Space Station Evolution Study
Oxygen Loop Closure

Final Report

by

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This document was revised to include customer comments. Changes were:
1. Update of the TOC (pgs 3 & 4)
2. Editorial changes to the Introduction (pg 5)
3. Modification to Figure 2-5 (pg 11)
4. Addition of text in section 3.5.1 (affected pgs 23 & 26)
5. Inclusion of Figure 3-7 (pg 25.1)
6. Inclusion of Figure 3-8 (pg 25.2)
7. Inclusion of Figure 3-9 (pg 25.3)

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TABLE OF CONTENTS

SECTION **PAGE**

TITLE PAGE 1
NOTICES 2
TABLE OF CONTENTS........ 3

1. **INTRODUCTION** 5

2. **MASS BALANCE**........ 6
2.1 STUDY OVERVIEW (Subtask 5.2.1.1)........ 6
2.2 OXYGEN REQUIREMENTS........ 6
2.3 CARBON DIOXIDE LOAD REQUIREMENTS........ 14
2.4 WATER DEMAND REQUIREMENTS FOR ELECTROLYSIS........ 14
2.5 VENTING BYPRODUCTS........ 14
2.6 WATER AVAILABLE TO PAYLOADS........ 14
2.7 STUDY RESULTS (Subtask 5.2.1.1)........ 14

3. **SCARRING OPTIONS**........ 17
3.1 STUDY OVERVIEW (Subtask 5.2.1.2) 17
3.2 LAB A INSTALLATION........ 17
3.2.1 Convert AR Open Loop Rack to Closed Loop........ 17
3.2.2 Replace Open Loop AR Rack with Closed Loop Rack........ 17
3.2.3 Provide Separate Rack at PMC with Closure Hardware........ 17
3.2.4 Closed Loop Hardware as ORUs in other Racks/Standoffs........ 19
3.3 HAB A INSTALLATION........ 19
3.3.1 Convert AR Open Loop Rack to Closed Loop........ 19
3.3.2 Replace Open Loop AR Rack with Closed Loop Rack........ 19
3.3.3 Closed Loop Hardware as ORUs in other Racks/Standoffs........ 19
3.3.4 Provide Hab A with Closed Oxygen Loop as Original Equipment........ 23
3.4 EVALUATION OF HOOKS........ 23
3.5 EVALUATION OF SCARS........ 23
3.5.1 Scars Required in Lab A to Accommodate the OGA and Sabatier CReA.... 23
3.5.2 Scars Required in Hab A to Accommodate the OGA and Sabatier CReA.... 23
3.5.3 Rack Scarring........ 26
3.6 SINGLE STRING OXYGEN LOOP CLOSURE........ 26
3.7 STUDY RESULTS (Subtask 5.2.1.2)........ 26

4. **VENTING CONSIDERATIONS**........ 27
4.1 STUDY OVERVIEW (Subtask 5.2.1.3)........ 27
4.2 SABATIER VENTING........ 27
4.2.1 Sabatier Venting Contamination Effects........ 27
4.2.2 Sabatier Vent Locations........ 28
4.3 OXYGEN GENERATOR VENTING........ 28
4.3.1 Oxygen Generation Venting Contamination Effects........ 29
4.3.2 Oxygen Generation Vent Locations........ 29
4.4 STUDY RESULTS (Subtask 5.2.1.3)........ 30

5. **TOPOLOGY AND PACKAGING (Subtask 5.2.1.4)**........ 31
5.1 STUDY OVERVIEW (Subtask 5.2.1.4)........ 31

TABLE OF CONTENTS (Continued)

SECTION PAGE

5.2 TOPOLOGY AND PACKAGING 31
5.3 WEIGHT, VOLUME AND COST IMPACTS FOR SCARRING 31
5.4 STUDY RESULTS (Subtask 5.2.1.4) 31

6. VERIFICATION (Subtask 5.2.1.5) 34
6.1 STUDY OVERVIEW (SUBTASK 5.2.1.5) 34
6.2 TEST AND VERIFICATION CONSIDERATIONS 34
6.2.1 Lab A ETA 34
6.2.2 Lab A Flight Article 34
6.2.3 ETA (pre Permanent Human Capability) 34

7. SUMMARY AND RECOMMENDATIONS 36

LIST OF FIGURES

2-1 CREW METABOLIC BALANCE 7
2-2 SSF PMC MASS BALANCE 8
2-3 O2, CO2 & H2O BALANCE (4 Crew and Animals) 9
2-4 NOMINAL O2 REQUIREMENT FOR OGA (OGA and Sabatier Configuration) 10
2-5 NOMINAL O2 REQUIREMENT FOR OGA (OGA and Bosch Configuration) 11
2-6 LCC Comparison 12
3-1 SSF BASELINE AR RACK - FRONT VIEW 18
3-2 CONCEPT LAYOUT-CLOSED LOOP OXYGEN IN LAC-6 20
3-3 CONCEPT LAYOUT-CO2 ACCUMULATOR TANKS IN STANDOFF X-1 21
3-4 CONCEPT LAYOUT-CO2 ACCUMULATOR TANKS IN LAF-1 22
3-5 OGA RACK FUNCTIONAL INTERCONNECT DIAGRAM 24
3-6 OGA AND SABATIER RACK FUNCTIONAL INTERCONNECT DIAGRAM 25
3-7 ISPR RACK INTERFACES 25.1
3-8 U.S. LAB-A AR EXORACK FID WITH SCARS 25.2
3-9 U.S. LAB-A WRM EXORACK FID WITH SCARS 25.3

LIST OF TABLES

2-I NOMINAL OXYGEN REQUIREMENTS 13
2-II WATER DEMAND 15
4-I RESULTS OF VENT EVALUATION 30
5-I SCAR IMPACT ASSESSMENT 32

SECTION 1, INTRODUCTION

In the current Space Station Freedom (SSF) Permanently Manned Configuration (PMC), physical scars for closing the oxygen loop by the addition of oxygen generation and carbon dioxide reduction hardware are not included. During station restructuring, the capability for oxygen loop closure was deferred to the B-modules. As such, the ability to close the oxygen loop in the U.S. Laboratory module (LAB A) and the Habitation A module (HAB A) is contingent on the presence of the B modules. To base oxygen loop closure of SSF on the funding of the B-modules may not be desirable. Therefore, this study was requested to evaluate the necessary hooks and scars in the A-modules to facilitate closure of the oxygen loop at or subsequent to PMC. The study defines the scars for oxygen loop closure with impacts to cost, weight and volume and assesses the effects of byproduct venting. In addition, the recommended scenarios for closure with regard to topology and packaging will be presented.

SECTION 2, MASS BALANCE

2.1 STUDY OVERVIEW (Subtask 5.2.1.1)

The objective of this task was to determine the need for carbon dioxide reduction based on the Space Station water mass balance. The mass balance was performed for the following four configurations:

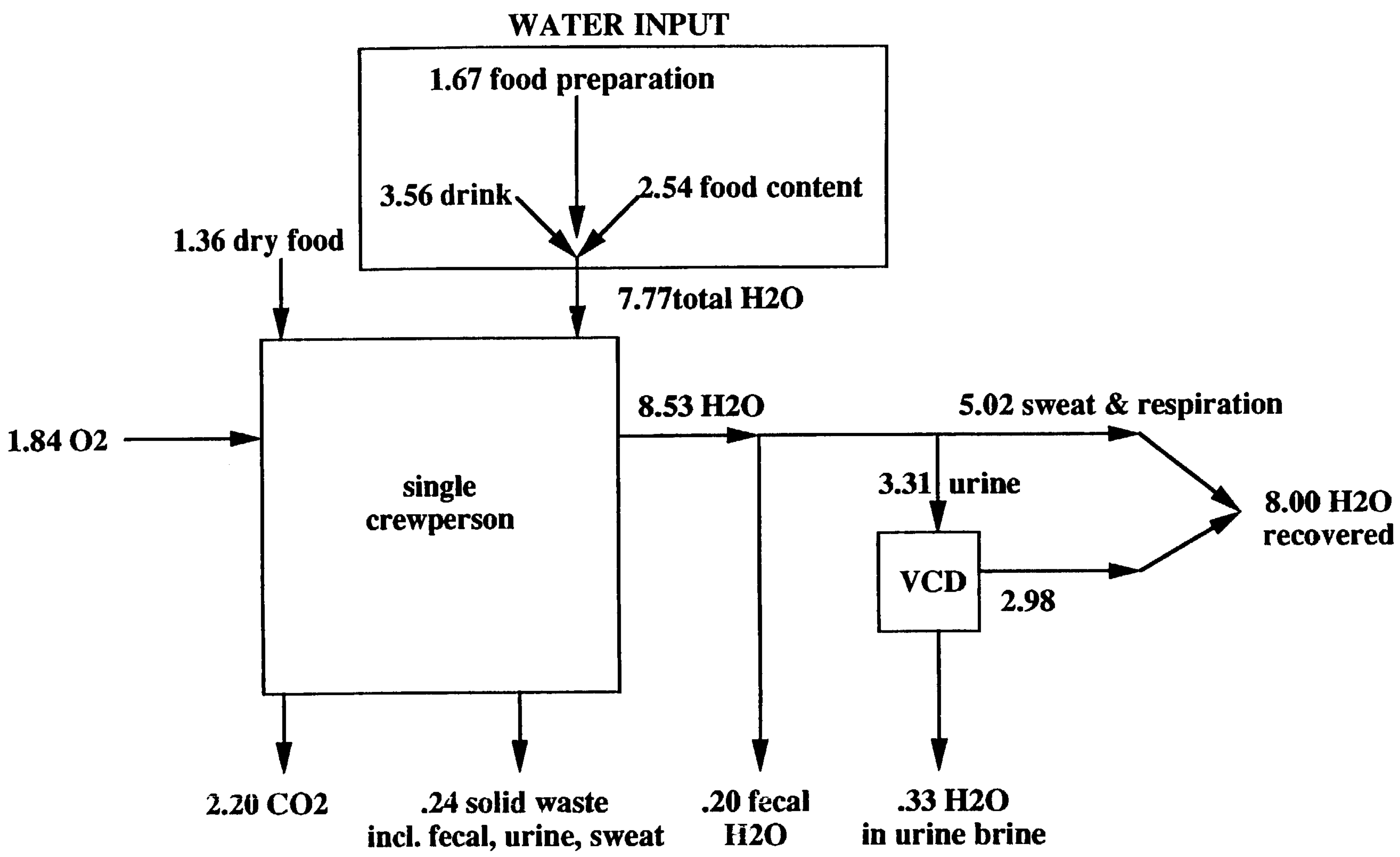
1) oxygen resupply, no oxygen generator
2) oxygen generation, minimal oxygen resupply for EVA activities, no CO2 reduction
3) oxygen generation and Sabatier CO2 reduction
4) oxygen generation and Bosch CO2 reduction

The mass balance was based on PMC Space Station Freedom requirements. Figure 2-1 depicts the metabolic balance for a single crew member, while Figure 2-2 provides the overall SSF PMC mass balance. The mass balance shown in Figure 2-3 establishes the O2, CO2 and H2O balance for 4 crew members and animals. Finally, Figures 2-4 and 2-5 provide the CO2, H2O and O2 balance for the oxygen loop closure configurations of Sabatier and Bosch, respectively.

A separate study was conducted to trade various oxygen supply configurations. The configurations traded consisted of various combinations of cryogenic O2/N2, high pressure O2/N2 and oxygen generation by water electrolysis supplemented with high pressure O2. This study is referenced here as it indicates a clear program savings in providing an onboard oxygen generator. Figure 2-6 provides a summary of the overall program savings for Option 3 which includes an Oxygen Generator Assembly (OGA). The acquisition costs and life cycle costs for the OGA traded in this reference study included costs associated with modifying the OGA to operate on a dayside/nightside basis. Options 1, 1a and 2 represent various configurations of high pressure gas and cryogenic gas without oxygen generation.

