UNITED TECHNOLOGIES
HAMILTON STANDARD

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MODEL DESCRIPTION DOCUMENT

FOR

A COMPUTER PROGRAM FOR THE EMULATION/SIMULATION OF A SPACE STATION ENVIRONMENTAL CONTROL AND LIFE SUPPORT SYSTEM

(ESCM)

PREPARED UNDER CONTRACT NO. NAS 1-17397

BY

HAMILTON STANDARD
DIVISION OF UNITED TECHNOLOGIES CORPORATION
WINDSOR LOCKS, CONNECTICUT

FOR

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LANGLEY RESEARCH CENTER
HAMPTON, VIRGINIA

September 1988

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ABSTRACT

ESCM computes the transient performance of a Space Station air revitalization subsystem with carbon dioxide removal provided by a solid amine water desorbed subsystem called SAWD.

This manual describes the mathematical modelling and equations used in the Emulation/Simulation Computer Model. For the system as a whole and for each individual component, the fundamental physical and chemical laws which govern their operations are presented. Assumptions are stated, and when necessary, data is presented to support empirically developed relationships.

FOREWORD

This Model Description Document has been prepared by Hamilton Standard, Division of United Technologies Corporation for the National Aeronautics and Space Administration's Langley Research Center in accordance with Contract NAS 1-17397, "Development of an Emulation/Simulation Computer Model of a Space Station Environmental Control and Life Support System (ECLSS)". This document describes the equations used in the computer model.

Appreciation is expressed to the Technical Monitors Messrs. John B. Hall, Jr. and Lawrence F. Rowell of the NASA Langley Research Center for their guidance and advice.

This manual was prepared by Mr. James L. Yanosy, Program Engineer. The program was conducted under the direction of Mr. Harlan Brose, Program Manager and Mr. Albert Boehm, Assistant Program Manager. Special thanks is given to Mr. Gordon Allen for his contributions to the development of the analytical model of the Solid Amine Water Desorbed process. Thanks are also extended to Messrs. Raymond Trusch and Edward O'Connor for their assistance and technical advice. Thanks and much appreciation is given to Ms. Denise Landis for typing the manuscript and to Mr. Raymond Levesque for his artwork and assembly of the document.

1.0 INTRODUCTION

1.1 Background

ESCM is a computer model which was developed to demonstrate the utility of a major portion of the Emulation/Simulation, Sizing, and Technology Assessment Program (ESSTAP). See Reference 1. ~~ESSTAP~~ is a concept for software tools that will support the total engineering process of the Space Station beginning with concept definition and continuing on through mission operations. The interaction of the software tools with the design and operational phases of a flight system is shown in Figure 1. The philosophy of this software concept is to have the analysis software for each step in the design process precede development of hardware in order to provide the greatest design and cost benefits.

Of the many systems in the Space Station, the Environmental Control and Life Support System (ECLSS) was selected to demonstrate the utility of the ESSTAP concept because of its complexity (number of components and dynamic operational capability), availability of operational data for checkout, and growth potential. The ESCM program was targeted to evaluate and demonstrate the benefits of phases 2 through 4 software. For this purpose, an evaluation of the six major ECLSS functions was performed as published in the program document "ESCM-EM-02" (Reference 2). As a result of this study, a subgroup of the Air Revitalization Subsystem (ARS) shown in Figure 2 was selected for modelling because of its dynamic complexity, growth potential, design tool utility, and the independent nature of the ARS compared to other subsystems.

The resulting ESCM model has been used to demonstrate the use of a computer program in the design, development, and test of applicable development hardware. Specifically, through the use of the program, design hardware and software can be verified, Failure Mode and Effect Analysis (FMEA) can be assisted, and test planning can be technically improved.

1.2 Overview of Modelled System

The ARS functions and components are depicted in Figure 2. The system to be simulated involves the Space Station cabin, crew, a heat exchanger for temperature control, a heat exchanger for humidity control, fans, a SAWD (Solid Amine Water Desorbed) carbon dioxide removal system, and a two-gas controller for oxygen replenishment and total pressure control.

The cabin is a volume which houses the crew, two-gas controller, and certain vehicle heat loads representing equipment. Air leakage out of the cabin is also modelled. The crew breathes in oxygen from the cabin air and releases sensible heat, latent heat in the form of respiratory water vapor, and carbon dioxide.

