENSI,QLAT,WC,UAA)
      QCOND=QSENSI+QLAT
      TCO=QCOND/WC +TCI
C     IF(TIME.GE.1680.AND.TIME.LT.6000.)WRITE(11,232)TCO,T5,AHXI,AHXO,
C    1T4,QS4
 30   DT=(T4-TCO-T5+TCI)/ALOG((T4-TCO)/(T5-TCI))
C       UA
      UAR=QT/DT
      IF(TIME.GT.0.0)UAR=QCOND/DT
C     IF (TIME.GT.1680.)WRITE(11,724)DT,UAR,TIME
  724 FORMAT(2X,3(2X,F12.2))
      IF((UAR/UAA-1.).GT.0.01.AND.TIME.GT.0.0)T5=T5+.125
      IF((UAR/UAA-1.).LT.0.01.AND.TIME.GT.0.0)T5=T5-.125
C   IS UA IN TOLERANCE
      IF(ABS(UAR/UAA-1.).LE.0.01.AND.TIME.NE.0.0)GO TO 899
      IF(NC.EQ.80.AND.TIME.NE.0.0)GO TO 899
      IF(ABS(UAR/UAA-1.).LE.0.01.AND.TIME.EQ.0.0) GO TO 72
C   IS HX STILL TO BIG
      IF(UAA.LT.UAR.AND.TIME.EQ.0.0) GO TO 200
C    YES-INCREASE BYPASSFLOW -HAS TMIN BEEN REACHED
      IF((T5-TCI).LT.2.1.AND.TIME.EQ.0.0) GO TO 72
C      NO
 200  CONTINUE
  232 FORMAT(2X,6(1X,F10.4))
C     LOOP NOT CONVERGED
C     WRITE(11,504) WHX,T5,T4,UAR
C     WRITE(6,504) WHX,T5,T4,UAR
 75   IF(TIME.EQ.0.0)WHX=WA
C  LOOP CONVERGED -SET UP FOR PRINT OUT - CABIN DEW PT
   72 EMCAB=CABVOL*RHO2
  707 FORMAT(2X,5(2X,F9.3))
      WBYP=WI+WSAWD-WHX
      AHMIX=(AHXI*WBYP+AHXO*WHX)/(WBYP+WHX)
      PMIX=PC/(.622/AHMIX+1.)
      CALL KANDK(PMIX,T7DP,1)
      IF(TIME.EQ.0.0) GO TO 13
      T7=(WHX*T5 + WBYP*T22)/(WI+WSAWD) + Q6/WA/.24/(1.+AHMIX)
      TDUCT=T7 + (QS1+QE1)/(WI+WSAWD)/.24/(1.+AHMIX)
      EMCAB=CABVOL*RHO2
      DELTI=TSTEP/3600.
      T1=(TDUCT*(WI+WSAWD)*DELTI + T1*EMCAB)/((WI+WSAWD)*DELTI + EMCAB)
C     WRITE(11,626)T7,TDUCT,T1,WBYP
  626 FORMAT(2X,4(2X,F8.2))
   13 CONTINUE
      AHCAB=(AHMIX*(WI+WSAWD)*DELTI+EMCAB*AHCO)/
     1((WI+WSAWD)*DELTI+EMCAB)
      IF(WSAWD.NE.0.0)ASAWD=QL4/WSAWD/1067.
      AHXI=(AHCO*WI+(ASAWD+AHCO)*WSAWD)/
     1(WI+WSAWD)
      AHXI4=.622*PXI22/(PC-PXI22)
C     IF(TIME.GE.5760.0.AND.TIME.LT.6000.)WRITE(11,464)AHXI,AHXI4,AHXO
C 464 FORMAT(2X,3(1X,F7.4))
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      IF(AHXI.GT.AHXI4)AHXI=AHXI4
C     AHCO=AHXI-QL4/WA/1067.
C     AHCO=AHCAB
      PDPC=PXI
      PDPC=PC/(.622/AHCO+1.)