2.2 OXYGEN REQUIREMENTS

To determine the water balance, it is first necessary to establish the O2 requirements for the OGA. Using the ECLSS ACD SSP 30262 requirements, the necessary oxygen production rate for the OGA can be calculated. A breakdown of the constituents which makeup the O2 requirements are given in Table 2-I. Table 2-I provides the total O2 requirements and delineates which portion of the Station requirements would be handled by the OGA and which portion would be handled by the Atmosphere Control and Supply (ACS) system. The O2 provided by the ACS is that which is either high pressure oxygen (e.g., EMU support) or high rate oxygen(e.g., prebreath). For this study it is assumed that the OGA will only provide oxygen at near atmospheric pressure (current OGA baseline). The O2 requirements given in Table 2-I are based on 2.56 lb/d recovered from EVA activities, one EVA per week and a Station leakage rate of 0.5 lb/d per element. From these requirements, the nominal O2 production rate can be established at 8.98 lb/d. This is the value which is used for the remaining trades in this task.



source: SSP 30262 'standard man'
all units are pounds mass per day

FIGURE 2-1 CREW METABOLIC BALANCE

All Values are Nominal lbs/day for a Crew of Four
Includes Average Daily Contribution of (13) 6 hr/2 man EVAs per 90 day Mission

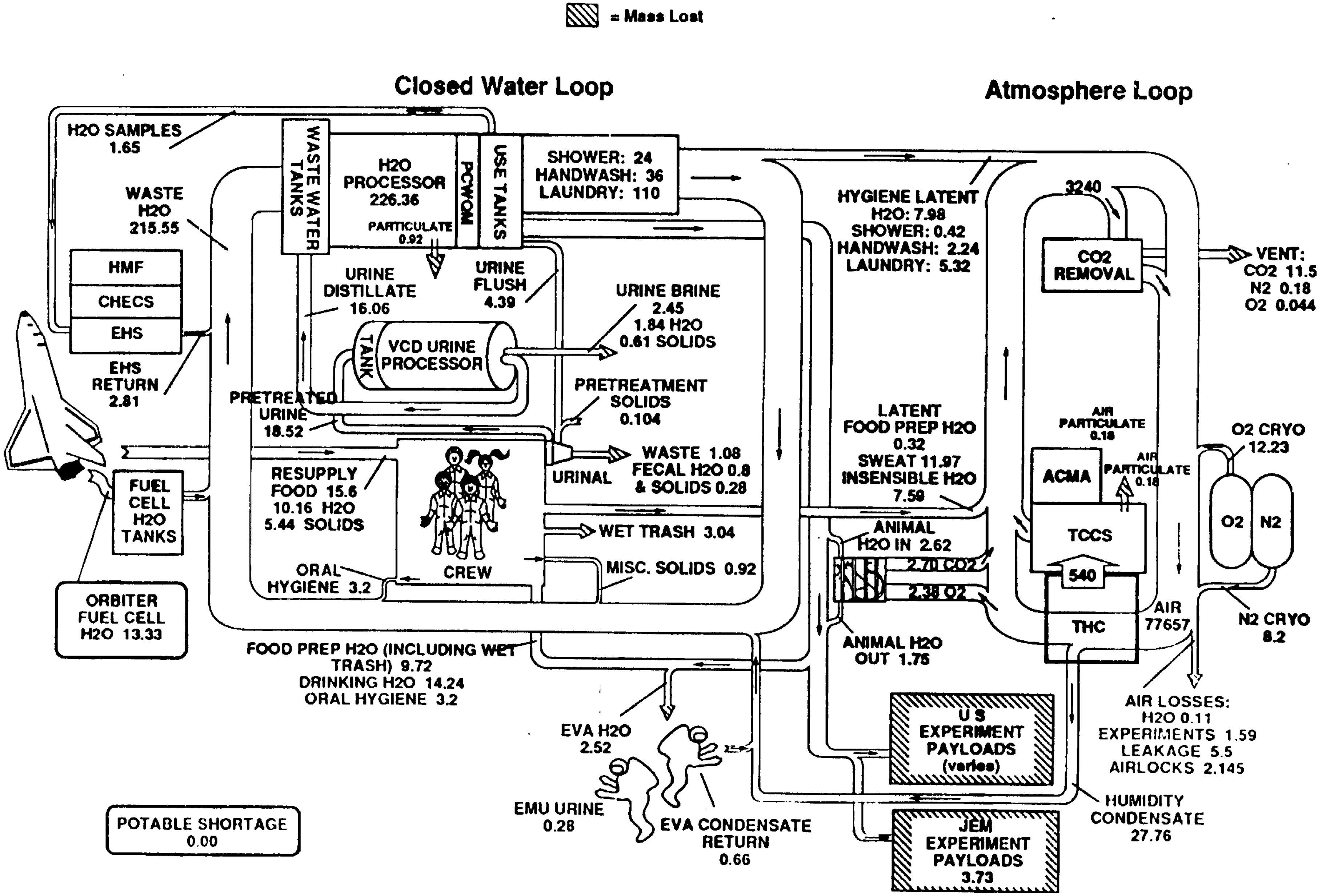
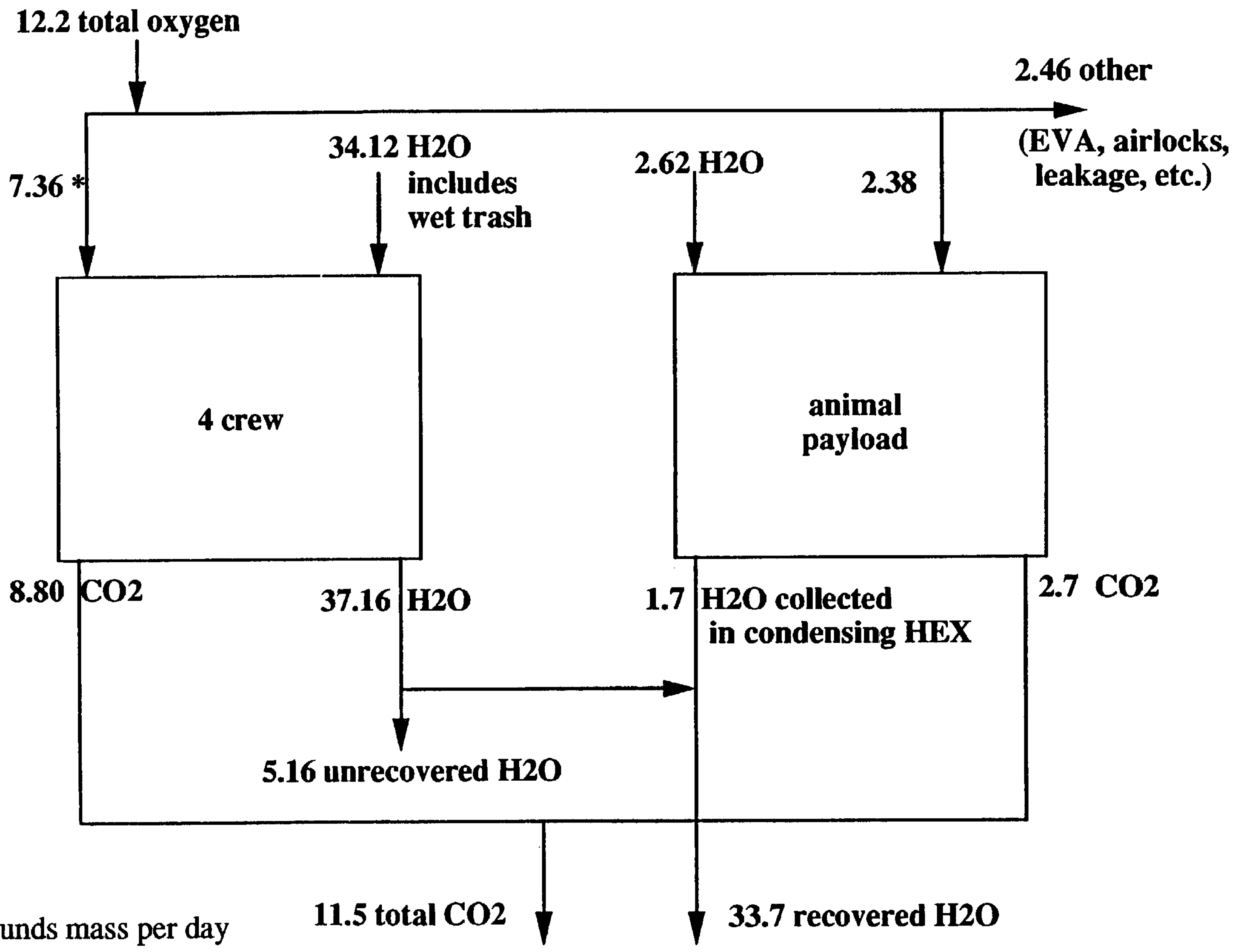