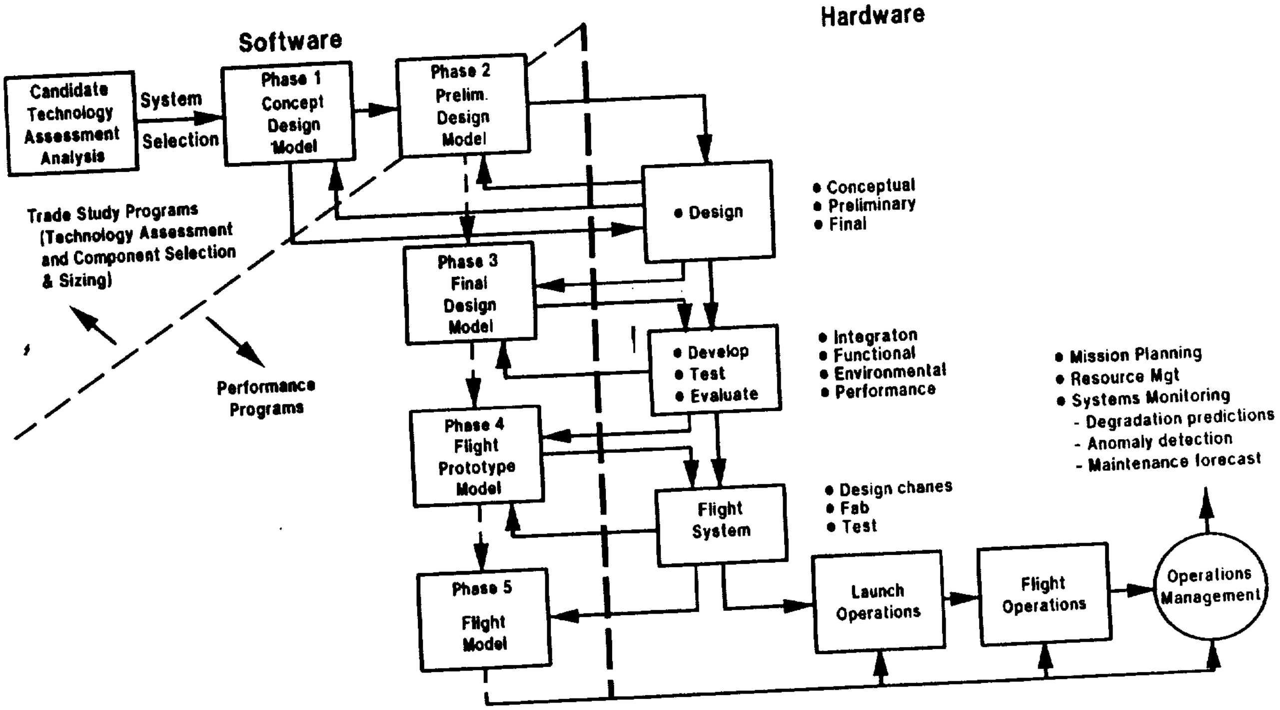

Figure 1

Application Of Software Tools To The Design And Operational Phases Of A Flight System