      CALL KANDK(PDPC,TDPC,1)
C     SET UP TEMPS FOR PRINTOUT
      TA=T1-459.6
      TB=T2-459.6
      TC=T3-459.6
      TD=T4-459.6
      TE=T5-459.6
      TF=T7-459.6
      TG=TCI-459.6
      TH=TCO-459.6
      TI=TDPC-459.6
      TJ=TDPI-459.6
      WCOND=(AHXI-AHXO)*WHX
      IF(WCOND.LT.0.0)WCOND=0.0
      WCAB=WI*(1.+AHCO)
      WHXT=WHX*(1.+AHXI)
      WSAWDT=WSAWD*(1.+ASAWD)
      WBY=WI+WSAWD-WHX
C     IF(WHX .EQ. WA) WBY = 0.
      WBYT=WBY*(1.+AHXI)
      IF(WBYT.LT.0.0)WBYT=0.0
      TIMET=TIME/60.-96.
C     PRINT OUTPUT DATA
      JCOUNT=ICOUNT
      IF(TIME.GT.5760.)ICYC=2
      NTIME=TIME
      ICOUNT=NTIME/60
      IF(TIME.GE.8700..AND.TIME.LE.8940.0.AND.NOBED.EQ.1)ICOUNT=NTIME/6
      IF(NOBED.EQ.2.AND.TIME.GE.7500.0.AND.TIME.LE.7620.)ICOUNT=NTIME/6
      IF(NCBED.EQ.2.AND.TIME.GE.8940.0.AND.TIME.LE.9080.)ICOUNT=NTIME/6
      IF(ICOUNT.GT.JCOUNT.AND.ICYC.EQ.2.OR.TIME.EQ.5760.)
     1WRITE(11,513)TIMET
  513 FORMAT(//5X,'TIME=',3X,F5.2,3X,'MINUTES INTO ORBIT')
  301 IF(ICOUNT.GT.JCOUNT.AND.ICYC.EQ.2.OR.TIME.EQ.5760.)WRITE(11,510)
     1TA,TB,TC,TD,TE,
     2  TF,TJ,TI,QT,QTS,QTL,WI,WHX,TG,TH,WCOND,WCAB,WHXT,WBYT
      IF(TIME.EQ.0.0)WRITE(8,989)
  989 FORMAT(
     A'00021'/,' TIME IN MINUTES'/,' CABIN TEMPERATURE--DEG F'/,
     D' FAN INLET TEMPERATURE--DEG F'/,
     E' FAN OUTLET TEMPERATURE--DEG F'/,
     F' CONDENSER AIR INLET TEMP--DEG F'/,
     G' CONDENSER OUTLET TEMP--DEG F'/,
     H' CABIN INLET TEMPERATURE--DEG F'/,
     I' CONDENSER INLET DEW POINT--DEG F'/,
     J' CABIN DEW POINT--DEG F'/,
     K' CONDENSER HEAT LOAD-TOTAL--BTU/HR'/,
     L' CONDENSER HEAT LOAD-SENSIBLE--BTU/HR'/,
     M' CONDENSER HEAT LOAD-LATENT--BTU/HR'/,
     N' AIR FLOW RATE-FAN--LBM/HR'/,
     O' AIR FLOW RATE-CONDENSER--LBM/HR'/,
     P' CONDENSER COOLANT INLET TEMP--DEG F'/,
     Q' CONDENSER COOLANT OUTLET TEMP--DEG F'/,
     R' CONDENSATE FLOW--LBM/HR'/,' CABIN AIR WT FLOW--LBM/HR'/,
     T' CONDENSER AIR WEIGHT FLOW--LBM/HR'/,
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     U' COND BYPASS AIR WT FLOW--LBM/HR'/,
     V' WVE REQUIRED CELL VOLTAGE--VOLTS'/,' (4(1X,6(F10.3,1X)/))')
      IF(ICOUNT.GT.JCOUNT.AND.ICYC.EQ.2.OR.TIME.EQ.5760.)
     2WRITE(8,979)TIMET,TA,TB,TC,
     1TD,TE,TF,TJ,TI,QT,QTS,QTL,WI,WHX,TG,TH,WCOND,WCAB,WHXT,WBY,EV
  979 FORMAT(4(1X,6(F10.3,1X)/))
      IF(ICOUNT.GT.JCOUNT.AND.ICYC.EQ.2.OR.TIME.EQ.5760.)