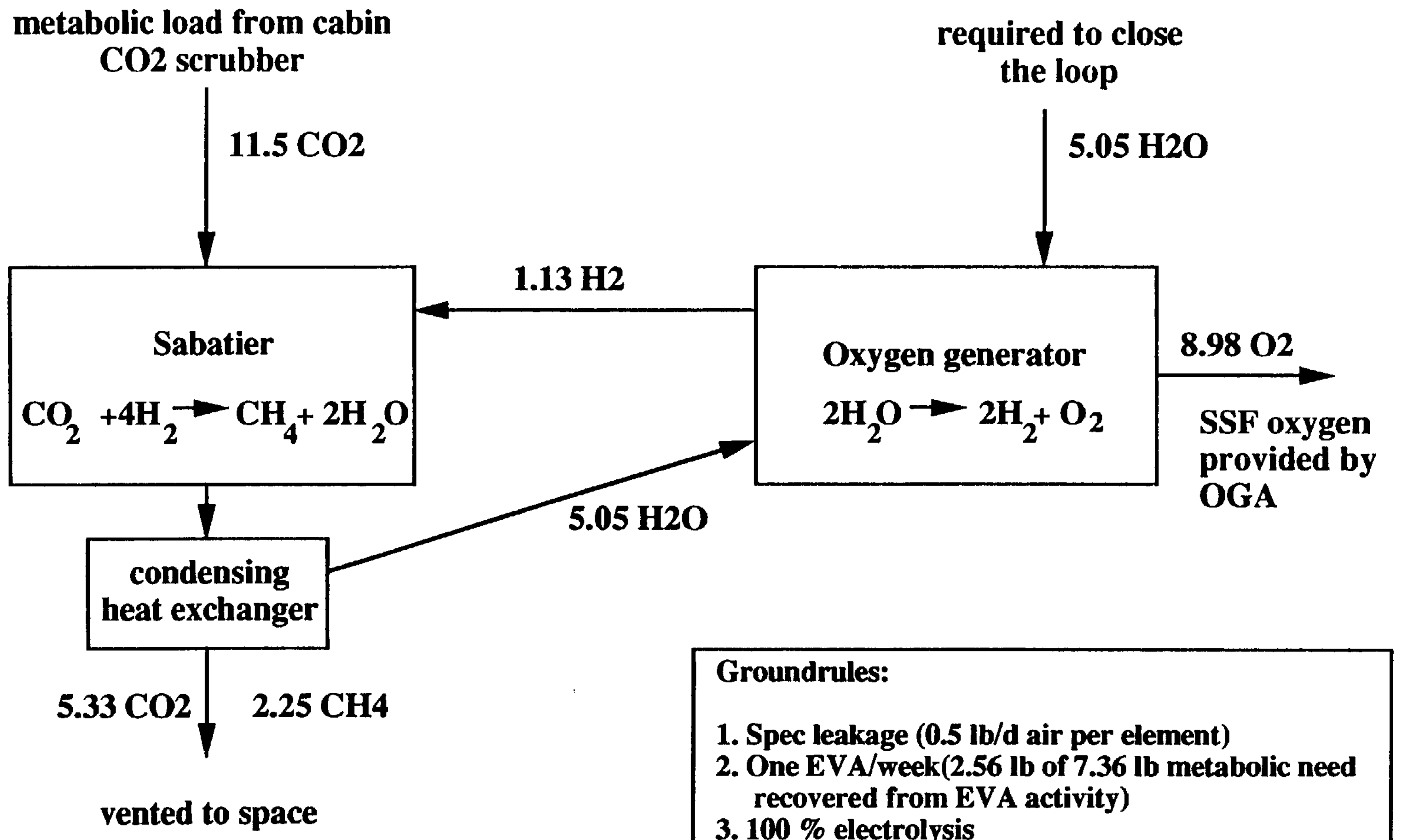
FIGURE 2-2 SSF PMC MASS BALANCE



all units are pounds mass per day

* 2.56 lb/d recovered from EVA activities

FIGURE 2-3 O2, CO2 & H2O BALANCE
4 CREW AND ANIMALS

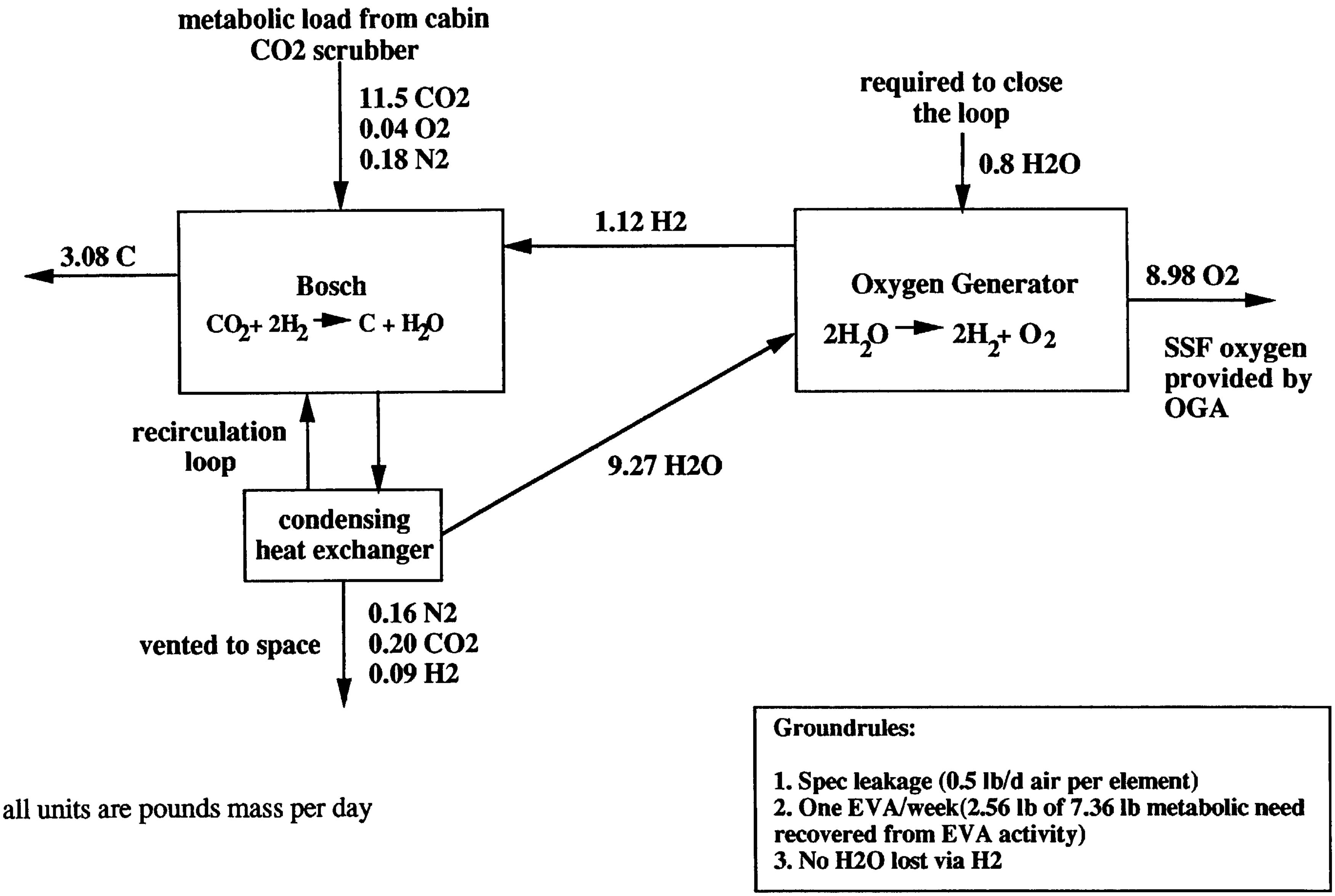


Groundrules:

1. Spec leakage (0.5 lb/d air per element)
2. One EVA/week(2.56 lb of 7.36 lb metabolic need recovered from EVA activity)
3. 100 % electrolysis
4. 100 % Sabatier conversion
5. No H2O lost via H2 or CH4/CO2 vent

all units are pounds mass per day

FIGURE 2-4 NOMINAL O2 REQUIREMENT FOR OGA OGA & SABATIER CONFIGURATION

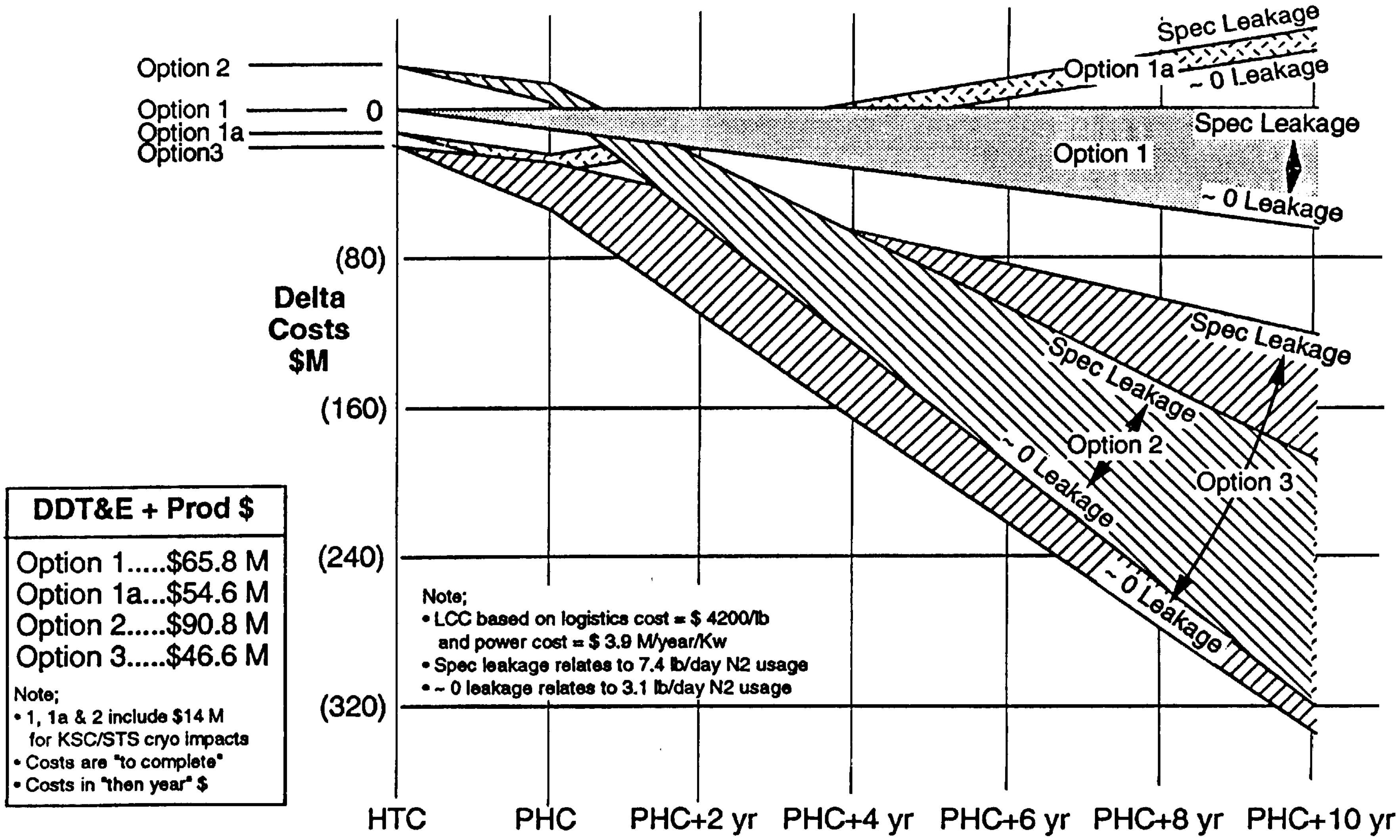


Groundrules:

1. Spec leakage (0.5 lb/d air per element)
2. One EVA/week(2.56 lb of 7.36 lb metabolic need recovered from EVA activity)
3. No H2O lost via H2

all units are pounds mass per day

FIGURE 2-5 NOMINAL O2 REQUIREMENT FOR OGA OGA & BOSCH CONFIGURATION



DDT&E + Prod $

Option 1.....$65.8 M
Option 1a...$54.6 M
Option 2.....$90.8 M
Option 3.....$46.6 M

Note;
- 1, 1a & 2 include $14 M for KSC/STS cryo impacts
- Costs are "to complete"
- Costs in "then year" $

Note;
- LCC based on logistics cost = $ 4200/lb and power cost = $ 3.9 M/year/Kw
- Spec leakage relates to 7.4 lb/day N2 usage
- ~ 0 leakage relates to 3.1 lb/day N2 usage

FIGURE 2-6 LCC COMPARISON

TABLE 2-I NOMINAL OXYGEN REQUIREMENTS

OGA Provided		**ACS Provided**	
O2 Rqmnt	Qty, lbm/d	O2 Rqmnt	Qty, lbm/d
Leakage	1.16	Prebreath	1.37
Experiment Ingestion	0.37	WRM	0.10
CO2 removal	0.11	EMU	0.81
PLM docking	0.01	EMU purge	0.12
Crew docking	0.07	HPGCA campout	0.68
Orbiter docking	0.06	HECA vent	0.02
JEM airlock	0.02	EMU checkout	0.10
Metabolic, human	4.80	**Total ACS provided =**	**3.20**
Metabolic, animal	2.38		
Total OGA provided =	**8.98**		

Total O2 requirement = 12.18 lb/d

Notes: 1. Total human metabolic load of 7.36 lb/d includes O2 recovered from EVA activities of 2.56 lb/d based on one EVA per week.

2. O2 lost during EVA activities = 0.61 lb/d

2.3 CARBON DIOXIDE LOAD REQUIREMENTS

The metabolic rates for carbon dioxide are also given in SSP 30262 and are shown in Figure 2-3 for a crew of four plus animals. The total CO2 load is established as 11.5 lb/d.

2.4 WATER DEMAND REQUIREMENTS FOR ELECTROLYSIS

Once the oxygen requirement for the OGA is defined, then it becomes straight forward in determining the OGA water feed requirement to meet the necessary O2 production requirements. The total water demand for an oxygen production rate of 8.98 lb/d is 10.1 lb/d. This water feed rate requirement assumes 100 % electrolysis and no water loss via humidification of the hydrogen byproduct. The water needed to generate 8.98 lb/d oxygen is reduced to 5.05 lb/d with Sabatier CO2 reduction and is reduced to 0.8 lb/d with Bosch CO2 reduction as shown in Figures 2-4 and 2-5, respectively. Note that the mass balance indicates that there is sufficient water available to support all O2 metabolic needs even without CO2 reduction. The presence of CO2 reduction only serves to increase the amount of excess water available to the payloads. This excess water availability is predicated on the availability of 13.33 lb/d fuel cell water. This value equates to 1200 lb of fuel cell water being provided every 90 days. The 1200 lbs also equates to the capacity of the SSF storage tank which is required by the ECLSS ACD 30262.

2.5 VENTING BYPRODUCTS

The quantity and type of byproducts vented for various configurations are given in Table 2-II. Venting considerations are addressed in Section 4 of this study.

2.6 WATER AVAILABLE TO PAYLOADS

From the overall SSF mass balance, the excess water available to payloads can be calculated. The water required for OGA electrolysis is then subtracted from the total water available to determine the remaining water available for payloads. Currently, there is no requirement that definitively states how much water is required to be provided to the payloads. Revision D of SSP 30262 stated that 0 to 18.2 lb/d of water shall be provided to the payloads. The Revision E draft only requires that excess water be provided to payloads. Table 2-II provides a summary of the excess water which will be available to payloads for the various configurations of O2 carrier supply, OGA only, OGA and Sabatier, and OGA and Bosch. It is noted again that there is no water shortfall without CO2 reduction capability, if 1200 lb of fuel cell water is available every 90 days.

2.7 STUDY RESULTS (Subtask 5.2.1.1)

The results of this task are summarized as follows:

1) The mass balance reveals that there is sufficient water available (assuming 13.3 lb/d shuttle fuel cell water) to meet the oxygen demands of the crew and animals even

TABLE 2-II WATER DEMAND

	PMC SSF crew requirements w/ O_2 resupply	Same, except OGA *	Same, except OGA & Sabatier *	Same, except OGA & Bosch *
Crew O_2 req't, lb/day	7.4	7.4	7.4	7.4
Total O_2 requirement lb/day	12.2	8.98	8.98	8.98
H_2O needed to generate O_2, lb/day	0	10.1	5.05	0.8
H_2O available to all payloads	19.79	9.69	14.74	18.99
H_2O available to payloads in addition to animals **	18.87	8.77	13.82	18.07
$CO_2/CH_4/H_2$ vented, lbm/day	11.5 / 0 / 0	11.5 / 0 / 1.13	3.33/ 2.25 / 0	0 / 0 / 0.09

* O_2 resupply necessary for 3.22 lb/d O_2 (EVA activities)
** animals require 2.62 lb/day H_2O but 1.7 lb/day is recovered

Assumptions: 13.33 lb/day H_2O average from shuttle fuel cells without the CO2 reduction hardware. As there are no definitive requirements for the quantity of water necessary to support payloads, it is difficult to justify the need for CO2 reduction. If a firm requirement for payload water is given in the future, then the need for CO2 reduction hardware can be assessed on the basis of comparing the cost to resupply the shortfall of payload water (if any) versus the cost of including a Sabatier or Bosch in the program. If water resupply cost is significantly greater than the the Sabatier/Bosch cost, then the need for these technologies may be justified and the scarring should be evaluated.

2) There is a clear cost advantage to using an oxygen generator on board SSF at PMC as shown in Figure 2-6.