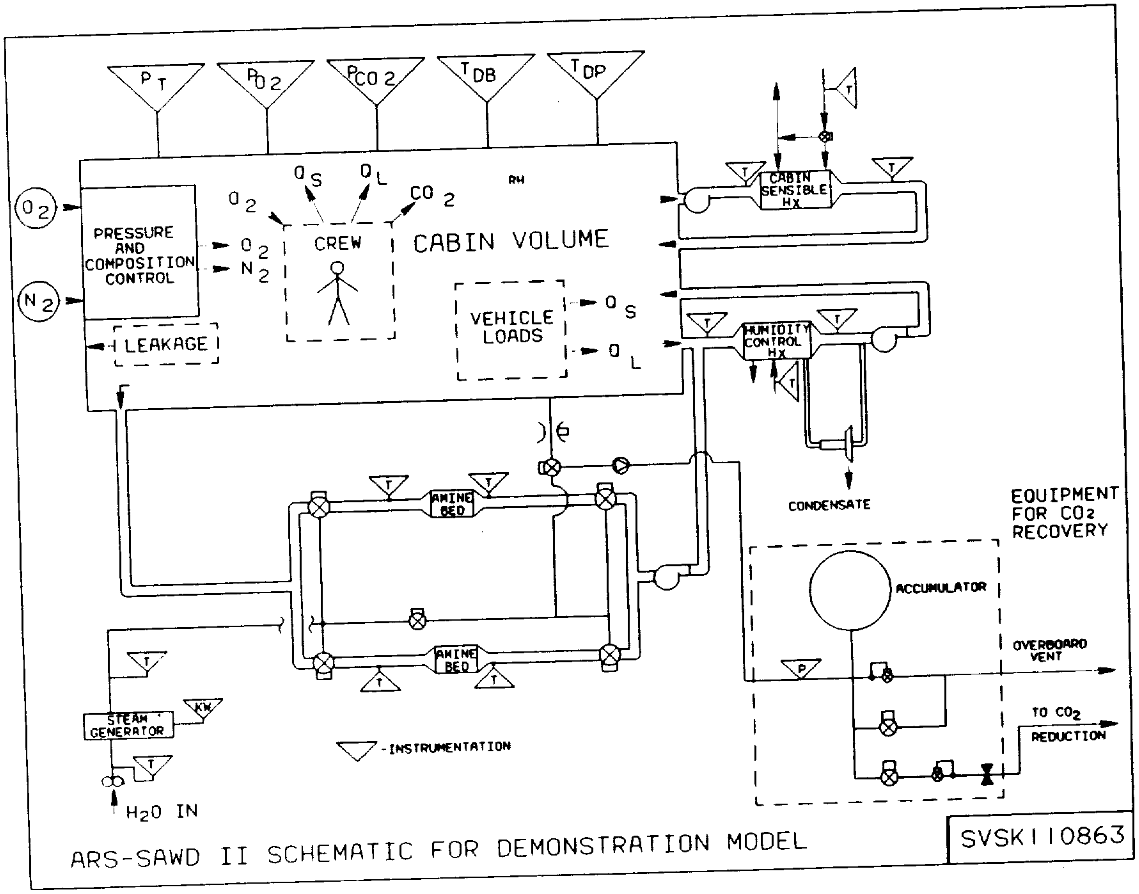

Figure 2

ARS - SAWD II Schematic For Demonstration Model

1.2 Overview of Modelled System (Continued)

Cabin air is drawn by fans into three different systems. One fan passes the air through a heat exchanger which removes sensible heat from the air. In the heat exchanger, the air gives off its heat to water which enters the heat exchanger at a temperature of 60°F. The cabin air temperature controller controls the flow of water to maintain the desired cabin air temperature. The heat exchanger is a plate-fin type similar to that on the Shuttle.

A second fan is used to draw air from the cabin into a humidity control heat exchanger. Air in this heat exchanger loses its heat to water which enters the heat exchanger at 45°F and 1.9 GPM. Water vapor in the air is condensed in this exchanger, and a portion of the main air stream, with condensed vapor, is sent to a water separator where the condensed vapor is removed. This humidity control heat exchanger also receives air flow directly from the SAWD carbon dioxide removal system. Thus, the effect of any residual moisture from the SAWD system on cabin relative humidity is lessened.

The third fan draws air from the cabin for use by the SAWD carbon dioxide (CO_2) removal system. This CO_2 removal system contains two amine beds, solenoid valves, a CO_2 accumulator, a water pump, a steam generator, a controller, and necessary plumbing and instrumentation. In general, the system operates to remove CO_2 continuously by alternately absorbing and desorbing each bed. During absorption, CO_2 collects on the amine particles of the bed. During desorption, steam is driven through the bed to raise the temperature to the saturation temperature to break the bond of CO_2 with the amine and carry the CO_2 out to the accumulator. Figure 3 shows a cross section of the bed canister.

Air from the SAWD bed undergoing absorption enters the humidity control heat exchanger where any moisture is removed. The air returning to the cabin from the SAWD system now has less CO_2. Cabin air total pressure and oxygen partial pressure are controlled by a Shuttle type two gas controller. It admits oxygen as required to maintain the oxygen partial pressure from 3.09 to 3.23 psia. It admits nitrogen to bring the total pressure up to 14.813 psia only after the oxygen partial pressure has been brought above 3.23 psia.

2.0 MODELLING OF ARS SUBGROUP FOR G189A

The ARS subgroup to be analyzed is shown in Figure 2. The following discusses how the ARS subgroup is to be modelled in terms of subroutines and requirements of the G189A computer program which is the basis for the ESCM computer program.