     1WRITE(11,512)QS1,QL1,UAA,QUAN,POWER
      IF(NCBED.EQ.2)GO TO 777
      IF(TIME.EQ.8640.0.OR.TIME.EQ.9120.)WRITE(11,778)DP,T7DP,QCOND,
     1QLAT,QSENSI,T22,QLWVE
  778 FORMAT(2X,7(1X,F10.1))
  777 IF(NCBED.EQ.1) GO TO 779
      IF(TIME.EQ.7440.0.OR.TIME.EQ.9120.)WRITE(11,778)DP,T7DP,QCOND,
     1QLAT,QSENSI,T22,QLWVE
  779 CONTINUE
      TIME=TIME+TSTEP
      IF(TIME.LE.TEND)GO TO 1
 999  RETURN
 501  FORMAT(1H '     ****** '
     1          ,'FLOW RATE LOOP NOT CONVERGED   ************  ITERATION
     2 NO.',I2 )
 502  FORMAT(1H F8.1,8H WA     F8.1,8H WACAL  F8.1,8H TFANIN F8.4,8H PDP
     2     ' ******'/)
 503  FORMAT(1H '      ****** '
     1          ,'CABIN TEMP LOOP NOT CONVERGED '/F8.2,8H TCAB   F8.1,8H
     2 WAIR  F8.5,8H AHXO   F8.1,8H UAR    F8.2,8H TDPI   F8.2,8H TAXO
     3 F8.2,8H TAXI    /F8.1,8H QTOT   F8.1,8H QSMET     )
 504  FORMAT(1H '       ****** ',
     1           'FLOW SPLIT LOOP NOT CONVERGED' /F8.2,8H WHX    F8.2,8H
     2TAXO   F8.2,8H TAXI   F8.2,8H UAR       '******'/)
 510  FORMAT(1H0' CABIN AIR LOOP PERFORMANCE '/
     2'    CABIN TEMP                  T1    ',F8.2,/
     3'    FAN INLET TEMP              T2    ',F8.2,/
     4'        OUTLET TEMP             T3    ',F8.2,/
     5'    CONDENSER AIR INLET TEMP    T4    ',F8.2,/
     6'                  OUTLET TEMP   T5    ',F8.2,/
     7'    CABIN INLET TEMP            T7    ',F8.2,/
     8'    CONDENSER INLET DEW POINT         ',F8.2,/
     9'    CABIN DEW POINT                   ',F8.2,/
     A'    CONDENSER HEAT LOAD - TOTAL       ',F9.1,/
     B'                          SENSIBLE    ',F8.1,/
     C'                          LATENT      ',F9.1,/
     D'    AIR FLOW RATE LB/HR - FAN         ',F8.1,/
     E'                          CONDENSER   ',F8.1,/
     F'    CONDENSER COOLANT INLET TEMP      ',F8.2,/
     G'                      OUTLET TEMP     ',F8.2,/
     H'    CONDENSATE FLOW - LB/HR           ',F8.3,/
     I'    CABIN AIR WEIGHT FLOW - LB/HR     ',F8.1,/
     J'    CONDENSER AIR WEIGHT FLOW -LB/HR',F8.1,/
     K'    CONDENSER BYPASS AIR FLOW -LB/HR',F8.1 )
 512  FORMAT(
     2'    SENSIBLE METABOLIC LOAD           ',F8.1,/
     3'    LATENT METABOLIC LOAD             ',F8.1,/
     4'    CONDENSER UA - BTU/HR/DEG F       ',F8.1,/
     5'    TOTAL WATER FROM BEDS LBM         ',F8.3,/
     6'    WVE REQUIRED POWER-KW             ',F8.3)
     END
      SUBROUTINE SAWD1(TCAB,TDPC,QS4,QL4,TSTEP,PC,CFM,Q,RHO2,AHCO,WSAWD,
     1QUAN,TIME)
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      REAL K,MWA,MDA,KA
      KOUNT=0
      K=1.0
      TINC=TIME/60.
      R=10.729
      MWA=28.97
      CPA=.24
      WCPS=31.2
      IF(TINC.LT.49.)ACONST=0.0
      IF(TINC.GE.49.)ACONST=1.0
      IF(TINC.GE.101.0.AND.TINC.LT.145.)ACONST=0.0
      IF(TINC.GE.145.)ACONST=1.0
      IF(TINC.GE.49.0.AND.TINC.LT 145.)KA=KA+1.0*TSTEP/60./5.
      WA=CFM*RHO2*60.