3) It appears that the Bosch CO2 reduction technology offers no logistics cost advantage as compared to the Sabatier as the added cannister resupply mass exceeds the water resupply mass saved. Consequently, the Bosch technology will not be addressed further in this study.

4) Based on the data generated in this task, it is recommended that the SSF be scarred for inclusion of an oxygen generator as a minimum. It is also recommended that firm requirements for fuel cell water availability and payload water requirements be established so that the optimum configuration can be determined.

SECTION 3, SCARRING OPTIONS

3.1 STUDY OVERVIEW (Subtask 5.2.1.2)

The objective of this task was to define the options for scarring to include oxygen generation and carbon dioxide reduction subsystems (if required) into each open loop Atmosphere Revitalization (AR) string. Options should include, but not limited to : flying a replacement AR closed-loop rack, scarring the PMC AR rack locations for eventual closure; flying a separate rack at PMC with closure hardware (CReA, OGA and CO2 accumulator) to be interfaced with existing on-orbit open loop AR racks. Hooks and scars are to be defined for each option.

3.2 LAB A INSTALLATION

3.2.1 *Convert AR Open Loop Rack to Closed Loop*

Rack LAF-6, the AR open loop rack, currently houses the Carbon Dioxide Removal Assembly (CDRA) configured for open loop operation with a dedicated vent to vacuum, the Major Constituent Analyzer (MCA) with its connection to the sample delivery system, the Trace Contaminant Control Subassembly (TCCS), an Avionics Air Assembly/Rack Essentials Package (AAA/REP) and a Remote Power Distribution Assembly (RPDA). The requirement to house the AAA/REP, generated by the change from centralized to distributed avionics air, necessitated relocating the resident Multiplexer-demultiplexer (MDM) from the rack to the aft endcone because of the high packaging density in the rack. Figure 3-1 depicts the current packaging layout of the open loop rack which is based on CDR drawings. Figure 3-1 does not include interconnect plumbing or avionics air ducting. Reexamination of the rack packaging yields the conclusion that there is no room for installation of the Oxygen Generation Assembly (OGA), Sabatier Carbon Dioxide Reduction Assembly (CReA) or the CDRA open-to-closed loop conversion kit (consisting of two cubic feet of tankage and appropriate valving). Nor is there room to package just the OGA.

3.2.2 *Replace Open Loop AR Rack with Closed Loop Rack*

Following the discussion above, the same constraints would apply to providing the crew with a replacement rack with all of the above equipment, to be switched with the AR open loop rack on orbit. There does not appear to be enough room to package the AR System in one rack.

3.2.3 *Provide Separate Rack at PMC with Closure Hardware*

Use of LAF-5 (currently a payload rack) for this purpose offers three major advantages. First, it minimizes the distance, hence the plumbing, between the CDRA and its closed loop conversion kit, and between the Sabatier CReA process waste exhaust (methane and excess carbon dioxide) and the CDRA dedicated vacuum vent line. Note that when the CDRA is reconfigured for closed loop operation, the CO2 exhaust is directed to the CO2 accumulator tank, thus freeing the CO2 vacuum vent for use as the CReA exhaust. The second major advantage of using LAF-5 for the OGA and CReA equipment is realized by fully assembling, integrating and testing LAF-5 as an AR rack on the ground prior to

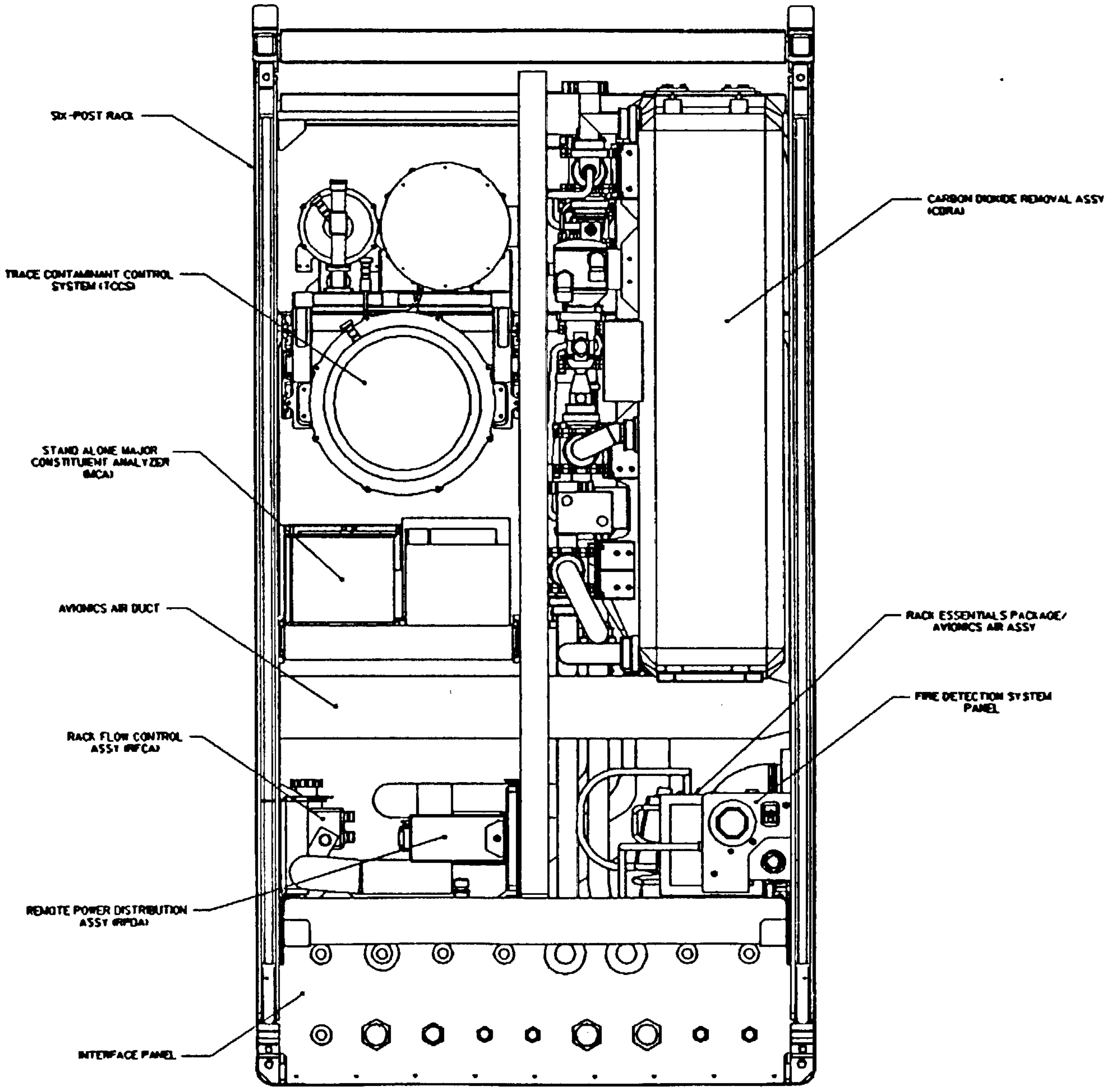


FIGURE 3-1 SSF BASELINE AR RACK - FRONT VIEW
FACEPLATE NOT SHOWN FOR CLARITY

launch. The third major advantage offered by this option is the minimization of the time and effort required by the crew to install, verify and start this rack level equipment as opposed to that for two subassemblies and the components of the CDRA closed loop conversion kit.

3.2.4 *Provide Closed Loop Hardware as ORUs for Installation in other Racks/Standoffs*

Another option, less desirable but plausible, is to provide for the installation of the subassemblies and conversion kit in other systems racks and in the standoffs. It is apparent that the OGA and possibly the Sabatier CReA could be installed in LAC-6 which currently houses the DMS/Audio as shown in Figure 3-2. In this scenario the CO2 accumulator tanks and the valving could be installed in standoff X-1 as shown in Figure 3-3. With this installation, however, fluid and electrical lines would be routed from standoff X-1 to standoff X-3 through the endcone. LAF-1 would also be another candidate for housing the CO2 accumulator tanks as shown in Figure 3-4, however, standoff X-1 would be the preferred location. It is noted that the CO2 accumulator tanks shown are 0.5 ft^3 tanks manifolded together. This tank configuration takes advantage of the existing 0.5 ft^3 tanks used in the current Fire Detection and Suppression system which are also standoff mounted. As such, common hardware for tanks and support brackets can be used.

3.3 HAB A INSTALLATION

3.3.1 *Convert AR Open Loop Rack to Closed Loop*

Rack HAF-6, the AR open loop rack is currently expected to house the CDRA configured for open loop operation with a dedicated vent to vacuum, the TCCS, an AAA/REP and an RPDA. Although the MCA will not be installed in this rack to duplicate the LAF-6 installation, it appears highly doubtful that enough room would be available to house an OGA, a Sabatier CReA or the CDRA closed loop conversion kit. Further, it is unlikely that there will be sufficient room to install only an OGA.

3.3.2 *Replace Open Loop AR Rack with Closed Loop Rack*

As in the case of the Lab A, the same constraints would apply to providing the crew with a replacement HAF-6 rack with closed loop equipment installed, to be switched with the AR open loop rack on orbit.

3.3.3 *Provide Closed Loop Hardware as ORUs for Installation in other Racks/Standoffs*

HAF-5, housing the Atmosphere Composition Monitor (ACM) with its Hydrogen Storage Assembly (HSA) for carrier gas and the Laundry (Freedom configuration) does offer a possibility in packaging the closure hardware. In the topology planned for the Space Station Alpha configuration, the Laundry system is deleted and HAF-5 is allocated for the ACM with its HSA and storage. Consequently, there should be sufficient rack volume to package an OGA and, if desired, the Sabatier CReA and accumulator tanks. There is also a potential side advantage in packaging the OGA in HAF-5 in that it may be possible to resupply the hydrogen carrier gas in the HSA (metal hydride tank) from the OGA H2 byproduct. This would offer a logistics savings in not having to fly a replacement HSA recharged on the ground.

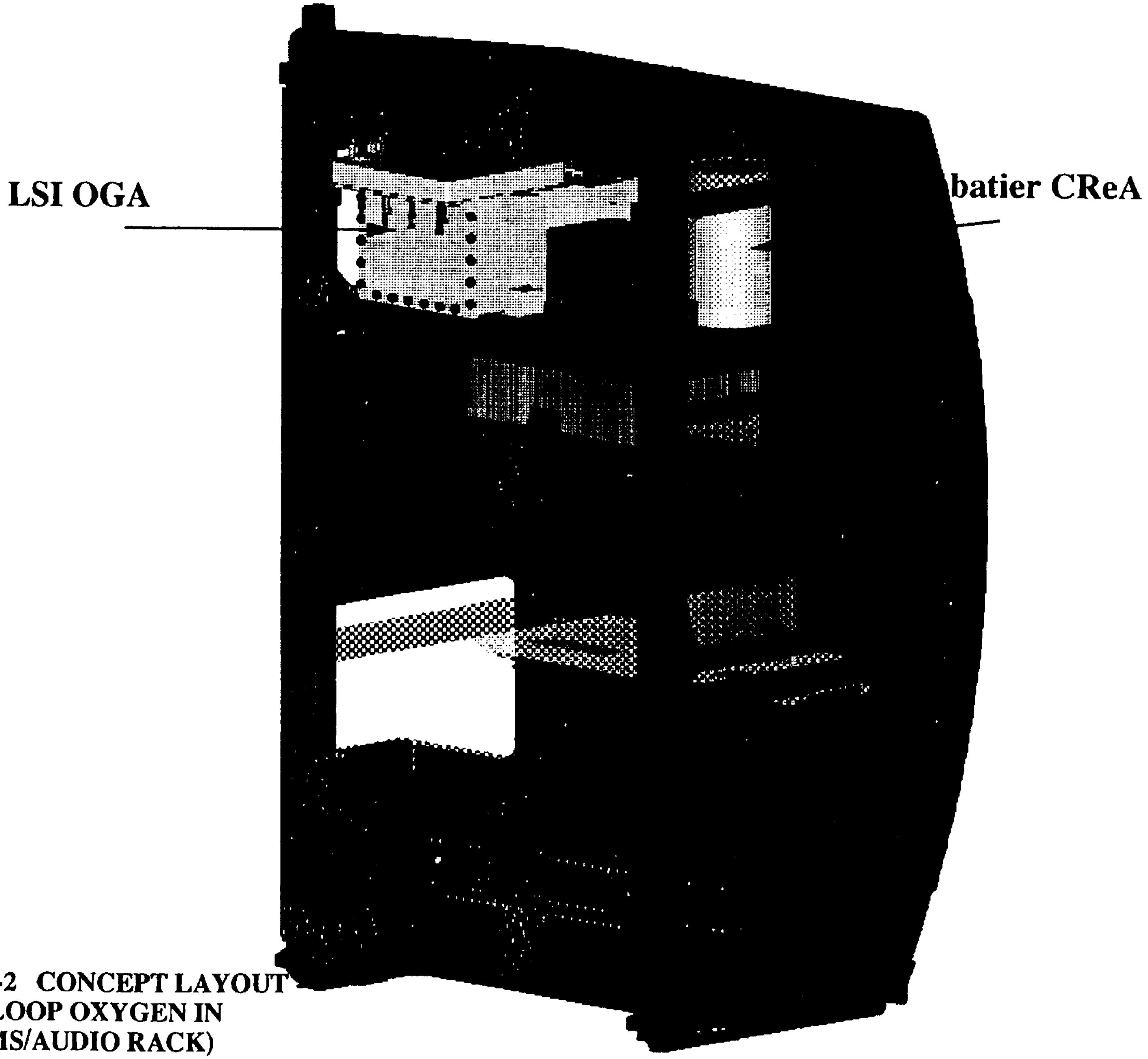


FIGURE 3-2 CONCEPT LAYOUT
CLOSED LOOP OXYGEN IN
LAC-6 (DMS/AUDIO RACK)