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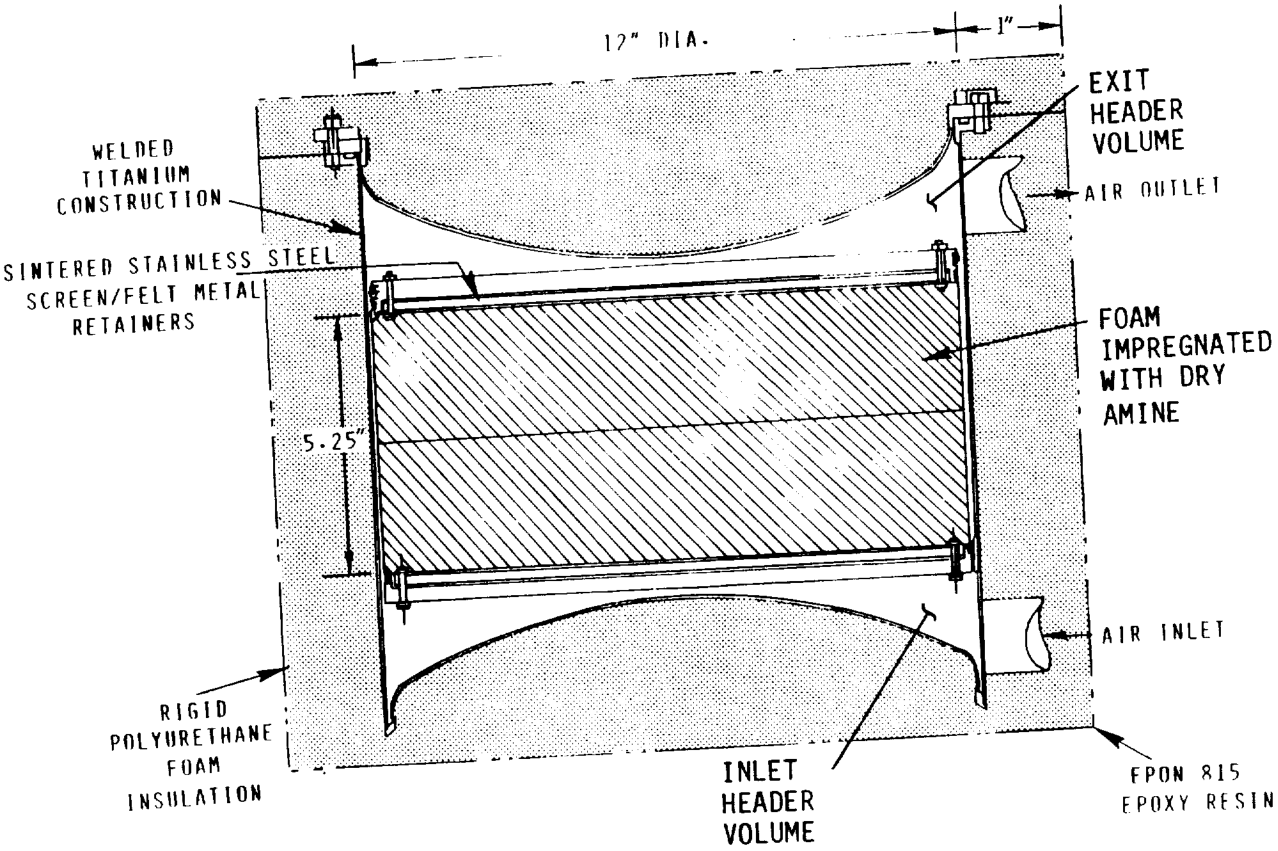

Figure 3
SAWD Canister Cross Section

2.0 MODELLING OF ARS SUBGROUP FOR G189A (Continued)

The modelled system shown in Figure 2 consists of many components. However, many are the same or similar such as valves, fans, and heat exchangers. Therefore, only the following component models are needed:

(1) Crew
(2) Cabin
(3) Fan
(4) Heat Exchanger
(5) IR45 Bed
(6) Tank
(7) Pump
(8) Steam Generator
(9) Splitter
(10) Mixer
(11) All Purpose Component

By combining these components together, the schematic shown in Figure 4 is generated to model the ARS subgroup shown in Figure 2. Table 1 presents a cross-reference between the ESCM item number and the corresponding subroutine. A comparison of these two figures reveals some subtle differences. First of all, the crew which consumes oxygen and produces carbon dioxide and water vapor is placed in series at the end of the loop that contains the sensible heat exchanger and fan. This was done to keep the schematic simple. An alternative would have been to place the crew in parallel with the sensible heat exchanger and fan; but this setup would have required an extra splitter and mixer, and the result to the cabin would be the same. The crew production of carbon dioxide and water vapor is independent of air temperature and sensible heat exchanger fan flow.

Another difference is the interfacing of the SAWD carbon dioxide removal system with the cabin. The G189A computer program permits only two sets of entrances and exits from an item - the primary and the secondary. For the cabin, the primary flow path is that which contains the sensible heat exchanger and the crew. The secondary flow path, therefore, must contain both the SAWD and the humidity control heat exchanger. This is accomplished by using a splitter (Item 3) to direct a portion of the flow to the SAWD and the remainder to the humidity control heat exchanger. The calculation of the split ratio will be discussed in Section 3.0. The return of the SAWD flow enters the inlet line to the humidity control heat exchanger in both figures.