      TINLET=TCAB+Q/WA/.24/(1.+AHCO)
      IF(IKOUNT.EQ.0)CALL KANDK(PC,TBED,1)
      IF(IKOUNT.EQ.0)PSAT2=PC
      IKOUNT=KOUNT+1
      IF(TIME.NE.8700.)GO TO 10
      CALL KANDK(PC,TBED,1)
      KA=0.0
   10 CONTINUE
      IF(TIME.GE.8700.)KA=KA+1.0*TSTEP/60./5.
      IF(KA.GT.1.0)KA=1.0
      CALL KANDK(PSAT1,TDPC,2)
C     WATER FROM BED (LBM/HR)
      IF(PC-PSAT2.LT.6.0)PSAT2=PC-6.0
      MDA=ACONST*CFM*PC*MWA/R/(TINLET)
      DELW=ACONST*MDA*.622*(PSAT2/(PC-PSAT2)-PSAT1/(PC-PSAT1))
     1*TSTEP/60.*K
C     IF(TIME.GT.8634.0.AND.TIME.LT.8700.)WRITE(11,1)MDA,PSAT2,DELW,TIME
    1 FORMAT(2X,4(2X,F10.2))
C     LATENT HEAT FROM BED (BTU/HR)
      QL4=1000.*DELW*3600./TSTEP
C     SENSIBLE HEAT (BTU/HR)
      QS4=MDA*CPA*(TBED-TINLET)*60.
      WWAT=WWAT-DELW
      WCP=WCPS+WWAT
      TBED=TBED-(QL4+QS4)/WCP*TSTEP/3600.
C     IF(TIME.GT.1680.)WRITE(11,222)TBED,QL4,QS4,TIME
  222 FORMAT(2X,4(1X,F10.1))
      CALL KANDK(PSAT2,TBED,2)
      QUAN=QUAN+DELW
      IF(TIME.LT.5760.)QUAN=0.0
      WSAWD=MDA*60.
      IF(WSAWD.EQ.0.0)TOUT=TCAB+Q/(CFM*RHO2*60.)/.24/(1.+AHCO)
      IF(WSAWD.EQ.0.0)WSAWD=CFM*PC*MWA/R/TOUT*60.
      IF(TIME.EQ.8640.0.OR.TIME.EQ.9120.)WRITE(11,2)QL4,TBED,QS4,WSAWD
    2 FORMAT(2X,4(2X,F10.3))
      RETURN
      END
      SUBROUTINE CONDUA(WA,QS,QL,WC,UA)
      DIMENSION HXUA(47)
      DATA HXUA /1.,8.,4.,
     A  250.,500.,750.,1000.,1250.,1500.,1750.,2000.,
     B  475.,600.,950.,1250.,
     C  210.,240.,270.,290.,
     D  360.,390.,420.,440.,
     E  500.,530.,560.,530.,
     F  600.,640.,700.,730.,
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     G  720.,770.,830.,870.,
     H  820.,870.,960.,1010.,
     I  850.,950.,1030.,1100.,
     J  870.,990.,1070.,1130./
C
      WE=WA*(QS+QL)/QS
      CALL BIQUAD(HXUA,1,WE,WC,UA,K)
      RETURN
      END
      SUBROUTINE SAWD2(TCAB,TDPC,QS4,QL4,TSTEP,PC,CFM,Q,RHO2,AHCO,TIME,
     1WSAWD,QUAN)
      REAL K,MWA,MDAA,MDAB,KA,KB
      KOUNT=0
      IF(IKOUNT.EQ.0)KA=0.0
      IF(IKOUNT.EQ.0)KB=0.0
      K=1.0
      TINC=TIME/60.
      R=10.729
      MWA=28.97
C    ACONST OR BCONST =1 MEANS AIR IS FLOWING THRU BED A OR B
      IF(TINC.LT.29.)ACONST=0.0
      CPA=.24
      WCPS=12.95
      IF(TINC.GE.29.)ACONST=1.0
      IF(TINC.GE.29.0.AND.TINC.LT.125.)KA=KA+1.0*TSTEP/60./5.
      IF(TINC.LT.53.)BCONST=0.0
      IF(TINC.GE.101.0.AND.TINC.LT.125.)ACONST=0.0
      IF(TINC.GE.53.)BCONST=1.0
      IF(TINC.GE.53.0.AND.TINC.LT.149.)KB=KB+1.0*TSTEP/60./5.