Top

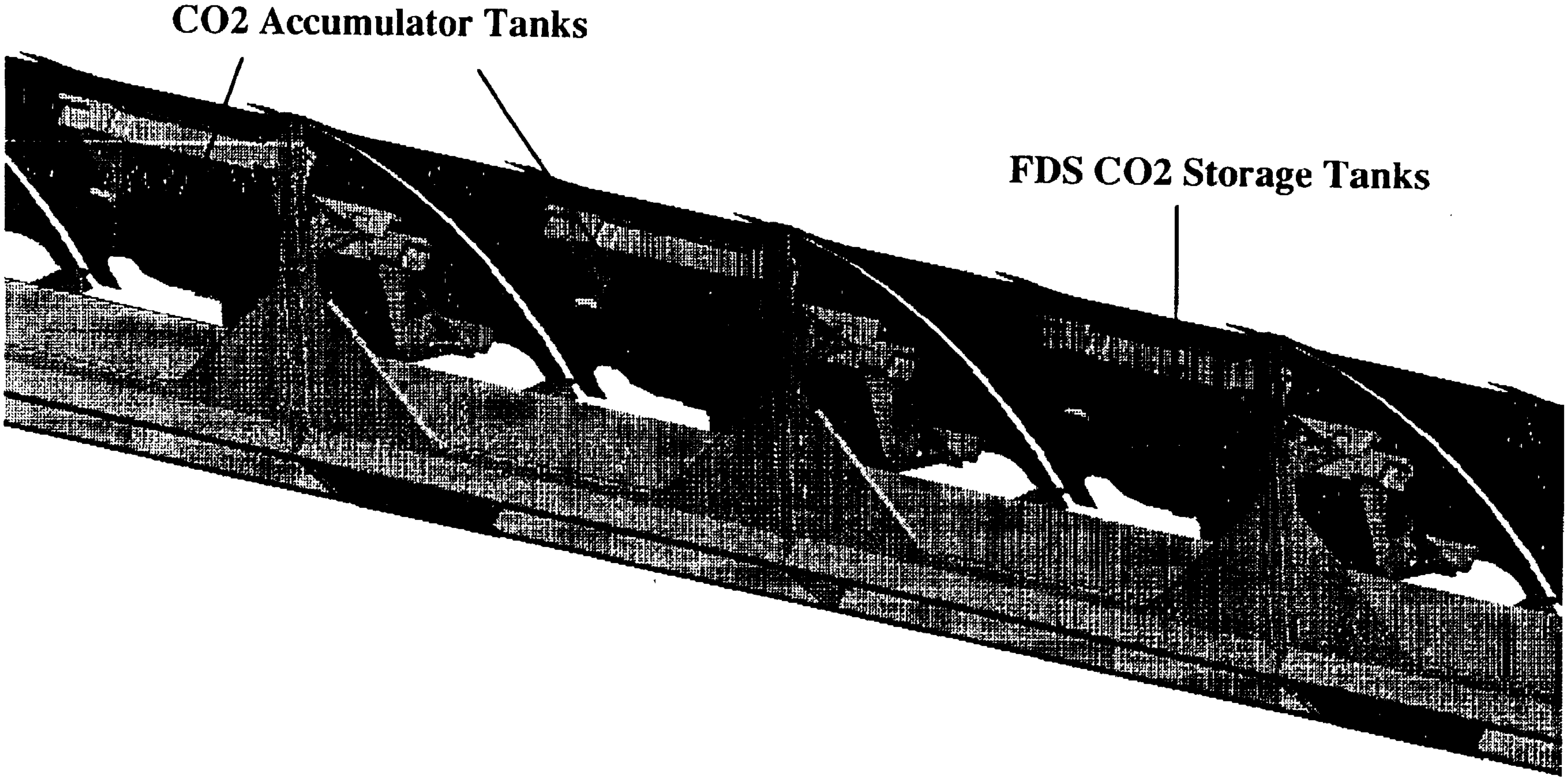


FIGURE 3-3 CONCEPT LAYOUT - CO2 ACCUMULATOR TANKS IN STANDOFF X-1

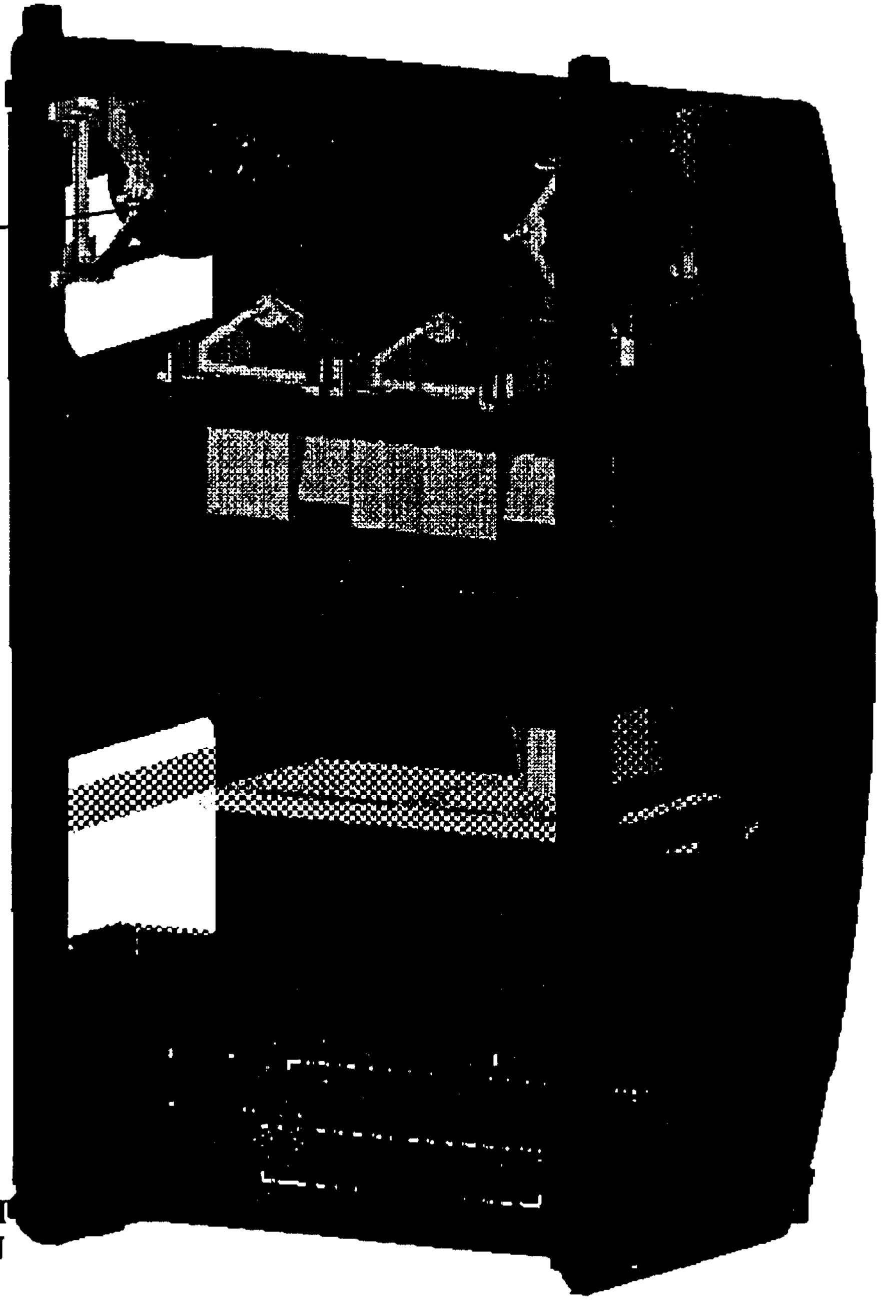


FIGURE 3-4 CONCEPT LAYOUT CO2 ACCUMULATOR TANKS IN LAF-1 (DMS/VIDEO RACK)

3.3.4 *Provide Hab A with Closed Oxygen Loop as Original Equipment*

If the assumption that the decision to scar the Lab A for closed loop oxygen will be made in time to outfit the Lab before launch is valid, then the Hab A can be designed for closed loop oxygen as its baseline without the need for scarring.

3.4 EVALUATION OF HOOKS

Since the OGA and Sabatier CReA have firmware controllers in their baseline design, the only software required is system executive level commands. As the PMC executive software has not been written, installation of the OGA and Sabatier command software can be developed in accordance the program schedule for PMC.

3.5 EVALUATION OF SCARS

3.5.1 *Scars Required in Lab A to Accommodate the OGA and Sabatier CReA*

The OGA requires electrical power, 1553 data control, water from the potable water supply for electrolysis, nitrogen for pressurization and purging and an interface with the moderate temperature loop of the Thermal Control System (TCS) to provide thermal control of the electrolysis process. In turn, the OGA produces oxygen and hydrogen and vents a mixture of hydrogen and nitrogen (varying from pure hydrogen to pure nitrogen) upon shutdown. A feedwater sidestream bleed will be required to allow dilution of the solids that concentrate in the feedwater compartment of the OGA. Refer to Figure 3-5 for a schematic which defines the OGA interfaces if only an OGA were manifested.

The Sabatier CReA requires electrical power, 1553 data control, carbon dioxide from the CDRA open to closed loop kit, hydrogen from the OGA, nitrogen for purging and an interface with the low temperature loop of the TCS to remove heat generated by the Sabatier reaction process. In turn the Sabatier produces water which is returned to the waste water bus, and methane and excess carbon dioxide which is vented overboard. Residual nitrogen from the shutdown purge of the hydrogen circuit of the OGA will also be vented through the Sabatier and overboard (residual nitrogen from the shutdown purge of the OGA oxygen circuit will be vented through the oxygen delivery line to the Temperature and Humidity Control air return duct and into the cabin). Figure 3-6 depicts the rack level interfaces for the OGA and Sabatier CReA configuration.

Standard interfaces for the payload rack location are shown in Figure 3-7 (pg 25.1). Modifications to the Lab would be required to provide process water to the rack and CH4/CO2 access to the CO2 vent line, H2 access to the water vent, O2 feed to the THC return duct, and process water effluent access to the waste water line. Figures 3-8 & Figure 3-9 (pgs 25.2 & 25.3) depict the SSF Lab-A AR & WRM FIDs with O2 closure scars to LAF5.

3.5.2 *Scars Required in Hab A to Accommodate the OGA and Sabatier CReA*

As noted above, a decision to close the oxygen loop in time to scar the Lab A will allow the original detail design of the Hab A to include the interfaces described in the scarring of the Lab A.