Another difference occurs in the modelling of the three-way valves, crosses, and tees which exist in the SAWD carbon dioxide removal system. Tees in lines are modelled in the ESCM by splitters or mixers depending on whether a flow is entering a tee and then splitting or whether two flows are entering a tee and then mixing. Accordingly, item 14 represents the tee (a splitter) entering the SAWD two bed system; while item 18 represents the tee (a mixer) leaving the system. Three-way valves can also be modelled as splitters or mixers depending on whether the three-way valve directs one flow to one of two directions or whether the valve selects one

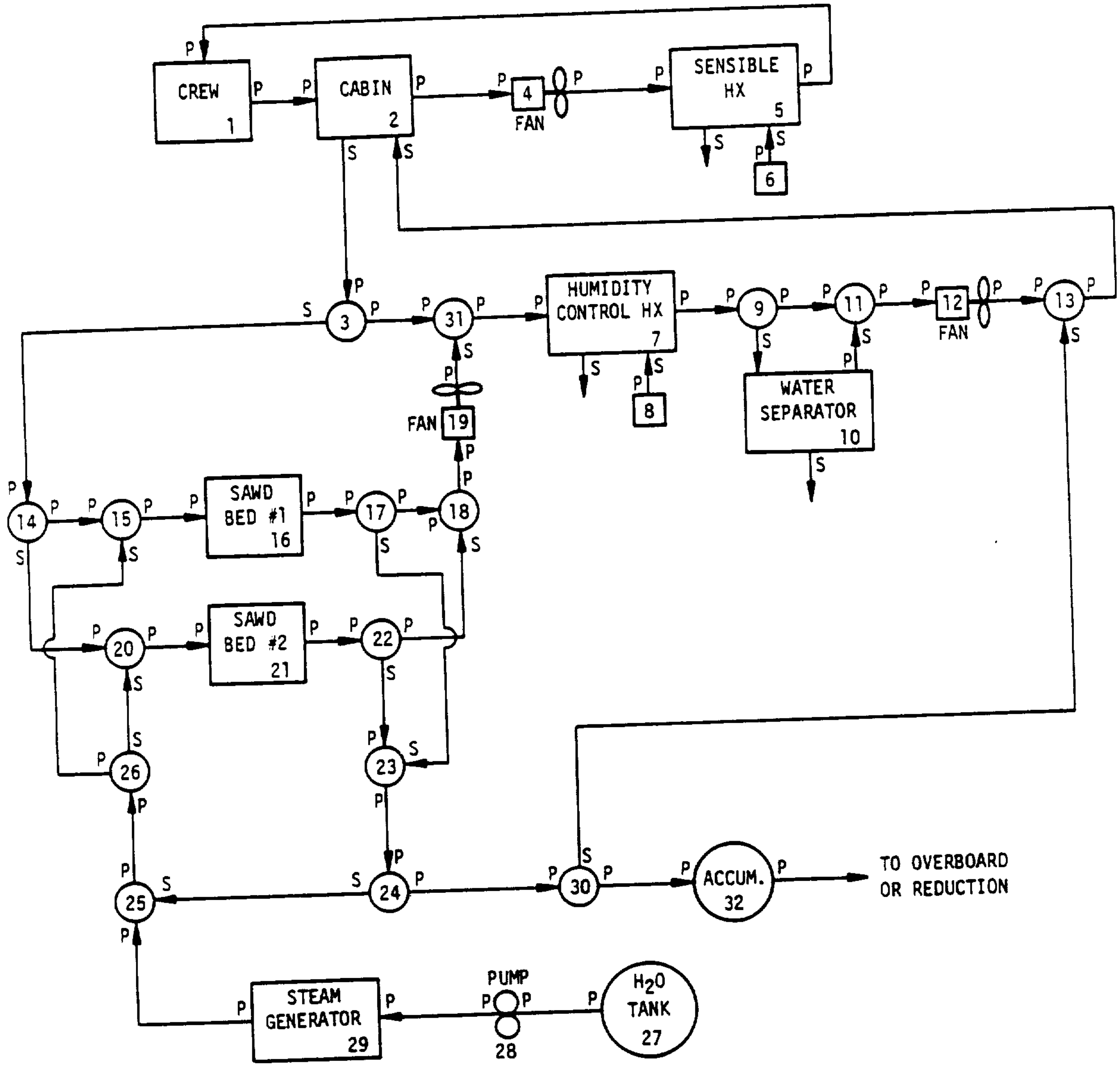

Figure 4

ARS - SAWD II Schematic As Implemented In
ESCM Computer Program

Table 1

ESCM Component Number - Subroutine Cross Reference Table

Component No.	Component Description	Subroutine Name	Subroutine No.
1	Crew in cabin	SUITS	2
2	Cabin	CABIN	1
3	Split to humidity control HX or SAWD	SPLIT	10
4	Cabin sensible HX fan	FAN	23
5	Cabin sensible HX	ANYHX	4
6	Cabin sensible HX cooling fluid boundary	ALTCOM	49
7	Cabin condensing HX	ANYHX	4
8	Condensing HX cooling fluid boundary	ALTCOM	49
9	Split to water separator or bypass	SPLIT	10
10	Water separator	ALTCOM	49
11	Mix water separator and bypass	GASMIX	6
12	Condensing HX fan	FAN	23
13	Mix SAWD and condensing HX flows	GASMIX	6
14	Split to SAWD bed #1 or #2	SPLIT	10
15	Mix steam or cabin air to bed #1	GASMIX	6
16	SAWD bed #1	IR45	73
17	Split to cond. HX or CO_2 recovery	SPLIT	10
18	Mix bed #1 and bed #2 flows	GASMIX	6
19	SAWD fan	FAN	23
20	Mix steam or cabin air to bed #2	GASMIX	6
21	SAWD bed #2	IR45	73
22	Split to cond. HX or CO_2 recovery	SPLIT	10
23	Mix bed #1 and bed #2 exit gases	GASMIX	6
24	Split to preheat or CO_2 accumulator	SPLIT	10
25	Mix steam generator and preheat streams	GASMIX	6
26	Split to SAWD bed #1 or #2	SPLIT	10
27	Water supply tank	TANKG	30
28	Water supply pump	PUMP	22
29	Steam generator	SMGEN	27
30	Split desorbed gas to cabin or CO_2 accumulator	SPLIT	10
31	Mix cabin air and SAWD air	GASMIX	6
32	Carbon dioxide accumulator tank	TANKG	30

2.0 MODELLING OF ARS SUBGROUP FOR G189A (Continued)