      IF(TINC.GE.125.)ACONST=1.0
      IF(TINC.GE.125.0.AND.TINC.LE.149.)BCONST=0.0
      IF(TINC.GE.149.)BCONST=1.0
      CFMA=ACONST*CFM
      CFMB=BCONST*CFM
      AWA=(43.)*RHO2*60.
      BWA=(43.)*RHO2*60.
      TINA=TCAB+Q/AWA/.24/(1.+AHCO)
      TINB=TCAB+Q/BWA/.24/(1.+AHCO)
      IF(IKOUNT.EQ.0)CALL KANDK(PC,TBEDA,1)
      IF(IKOUNT.EQ.0)CALL KANDK(PC,TBEDB,1)
      IKOUNT=KOUNT+1
      IF(TIME.NE.7500.) GO TO 11
      CALL KANDK(PC,TBEDA,1)
      KA=0.0
      PA=PC
   11 IF(TIME.NE.8940.) GO TO 10
      CALL KANDK(PC,TBEDB,1)
      KB=0.0
      PB=PC
   10 CONTINUE
C   SAWD VALVE OPENS IN 2 MINUTES--SLOW MODULATION
      IF(TIME.GE.7500.)KA=KA+1.0*TSTEP/60./5.
      IF(TIME.GE.8940.)KB=KB+1.0*TSTEP/60./5.
      IF(KA.GT.1.0)KA=1.0
      IF(KB.GT.1.0)KB=1.0
      CALL KANDK(PSAT1,TDPC,2)
      IF(PC-PA.LT.5.0)PA=PC-5.0
      IF(PC-PB.LT.5.0)PB=PC-5.0
      MDAA=CFMA*PC*MWA/R/TINA
      MDAB=CFMB*PC*MWA/R/TINB
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C     WATER FROM BEDS (LBM/TIME-STEP)                                   00005170
      DELWA=ACONST*MDAA*.622*(PA/(PC-PA)-PSAT1/(PC-PSAT1))*TSTEP/60.*K  00005180
C     IF(TIME.GT.1680.)WRITE(11,242)MDAA,PA,PC,DELWA,TIME               00005190
  242 FORMAT(2X,5(1X,F11.2),2X,F12.4)                                   00005200
      DELWB=BCONST*MDAB*.622*(PB/(PC-PB)-PSAT1/(PC-PSAT1))*TSTEP/60.*K  00005210
      IF(DELWA.LT.0.0)DELWA=0.0                                         00005220
      IF(DELWB.LT.0.0)DELWB=0.0                                         00005230
C     LATENT HEAT FROM BEDS (BTU/HR)                                    00005240
      QL4A=1000.*DELWA*3600./TSTEP                                      00005250
      QL4B=1000.*DELWB*3600./TSTEP                                      00005260
C     SENSIBLE HEATS (BTU/HR)                                           00005270
      QS4A=ACONST*MDAA*CPA*(TBEDA-TINA)*60.                             00005280
      QS4B=BCONST*MDAB*CPA*(TBEDB-TINB)*60.                             00005290
      WWATA=WWATA-DELWA                                                 00005300
      WWATB=WWATB-DELWB                                                 00005310
      WCPA=WCPS+WWATA                                                   00005320
      WCPB=WCPS+WWATB                                                   00005330
      TBEDA=TBEDA-(QL4A+QS4A)/WCPA*TSTEP/3600.                          00005340
C     IF(TIME.GE.1680.)WRITE(11,242)TBEDA,TBEDB,QL4A,QS4A,PA            00005350
      TBEDB=TBEDB-(QL4B+QS4B)/WCPB*TSTEP/3600.                          00005360
      QL4=QL4A+QL4B                                                     00005370
      QS4=QS4A+QS4B                                                     00005380
      CALL KANDK(PA,TBEDA,2)                                            00005390
      CALL KANDK(PB,TBEDB,2)                                            00005400
      WSAWD=(MDAA+MDAB)*60.+(50.-(ACONST+BCONST)*CFM)*PC*MWA/R/TCAB*60. 00005410
      DELW=DELWA+DELWB                                                  00005440
      QUAN=QUAN+DELW                                                    00005450
      IF(TIME.LT.5670.)QUAN=0.0                                         00005460
      IF(TIME.EQ.7440.0.OR.TIME.EQ.9120.)WRITE(11,2)QL4A,QL4B,TBEDA,    00005462
     1TBEDB,QS4A,QS4B,MDAA,MDAB                                         00005464