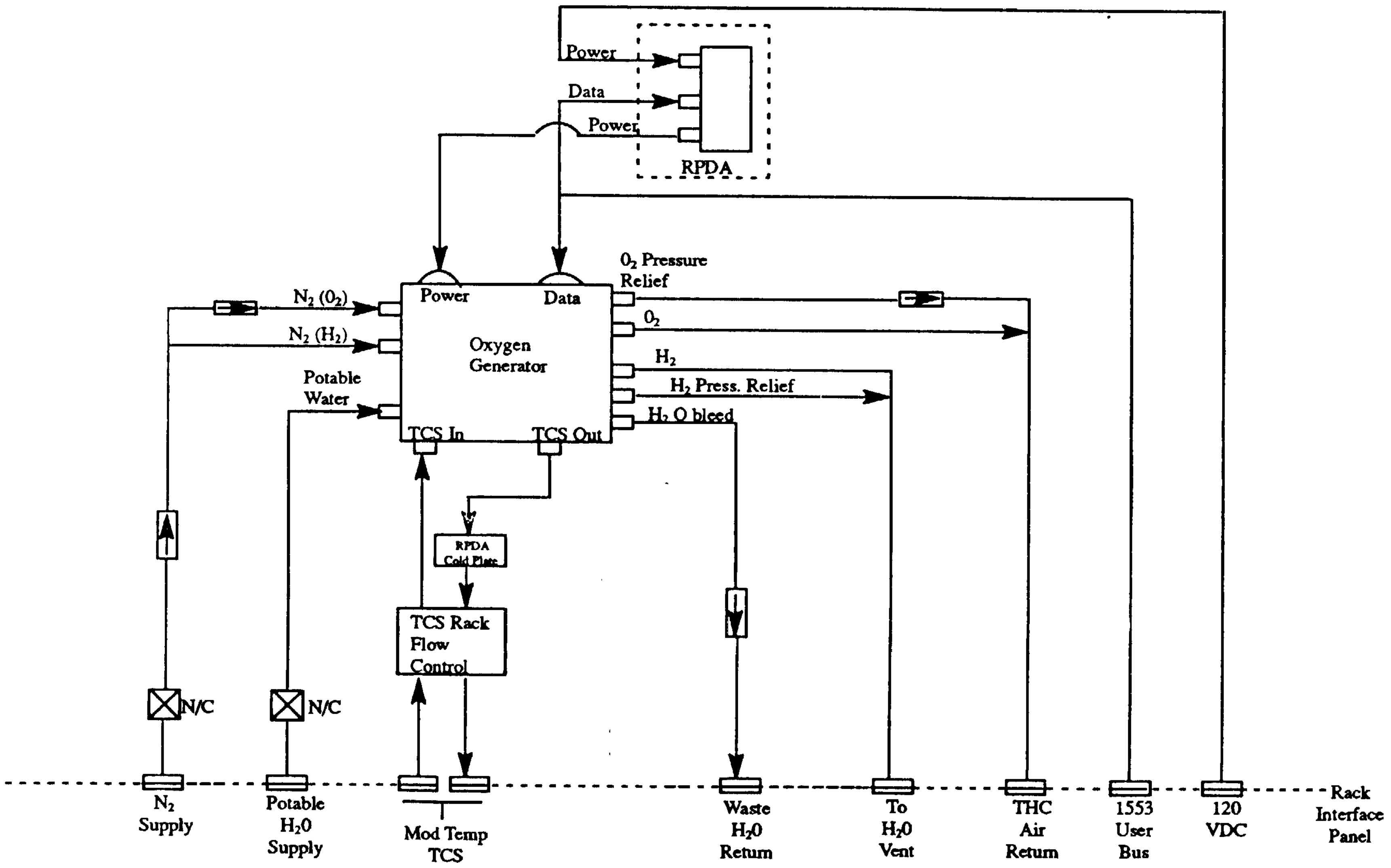


FIGURE 3-5 OGA RACK FUNCTIONAL INTERCONNECT DIAGRAM

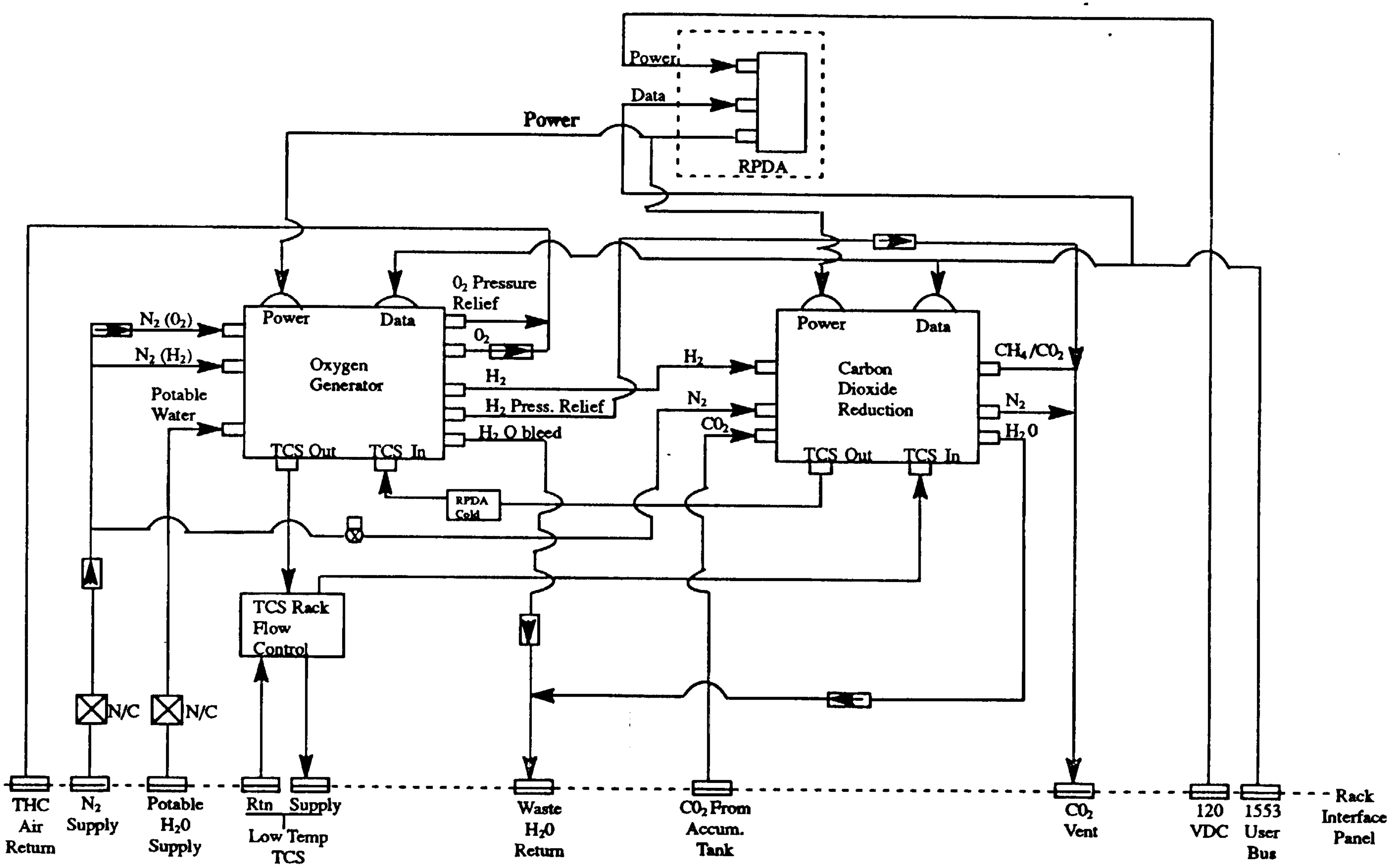


FIGURE 3-6 OGA AND SABATIER RACK FUNCTIONAL INTERCONNECT DIAGRAM

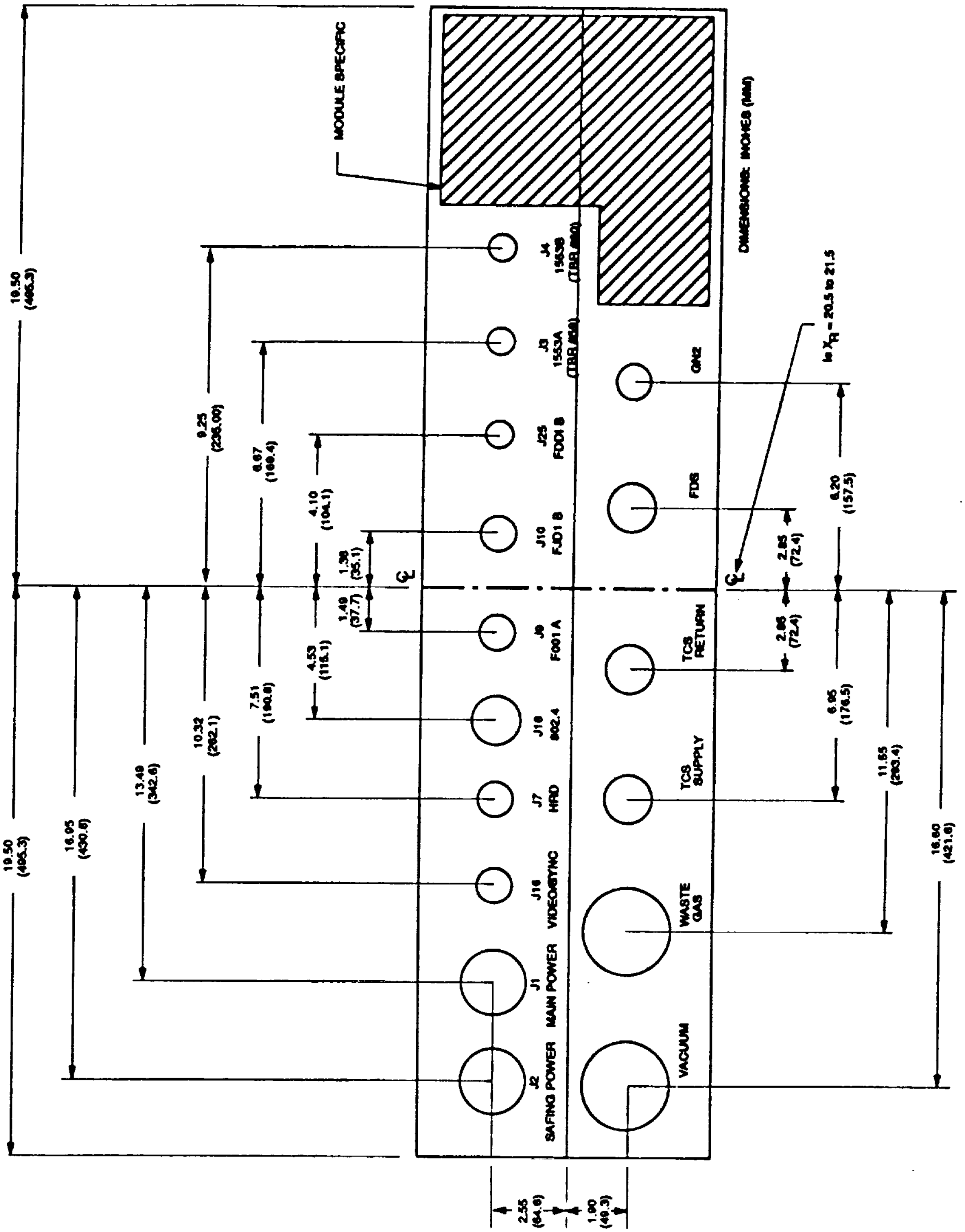


FIGURE 3-7 ISPR RACK INTERFACES

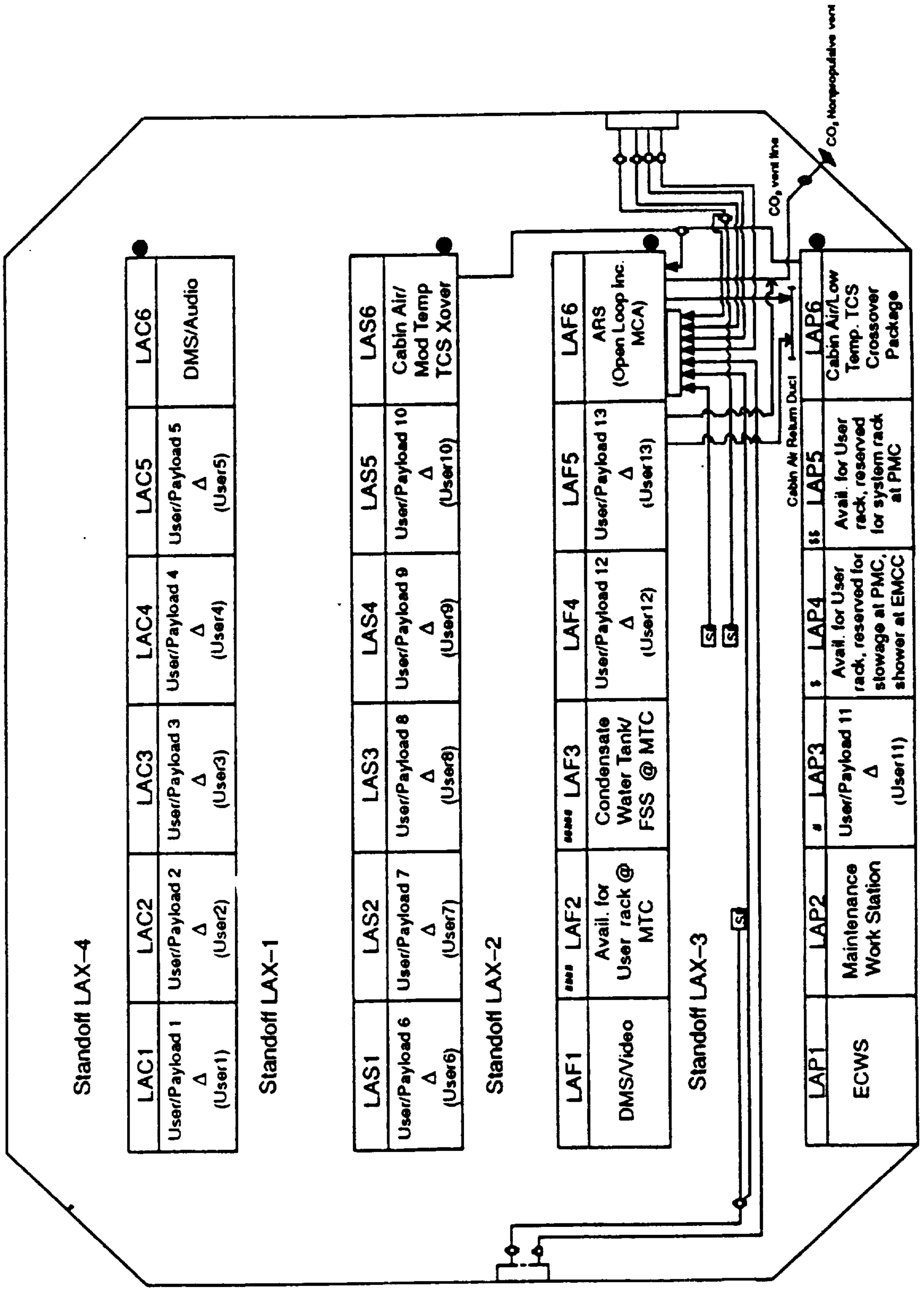


FIGURE 3-8 U.S. LAB-A AR EXORACK FID WITH SCARS

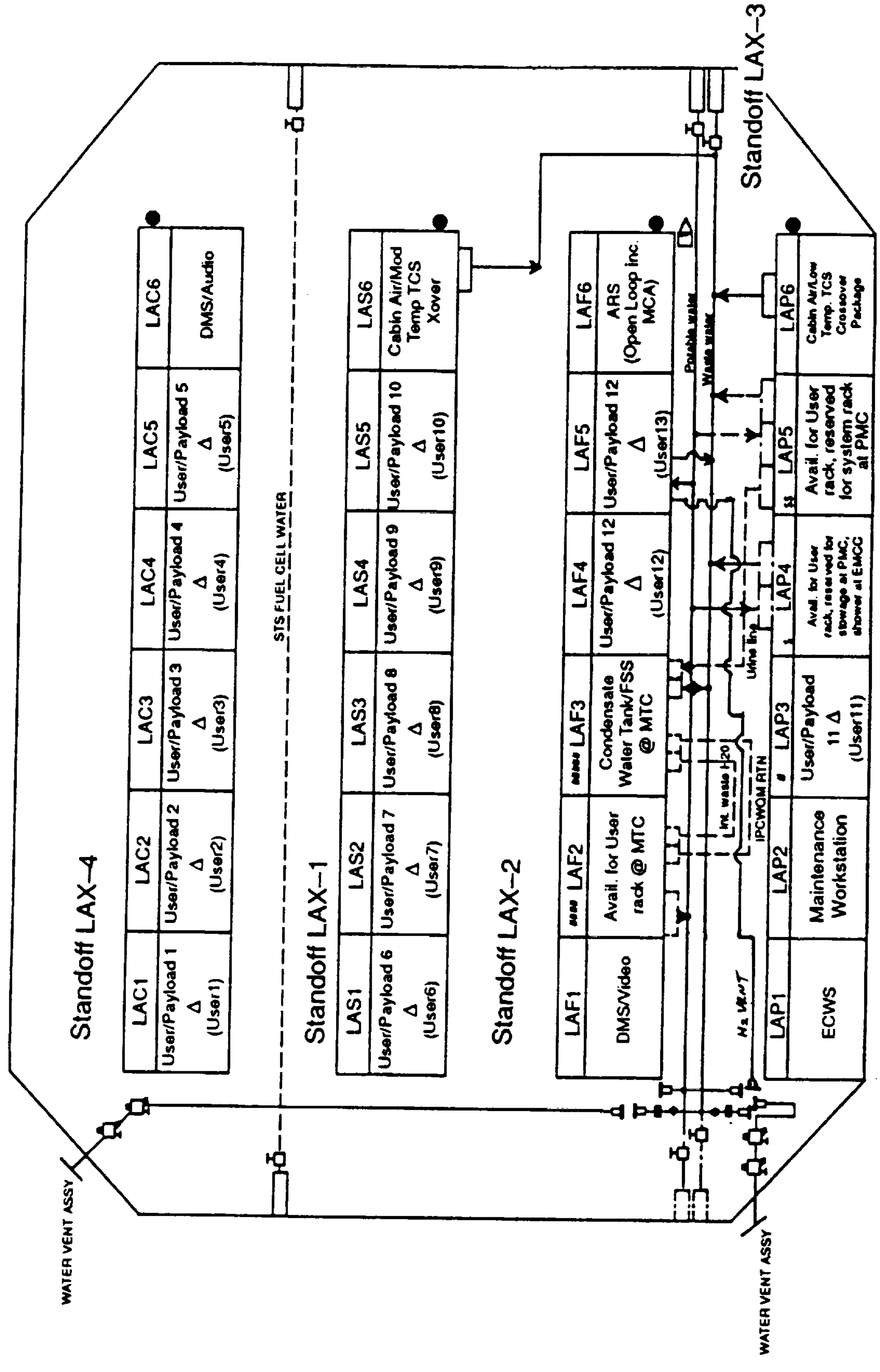


FIGURE 3-9 U.S. LAB-A WRM EXORACK FID WITH SCARS

3.5.3 *Rack Scarring*

Dependent on the rack and equipment installed in the rack, plumbing and electrical/electronic provisions which satisfy the requirements of the hardware as detailed above and shown in Figures 3-5 and 3-6 would be installed in the rack as a scar prior to installation of the rack in the element for flight.

3.6 SINGLE STRING OXYGEN LOOP CLOSURE

It may be plausible to provide oxygen generation in the Hab A only and use maintenance as the first leg of redundancy and the Assured Crew Return Vehicle (ACRV) as the second leg of redundancy. In this scenario the ACS would have sufficient O2 available to support the station O2 demands while maintenance is performed on the failed OGA or failed water delivery hardware. For example, there is approximately one month of high pressure O2 on orbit. Therefore, the repair of the failure must be completed in this time frame. Failure to make the repair would be due to a failure of the spare OGA which is considered a second failure leading to use of the ACRV. It is noted that this approach will require sufficient spares on orbit to repair the OGA or water delivery failures. Contingencies would be met by the following approach:

1) Skip cycle O2 contingency is currently ~ 900 lb O2 at 0 failure tolerant. This is met with a combination of the OGA and high pressure gas. ~250 lb of high pressure gas is available and ~ 900 lb of H2O is available. This sums up to 1050 lb of O2. Note that this assumes that water is not used by experiments during normal station operation.

2) Depress/repress O2 contingency is 200 lb at 1 failure tolerant. This is provided with high pressure gas delivery and/or electrolysis O2 delivery.

Rack level scarring for the OGA only is defined in Figure 3-5.

3.7 STUDY RESULTS (Subtask 5.2.1.2)

The key results of this task are summarized as follows:

1) The scars for the OGA only and the OGA and Sabatier CReA combination are defined in Figures 3-5 and 3-6, respectively. The optimum locations for scarring in Lab A are racks LAF-5 (OGA only or OGA & CReA) followed by LAC-6 (OGA only or possibly OGA & CReA). The optimum location for scarring in Hab A is rack HAF-5.

2) It does not appear viable to convert the existing open loop AR racks to closed loop.

SECTION 4, VENTING CONSIDERATIONS

4.1 STUDY OVERVIEW (Subtask 5.2.1.3)

The objective of this task was to study the available methods of handling the Sabatier vent gases (i.e., CH_4 and unreacted CO_2). This study consisted of determining whether free venting would meet the external contamination requirements or if Sabatier venting would be dependent on Supplemental Reboost System availability. This task was further expanded in the June 1993 monthly status meeting to evaluate the effects and means of venting hydrogen from the OGA in the event that the OGA was manifested without CO_2 reduction.

Analyses were conducted to determine whether or not Sabatier CH_4/CO_2 venting and H_2 venting meets the external contamination requirements of SSP 30246 Revision B. This evaluation was based on venting the Sabatier gases via the existing CDRA CO_2 vent and venting the OGA hydrogen through the existing water vent(s).

4.2 SABATIER VENTING

4.2.1 Sabatier Venting Contamination Effects