of two entering flows to be passed through the valve. Accordingly, the three-way valves upstream of each amine bed are modelled as mixers (items 15 and 20); while the three-way valves downstream of each amine bed are modelled as splitters (items 17 and 22). The cross, valve, and two tees between the two amine beds in the Figure 2 schematic are modelled as a combination of mixers and splitters. The action of a cross or two tees, which mix two flows together and then direct the mixed flow to one of two distinct paths, can be modelled as a series combination of a mixer and a splitter.

The last difference occurs in the equipment for carbon dioxide recovery. The back pressure regulators, downstream pressure regulators, orifice, and valves which regulate the pressure in the accumulator and the flow out of the accumulator are not modelled as separate components; but instead, their action is input in the form of equations which compute the flow leaving the item 32 accumulator.

3.0 MODELLING OF COMPONENTS

As discussed in Section 2.0, only eleven component analytical models need be available to analyze the ARS subgroup. The following sections will discuss these analytical models, the generation of performance constants, and any other parameters necessary to describe the analytical model. In many instances, the analytical model is already described in the Reference 3 G189A Manual. In those cases, the reader will be referred to the G189A manual for a description of the analytical model.

In addition to the eleven components, the control of cabin temperature, cabin air total pressure, cabin oxygen partial pressure, and the SAWD system are performed in GPOLY1 and GPOLY2 subroutines. A description of these control laws will be provided.

3.1 Crew

The crew affects the gas stream temperature, oxygen content, carbon dioxide content, and water content as a result of its metabolic functions. To solve for these influences, first a crewman total metabolic load schedule is required. The loading shown in Figure 5 shows a probable profile with different loadings for eating, working, exercising, and sleeping. The average loading over the 24 hour period is 477 Btu/man-hour. This is equivalent to a carbon dioxide generation rate of 2.2 lbm/man-day. From the crewman metabolic load, the per man sensible and latent splits are calculated in GPOLY1 using the following relations:

QL = MR - 430 + (MR/1000 + 10) * (TCAB - 60)
QLMIN = 0.22 * MR + 2.6 * (TCAB - 60)
QL = Larger of QL and QLMIN
QS = MR - QL