    2 FORMAT(2X,4(2X,F10.3),/2X,4(2X,F10.3))                            00005466
      RETURN                                                            00005470
      END                                                               00005480
      SUBROUTINE QMET(TCAB,QSM,QLM)                                     00005490
      COMMON /YY/ X(500),QS1,QL1                                        00005500
      COMMON /SK/SKCARD(20,400),SKDATA(8000),ICARD(12,400),LSK,MSK      00005510
      EQUIVALENCE (X(10),QMNOM),(X(11),QMMAX),(X(43),XMNOM),            00005520
     2 (X(44),XMMAX)                                                    00005530
C        NOMINAL LATENT/MAN                                             00005540
      QLNOM=QMNOM-430.+(10.+QMNOM/1000.)*(TCAB-60.)                     00005550
      IF(QLNOM.GT.QMNOM) QLNOM=QMNOM                                    00005560
      QLNMIN=.22*QMNOM+2.6*(TCAB-60.)                                   00005570
      IF(QLNMIN.GT.QLNOM) QLNOM=QLNMIN                                  00005580
C        MAXIMUM LATENT/MAN                                             00005590
      QLMAX=QMMAX-430.+(10.+QMMAX/1000.)*(TCAB-60.)                     00005600
      IF(QLMAX.GT.QMMAX) QLMAX=QMMAX                                    00005610
      QLMMIN=.22*QMMAX+2.6*(TCAB-60.)                                   00005620
      IF(QLMMIN.GT.QLMAX) QLMAX=QLMMIN                                  00005630
C        TOTAL LATENT LOAD                                              00005640
      QLM=XMNOM*QLNOM+XMMAX*QLMAX                                       00005650
      QLM=IFIX(QLM+.5)                                                  00005660
C         TOTAL METABOLIC LOAD                                          00005670
      QTM=XMNOM*QMNOM+XMMAX*QMMAX                                       00005680
C          TOTAL SENSIBLE LOAD                                          00005690
      QSM=QTM-QLM                                                       00005700
      RETURN                                                            00005710
      END                                                               00005720
      SUBROUTINE WVE(TSTEP,T,PXI,P,DPEXIT,T2,VDOT,EV,TIME,POWER,DP,     00005730
     1AWVEX)                                                            00005735
C     WATER VAPOR ELECTROLYSIS FOR LARS                                 00005740
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SVHSER 7224

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      DIMENSION VOLTS(51),VPRESS(38)
      DATA VOLTS/1.,6.,6.,42.,50.,54.,56.,58.,64.,1.6,1.7,1.8,1.85,
     11.875,1.9,1.55,3.45,5.2,6.2,7.05,7.35,1.95,4.2,6.90,7.05,8.10,
     19.45,2.15,4.9,7.64,
     29.0,9.7,10.5,2.25,5.15,8.04,9.5,10.12,11.05,2.37,5.42,8.42,10.0,
     310.58,11.6,2.70,6.25,9.63,11.47,11.89,13.28/
      DATA VPRESS/1.,5.,5.,60.,70.,80.,90.,100.,55.,60.,65.,70.,75.,
     13.3,2.14,1.2,.525,.205,4.75,3.2,1.75,.79,.31,6.8,4.4,2.5,
     21.18,.46,9.5,6.2,3.6,1.68,.68,13.5,8.7,5.0,2.4,1.0/
      IF(TIME.NE.0.0)GO TO 5
      EV=0.0
      T21=T-460.
      TE1=T-460.
      H2OMTX=.1946
      ICOUNT=0
      O2=0.0
    5 CONTINUE
      IF(TIME.GE.300.) O2=5.41
      CELLS=15.
      T=T-460.
      TCN=3480.
      TEND=5760.
      CALL KANDK(PXI,DP,1)
      IF(TIME.GT.3480.)O2=0.0
      IF(TIME.GE.6060.0.AND.TIME.LE.9240.)O2=5.41
      IF(TIME.GE.6060.0.AND.TIME.LE.9240.)EV=1.[illegible].