The requirements applicable to the CO_2/CH_4 vent are that any resultant deposition not exceed 1×10^{-14} gm/cm^2-sec on a daily average and that the resulting molecular column densities not exceed 1×10^{14} molecules/cm^2 per molecular species. Since the CO_2/CH_4 vent will be in use continually while the Space Station is manned, these requirements are essentially instantaneous requirements rather than averaged requirements.

The flowfield of the CO_2/CH_4 vent plume was calculated using a method of characteristics computer code. Calculations were made to a distance sufficiently far from the vent so that the flow could be accurately described by a source flow model. In such a model, the mass flux at any point in the flow is given by:

$$\text{flux} = \text{Å}/r^2 \cos \text{ß}\text{ø} \qquad (1)$$

where

r is the distance from the vent to the point,
ø is the angle of the point off the plume centerline, and
Å and ß are constants

An excellent fit to the computed results was found by

$$\text{Å} = 3.922 \times 10^{-5} \text{ lbm/sec} \qquad (2)$$

and

$$\text{ß} = 1.0 \qquad (3)$$

Consequently

$$\text{flux} = \frac{3.922 \times 10^{-5} \cos \phi}{r^2} \text{ lbm/sec} \qquad (4)$$

Equation (4) is of the proper form for input into the MOLFLUX computer code and was used with MOLFLUX to calculate the molecular column density. MOLFLUX uses Space Station material outgassing rates, module leakage rates, and concentrated source flow models to calculate deposition rates and molecular column densities.

Using a mass flow of CO2 to be 3.1 lbm/day and the mass flow of CH4 to be 3.05 lbm/day for a total mass of 6.15 lbm/day, the mass fractions of CO2 and CH4 are

$$m_f \, CO2 = 0.504 \qquad (5)$$

and

$$m_f \, CH4 = 0.496 \qquad (6)$$

The vent plume model and the mass fractions were used in the MOLFLUX code to calculate the molecular column densities along the same line of sight as for the CDRA CO2 vent. The maximum molecular column densities found were

$$MCD_{CO2} = 9.97 \times 10^{12} \text{ molecules/cm}^2 \qquad (7)$$

and

$$MCD_{CH4} = 2.70 \times 10^{13} \text{ molecules/cm}^2 \qquad (8)$$

Both of these values are below the value for CO2 alone (i.e., CDRA open loop venting) and each satisfies the requirements of SSP 30246 Revision B.

At pressures below 1 torr, the sublimation temperature for CH4 is less than -340 ° F which is significantly less than the minimum expected Space Station temperature and, consequently, there will be no CH4 deposition. Therefore, venting unreacted CO2 and CH4 from the Sabatier CO2 reduction assembly meets all of the requirements of SSP 30246 Revision B.

4.2.2 *Sabatier Vent Locations*

The gaseous byproducts of the Sabatier reaction (CH4 and unreacted CO2) will be vented using the existing CDRA CO2 vents. Since no unique vents will be required, the cost of scarring for the Sabatier with regard to venting would be minimal.

The method of characteristics calculations of the CO2/CH4 vent plume yielded a vent thrust of 0.0077 lbf. This is a net reduction of 48 percent from the CDRA CO2 venting of 0.015 lbf.

4.3 OXYGEN GENERATOR VENTING

4.3.1 *Oxygen Generation Venting Contamination Effects*

The requirements applicable to the H2 vent are that any resultant deposition not exceed 1 x 10^{-14} gm/cm^2 -sec on a daily average and that the resulting molecular column densities not exceed 1 x 10^{14} molecules/cm^2 per molecular species. Since the H2 vent will be in use for 60 minutes of each orbit (day/night operation) while the Space Station is manned, these requirements are essentially instantaneous requirements rather than averaged requirements.

For this evaluation the H2 venting rate was set at 1.30 lbm/day which corresponds to an O2 production rate of ~10.3 lbm/day. The H2 is also calculated to be saturated with water with an expected flowrate of 0.186 lbm/day. Therefore, the combined H2 vent flow rate is 1.486 lbm/day. As the OGA electrolysis process is a high consumer of electricity, it is planned to only operate the OGA for 60 minutes of the 90 minute orbit. This results in a flow rate of 2.58 x 10^{-5} lbm/sec when venting.