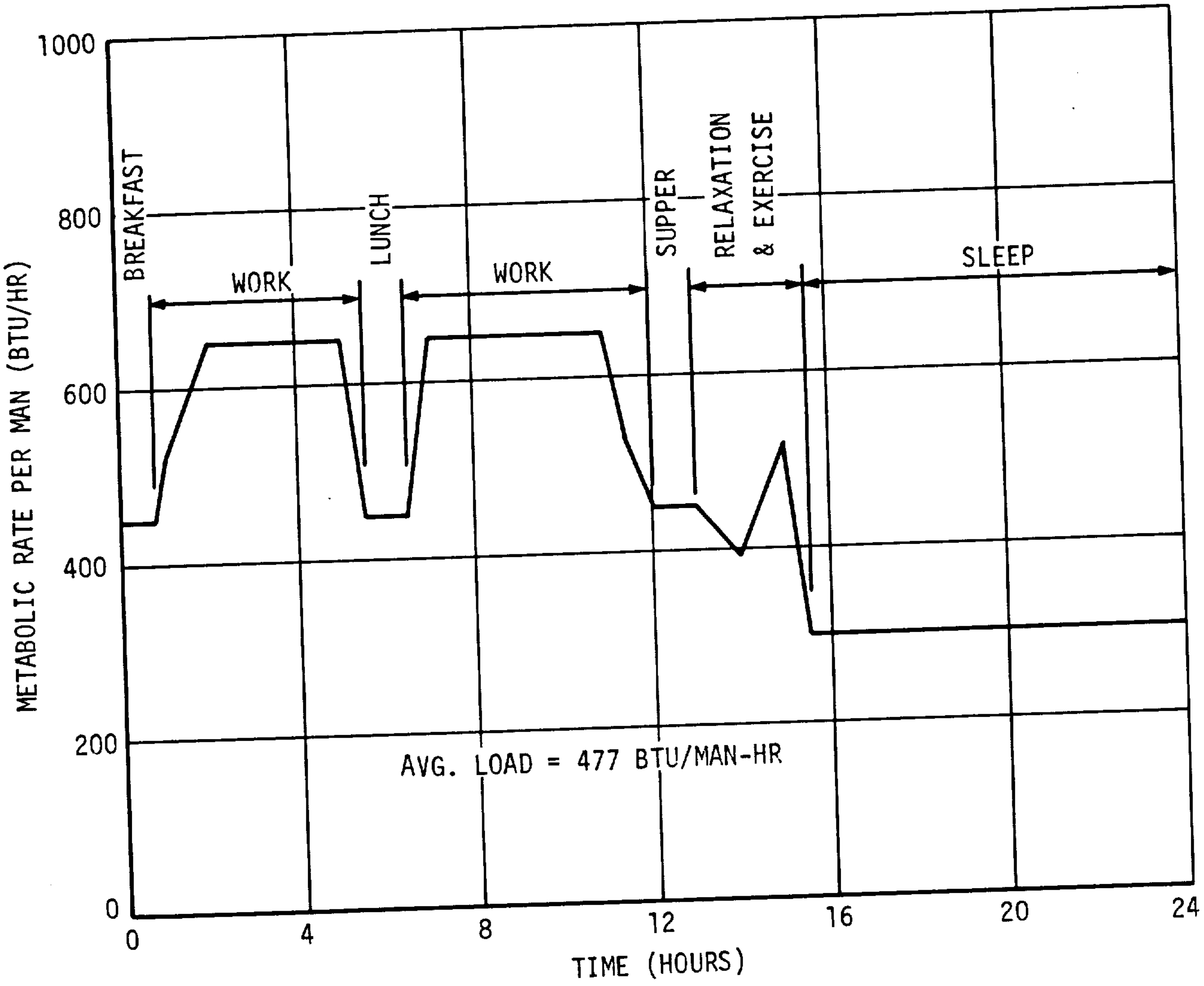

Figure 5

Crewman Metabolic Heat Load Profile

3.1 Crew (Continued)

Where:
MR = per man metabolic heat load, Btu/man-hr
TCAB = cabin air temperature, °F
QL = latent heat added to the gas stream per man, Btu/man-hr
QLMIN = minimum latent heat added to the gas stream per man, Btu/man-hr
QS = sensible heat added to the gas stream per man, Btu/man-hr

With the sensible and latent heat loads known, subroutine SUITS is used to compute the following:

QT = total gas stream heat load from the crew, Btu/hr
WCO2 = total crew carbon dioxide generation rate, lbm/hr
WO2 = crew oxygen gas usage, lbm/hr
WH2O = crew water vapor generation rate, lbm/hr

The equations used to compute the above are described in Reference 3. To compute the new temperature of the gas stream due to the sensible heat input by the crew, the following relation is used which is not described in Reference 3:

$$T_e = (m_i\, c_p\, T_i + N * QS) / (m_i\, c_p)$$

Where:
T_e = exiting temperature of flow to which the crew sensible heat is added, °F
m_i = flow to which crew sensible heat is added, lbm/hr
c_p = specific heat of flow, Btu/lbm-°F
T_i = inlet temperature of flow, °F
N = number of people in crew
QS = sensible heat added to the gas stream per man, Btu/man-hr

The only options available in the SUITS subroutine are to decide if (1) the inlet or outlet dew point and temperature are to be compared against design criteria and (2) if steady state or transient crew analyses are to be performed. The options selected as appropriate for ESCM are to perform steady state analyses and not to perform any comparisons against design criteria.

3.2 Cabin

The cabin as used in the ESCM is essentially a mixing chamber for the flows that come from the sensible heat exchanger, condensing heat exchanger, the crew, the SAWD carbon dioxide removal system, and the oxygen and nitrogen supply systems. Two separate subroutines are used for steady state and transient calculations. The steady state performance of the cabin is calculated in Subroutine CABIN; while the transient performance calculations are performed in subroutine CABINT. A complete description of the analyses performed in these subroutines is given in Reference 3.

3.2 Cabin (Continued)

The following options are used in the ESCM application:

(1) The primary source flow pressure is used as the cabin mixture pressure during steady state calculations.