      IF(TIME.GT.9240.)O2=0.0
C     OXYGEN PRODUCTION REQUIRED PER HOUR
      O2PROD=O2*4./53.
C     WATER CONSUMED PER TIME STEP PER CELL
      H2OCON=1.152*O2PROD*TSTEP/3600./CELLS
      AMPS=O2PROD*1519.3
      DPDEGR= DP
C     DETERMINE H2O PARTIAL PRESSURE IN INCOMING AIR STREAM
      CALL KANDK(PPH2OI,DPDEGR,2)
      PPH2OI=PPH2OI*51.7
      IF(TIME.EQ.0.0)PPMTX=PPH2OI
      VH2OV=PPH2OI/P*VDOT
      TDEGR=T+460.
C     WATER VAPOR IN INCOMING AIR (LBM/MIN)
      H2OVI=1.678*P*VH2OV/TDEGR
      IF(O2.EQ.0.0) GO TO 2
      KOUNT=0
      DPFAKE=DPFAKE-460.
C     ITERATION ON REQUIRED CELL VOLTAGE
      IF(PFAKE.EQ.0.0)GO TO 2
    1 KOUNT=KOUNT+1
      IF(KOUNT.GT.101) GO TO 2
      CALL BIQUAD(VOLTS,1,DPFAKE,EV,OGUESS,K)
      OGUES=CELLS/10.*OGUESS
      IF((OGUES-O2).GT.0.05)EV=EV-.002
      IF((OGUES-O2).GT.0.05)GO TO 1
      IF((OGUES-O2).LT.-0.05)EV=EV+.002
      IF((OGUES-O2).LT.-0.05) GO TO 1
    2 CONTINUE
      ENCP=.2875*CELLS
      Q=3.41*AMPS*(EV-1.256)
      RE=10.9*P*VDOT/CELLS*(460./TDEGR)**1.65
      HBARL=8.E-05*RE*(9.5-RE**.3)+.315*RE**.3
      PHI=.3125/(HBARL*CELLS)+6.65/(P*VDOT)
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C     CALCULATING ELECTRODE TEMPERATURE
      IF(TIME.NE.0.0)TE2=TE1+2.76E-04/EMCP*(Q-(TE1-T)/PHI)
      THETA=.043/(TDEGR)**.275*SQRT(CELLS*VDOT/P)
      DELP=PPH2OI-PPMTX
C     WATER VAPOR ABSORBED BY CELLS (LBM/TSTEP)
      H2OABS=2.717E-04*DELP*TSTEP/60.
      H2ODEL=H2OCON-H2OABS
      H2OMTX=H2OMTX-H2ODEL
C     WEIGHT PERCENT OF SULFURIC ACID IN CELLS
      WH2SO4=.2853/(.2853+H2OMTX)*100.
      PMTX=PPMTX
      CALL BIQUAD(VPRESS,1,TE2,WH2SO4,PPMTX,K)
C
C     STEADY STATE MATRIX PARTIAL PRESSURE
C
      PMTXSS= PPH2OI-1.183E-03*AMPS*SQRT(P)
      PFAKE=(PPH2OI+  PFMTX-PMTXSS )/51.7
      IF(AMPS.NE.0.0) CALL KANDK(PFAKE,DPFAKE,1)
C     AIR CELL EXIT TEMPERATURE
      IF(TIME.NE.0.)T22=T21+3.7E-03/(P*VDOT*EMCP*PHI)*(Q-(TE1-T)/PHI)
      IF(TIME.EQ.0.0)TE2=TE1
      TE1=TE2
      IF(TIME.EQ.0.0)T22=T21
      T21=T22
      T2=T22+460.
      T=T+460.
C     EXIT AIR PARTIAL PRESSURE AND DEWPOINT
      PPH2OX=(PPH2OI-TDEGR/(1.95*VDOT)*THETA*(PPH2OI-PMTX))/51.7
      IF(TIME.EQ.0.0)PPH2OX=PPH2OI/51.7
      CALL KANDK(PPH2OX,DPEXIT,1)
      AWVEX=.622*PPH2OX/(PC-PPH2OX)
      IF(O2.EQ.0.0)EV=0.0
C   WVE POWER REQUIREMENTS
      POWER=EV*CELLS*AMPS/1000.
      RETURN
      END
```