The flowfield of the H2 vent plume was calculated using a method of characteristics computer code. The required mass flow was determined to be achievable with a stagnation pressure of 1.64 psia just upstream of the vent. Flowfield calculations were made to a distance sufficiently far from the vent so that the flow could be accurately described by a source flow model. In such a model, the mass flux at any point in the flow is given by:

$$\text{flux} = \text{Å}/r^2 \cos ß\phi \qquad (1)$$

where

r is the distance from the vent to the point,
ø is the angle of the point off the plume centerline, and
Å and ß are constants

An excellent fit to the computed results was found by

$$\text{Å} = 1.55 \times 10^{-5} \text{ lbm/sec} \qquad (2)$$

and

$$ß = 1.0 \qquad (3)$$

Consequently

$$\text{flux} = \frac{1.55 \times 10^{-5}\cos \phi}{r^2} \text{ lbm/sec} \qquad (4)$$

Equation (4) is of the proper form for input into the MOLFLUX computer code and was used with MOLFLUX to calculate the molecular column density. Molecular column densities were calculated for each water vent. Fifteen lines of sight were used in the calculations and the results varied from a minimum of 1.25 x 10^{11} molecules/cm^2 to a maximum of 7.84 x 10^{13} molecules/cm^2 for H2. These column densities satisfy the requirements of SSP 30246.

At pressures below 1 torr, the sublimation temperature of H2 is less than -263 ° C which is significantly less than the minimum expected Space Station temperature and, consequently, there will be no H2 deposition of Space Station external surfaces. As such, H2 venting will meet all of the requirements of SSP 30246 Revision B.

4.3.2 *Oxygen Generation Vent Locations*

This study proposes that the existing water vents located in the LAB A module be used for venting of the OGA hydrogen byproduct. It is also assumed that a water vent will be added to the HAB A to provide a vent access for an OGA located in the HAB. The water vents were chosen for hydrogen venting for the following reasons:

A. The water vents are only used for contingencies at post PMC and as such will be available for H2 venting. Should water need to be vented subsequent to bringing the OGA online, the OGA need only be temporarily shutdown to accommodate the water venting.
B. The CO2 vent for the CDRA cannot be shared with the OGA due to the delivery pressure of the H2 (~ 25 psia) and the CDRA bed operating pressure (~ 0.5 psia). H2 would backflow into the CDRA if a common vent were used.
C. The water vents(s) are heated which has an additional advantage in the event of H2 vent freezing (NOTE: Dewpoint of the H2 product is ~ 57 ° F).

Note: If a water vent is not implemented in Hab A, then a dedicated H2 vent similar to the existing water vent will be required.

The method of characteristics calculations of the H2 vent plume yielded a vent thrust of 0.0051 lbf. If only one water vent is used to vent the hydrogen, then there will be some propulsive effect which may cause microgravity or control problems. These effects should be examined further.

4.4 STUDY RESULTS (Subtask 5.2.1.3)

The Sabatier CO2/CH4 venting and the OGA H2 venting both meet the requirements of SSP 30246 Revision B. As such, the use of the Sabatier is not dependent on the availability of a Supplemental Reboost System. Table 4-I summarizes the results of the venting evaluation and compares the results to open loop CO2 venting.

TABLE 4-I RESULTS OF VENT EVALUATION

Subsys/ species	MCD, molecules/cm ^{2} (requirement)	MCD, molecules/cm ^{2} (calculated)	Vent Thrust, lbf	Meets requirements
CDRA/ CO2	1×10^{14}	7.13×10^{13}	0.015	yes
Sabatier/ CO2	1×10^{14}	9.97×10^{12}	0.0077	yes
CH4	1×10^{14}	2.70×10^{13}		yes
OGA/ H2	1×10^{14}	1.25×10^{11} (min) $7.84 \text{X} 10^{13}$ (max)	0.0051	yes

SECTION 5, TOPOLOGY AND PACKAGING

5.1 STUDY OVERVIEW (Subtask 5.2.1.4)

The objective of this task was to trade options with respect to topology, packaging and integration factors to arrive at recommended scenarios for scarring. Include impacts to power and DMS. Quantify impacts to weight, volume, schedule and cost for incorporating scars into the baseline program.

5.2 TOPOLOGY AND PACKAGING

The trades with respect to topology and packaging were primarily discussed in task 5.2.1.2. Based on packaging limitations, the optimum locations for scarring are locations LAF-5 or LAC-6 in Lab A and HAF-5 in Hab A.

5.3 WEIGHT, VOLUME AND COST IMPACTS FOR SCARRING

Impacts were assessed for the following scarring options and are summarized in Table 5-I :

Option 1. Install OGA alone
Option 2. Install OGA, Sabatier and CDRA conversion kit in three different places
Option 3. Install OGA and Sabatier in the same rack and install CDRA conversion kit in a different location
Option 4. Install OGA, Sabatier and CDRA conversion kit in the same rack

The cost impact based on the tasks identified in Table 5-I are given as follows:

Option 1: Fy 94 $0.85M	Fy 95 $0.27M	Fy 96 $0.18M	Total $1.29M
Option 2: Fy 94 $1.98M	Fy 95 $0.58M	Fy 96 $0.25M	Total $2.81M
Option 3: Fy 94 $1.98M	Fy 95 $0.50M	Fy 96 $0.25M	Total $2.73M
Option 4: Fy 94 $1.70M	Fy 95 $0.55M	Fy 96 $0.25M	Total $2.51M

5.4 STUDY RESULTS (Subtask 5.2.1.4)

The impacts to weight, volume and schedule have been defined as shown in Table 5-I. The cost impacts for scarring have been identified as given in 5.3 above.

TABLE 5-I SCAR IMPACT ASSESSMENT

IMPACTS	OGA only	Sabatier	CDRA Conversion Kit	OGA and Sabatier	OGA ,Sabatier and Conversion Kit
SUBASSEMBLY/KIT					
Volume, ft3	3.8 (1)	2.1 (2)	2.0 (3)	5.9	7.91
Weight, lb	206	90	30 (4)	296	326
Power, peak, W	1372	276 (5)	1500	2872	3148
Power, time-average, W	1310 (6)	56 (5)	160	1366	1562
DMS, I/O (7)	1/1	1/1	1/1	2/2	3/3
Heat rejection to TCS, W (11)	200	283	neg	483	483
Design, prepare and install closed loop interface hardware to racks for Lab ETA and Flight element build up to support ETA in 1995					
Design interface	8 mm	8 mm	8 mm	14 mm	18 mm
Design installation	15 mm	15 mm	15 mm	28 mm	40 mm
Fab & instl scar plumb., harnesses & support struct. in ETA & Lab A (8)	8 mm	8 mm	N/A	16 mm	22 mm
Replacement rack (9)	N/A	N/A	N/A	N/A	N/A
Design, prepare & instl closed loop interface hardware to Lab A for ETA and Flight element buildup to support ETA in 1995					
EPS	2 mm	2 mm	2 mm	4 mm	4 mm
Cable design	2 mm	2 mm	2 mm	3 mm	4 mm
DMS	3 mm	3 mm	3 mm	3 mm	3 mm
Potable water	2 mm	N/A	N/A	2 mm	2 mm
Nitrogen	2 mm	2 mm	N/A	2 mm	2 mm
Oxygen	2 mm	N/A	N/A	2 mm	2 mm

TABLE 5-I SCAR IMPACT ASSESSMENT (CONTINUED)

IMPACTS	OGA only	Sabatier	CDRA Conversion Kit	OGA and Sabatier	OGA ,Sabatier and Conversion Kit
Hydrogen	2 mm	2 mm	N/A	2 mm	2 mm
Waste/product H2O	2 mm	2 mm	N/A	2 mm	2 mm
Carbon Dioxide	N/A	2 mm	4 mm	2 mm	2 mm
Waste gas to vent	N/A	2 mm	N/A	2 mm	2 mm
TCS MTL	4 mm	N/A	N/A	4 mm	4 mm
TCS LTL	N/A	4 mm	N/A	4 mm	4 mm
Thermal analysis	1 mm	(12)	N/A	1 mm	1 mm
Fab & Installation IN ETA & Lab-A	8 mm	8 mm	3 mm	11 mm	11 mm
System requirements (inc SE27)	2 mm	4 mm	1 mm	6 mm	7 mm
SRM & QA	12 mm	4 mm	1 mm	13 mm	14 mm
Systems test	6 mm	4 mm	N/A	10 mm	10 mm
Ops - procedure	4 mm	N/A	N/A	4 mm	4 mm
TOTAL - mm	85 mm	72 mm	39 mm	135 mm	160 mm
Option 1 Total (column 1)	85 mm				
Option 2 Total (columns 1,2,3)		196 mm			
Option 3 Total (columns 3,4)				174 mm	
Option 4 Total (column 5)					160 mm

NOTES :

(1) rough cube

(2) mechanical subassembly 15"x17"x12.5"; separate electrical subassembly 5.9"x7.8"x10.0"

(3) Volume does not include 4 stage pump changeout & valving for CDRA (accounted for in CDRA env.)

(4) 2 ft3 tank - 20 lb; pump differential and new valving - 10 lb

(5) Includes 21 W for signal conditioner

(6) Includes current controller @ 81% efficiency @ 10.251 lb O2/day rate

(7) OGA and CReA include firmware controllers

(8) Includes EPS, DMS, N2, H2, O2, CO2, waste gas, potable H2O, waste H2O and TCS, as reqd

(9) If a replacement ISPR option were selected, a spare rack will be used; the replacement rack becoming the spare on return from orbit

(10) peak power for upgrade kit is 500 W; peak power for closed loop CDRA is 1500 W; will impact payload allocation

(11) Heat rejection will impact payload allocation

(12) Thermal analysis requires 1 mm regardless of configuration

SECTION 6, VERIFICATION

6.1 STUDY OVERVIEW (Subtask 5.2.1.5)

The objective of this task was to address verification and testing issues with respect to scars. Identify any additional testing needed for the PMC configuration to accommodate later incorporation of closure hardware.

6.2 TEST AND VERIFICATION CONSIDERATIONS

The following paragraphs identify the additional verification activities with regard to closed loop scarring. Note that the following verification activities pertain to scars for the Lab A only.

6.2.1 *Lab A ETA*

1) Modify ETA rack/racks/standoff with simulated structural, plumbing and cabling scars for closed loop O2.
2) Verify leakage, continuity, insulation resistance and pressure drop as manufacturing in-process checks.
3) Modify ETA element with plumbing and cabling scars.
4) Install ETA rack(s) in ETA element.
5) Test element scars for leakage, continuity, insulation resistance and pressure drop as manufacturing in-process checks.
6) Perform system verification of scars

NOTE: The above is not required if manifesting the OGA in the Hab only.

6.2.2 *Lab A Flight Article*

1) Modify flight rack/racks/standoff to include plumbing and cabling scars.
2) Verify leakage, continuity, insulation resistance and pressure drop as manufacturing in-process checks.
3) Modify Lab A to include plumbing and cabling scars.
4) Install flight racks into Lab A.
5) Test leakage, continuity, insulation resistance and pressure drop as manufacturing in-process checks.
6) Perform system verification of scars

6.2.3 *ETA (pre Permanent Human Capability)*

1) Remove modified racks.
2) Prepare and validate installation procedure.
3) Install qualification subassemblies/ORUs in rack(s).
4) Perform rack functional qualification test.
5) Perform EMI tests.
6) Reinstall rack(s) in ETA element.
7) Operate in start-up/all modes/shutdown. Validate software control and perform system PMC functional qualification.
8) Support BOST/MOST closed loop testing.
9) Remove qualification subassemblies/OURs.
10) Install flight subassemblies/ORUs.

11) Validate installation procedure.
12) Perform acceptance tests of software and hardware.
13) Remove flight subassemblies/ORUs and prep for shipment.
14) Reinstall qualification subassemblies/ORUs in ETA.

SECTION 7, CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

The following specific conclusions can be drawn from this study:

A There is sufficient water available to support oxygen generation without CO2 reduction with an excess of 9.69 lb/day water available for payload use. Note: If a firm requirement for water to payloads is developed or the amount of fuel cell water available is reduced, then this conclusion must be revisited.

B. There is insufficient volume to close the oxygen loop in the existing open loop AR rack.

C. Scarring locations for oxygen loop closure have been identified as:

1.LAF-5 (primary) or LAC-6 (secondary) in Lab A.
2. HAF-5 in Hab A.

NOTE: A second option which represents the lowest risk to cost and schedule would be to scar for or manifest an OGA in the Hab A only in rack HAF-5.

D. Both H2 venting and Sabatier venting will meet Station requirements of SSP 30246 Revision B.

E. The impact to weight, volume and cost for implementing scars have been defined as given in Section 5.

7.2 RECOMMENDATIONS

Based on the results of this study it is recommended that onboard oxygen generation be included in the baseline program. Decisions regarding implementation must be based on program funding and schedule constraints. Without consideration of program costs and schedule, it is recommended that the Lab A be scarred for OGA installation and the Hab A include an OGA in the baseline design. The Lab A would then be retrofitted at PMC with a redundant OGA .