(2) Reset the cabin primary and secondary side outflow data equal to the initial input data for five steady state passes.

(3) Calculated entrained liquid in the cabin will remain in the cabin air mixture.

(4) Cabin outflows will be calculated for both the primary and secondary paths.

(5) Mass addition temperatures are specified.

(6) During transient analyses, the net constituent mass flows in the cabin are computed in GPOLY. These flows are the oxygen and nitrogen addition rates input by the two gas controller.

(7) The inner wall is considered to be a boundary temperature.

(8) The furnishings are considered to be a boundary temperature.

(9) The outer wall is considered to be a boundary temperature.

Input specific to the ESCM application are as follows:

(1) Initial flows, temperatures, and pressures:

	Primary	Secondary
Cabin gas exit temperature, °F	70	70
Inlet pressure, psia	14.7	14.7
Exit pressure, psia	14.7	14.7
Water vapor flow, lbm/hr	89.7	13.0
Oxygen flow, lbm/hr	2046.8	303.76
Nitrogen flow, lbm/hr	7199.4	1068.67
Carbon dioxide flow, lbm/hr	63.4	9.45

(2) Control setpoints, tolerances, and limits:

Cabin gas temperature control setpoint, °F	70
Cabin gas temperature control tolerance, °F	10
Cabin gas total pressure control setpoint, psia	14.7*
Cabin gas total pressure control tolerance, psia	0.5*
Cabin gas oxygen pressure control setpoint, psia	2.9*
Cabin gas oxygen pressure control tolerance, psia	0.5*
Cabin gas dew point control setpoint, °F	50
Cabin gas dew point control tolerance, °F	10
Maximum allowable CO_2 pressure, mmHg	7.5
Maximum allowable trace contaminant level, ppm	250

*These values are merely to describe the approximate two gas control setpoints and tolerances which are hardwired into the computer program. The actual control is described in Section 3.12.1. Accordingly, a change in these inputs has no influence on the two gas control setpoints and tolerances.

3.2 Cabin (Continued)

(3) Mass addition rates and temperatures:

Water vapor addition rate, lbm/hr	0.233
Entrained water addition rate, lbm/hr	0.000
Water vapor addition temperature, °F	70
Oxygen addition temperature, °F	70
Nitrogen addition temperature, °F	70
Carbon dioxide addition temperature, °F	70
Trace contaminants addition temperature, °F	70
Special flow no. 1 addition temperature, °F	70

(4) Net flows into cabin resulting from primary and secondary flow stream conditions:

Net carbon dioxide addition, lbm/hr	0.0
Net trace contaminants addition, lbm/hr	0.0
Net special flow no. 1 addition, lbm/hr	0.0

(5) Miscellaneous cabin parameters:

Equipment, lighting, and miscellaneous heat loads, Btu/hr	17065
Outboard leakage rate, lbm/hr	0.0833
Cabin free volume, ft^3	8000

The above listed values are determined as follows:

(1) Water vapor addition rate:

From Reference 2 Table 1,

Hygiene latent load = 0.96 lbm/man-day
Food preparation latent load = 0.06 lbm/man-day
Experiments latent load = 1.00 lbm/day-module
Laundry latent load = 0.13 lbm/man-day

Assume number of men = 4 for conservative sizing

Hygiene = 4 x 0.96 = 3.84
Food = 4 x 0.06 = 0.24
Experiments = 1.00 = 1.00
Laundry = 4 x 0.13 = $\underline{0.52}$
5.60 lbm/day = 0.233 lbm/hr

(2) Equipment, lighting, and miscellaneous heat loads:

From Reference 2 Table 1, the Non-ECLSS thermal load is 5.00 kw per module. Therefore:

Q = 5.00 x 3.413 = 17065 Btu/hr-module

3.2 Cabin (Continued)

(3) Outboard leakage rate:

From Reference 2 Table 1, the cabin atmosphere leakage is 2.00 lbm/day-module. Accordingly, the per hour leakage rate is 0.0833 lbm/hr-module.

(4) Cabin free volume:

Any volume can be input by the user for the cabin volume. An assumed volume of 8000 cubic feet is used.

(5) Control setpoints are taken as roughly the midpoint of the band for allowable temperatures and gas compositions specified in Reference 2.

	Ref. 2 Range	Selected Value
Cabin gas total pressure, psia	10.0-14.7	14.7
Oxygen pressure, psia	2.7-3.2	2.9
Water vapor pressure, psia	0.12-0.26	0.20
Dew point, °F	40-60	50
Carbon dioxide pressure, mmHg	3 avg 7.6 max	7.6 max
Dry bulb temperature, °F	65-75	70

(6) Initial flows:

A rough guess at initial flows out of the cabin through the primary and secondary flow paths is obtained by the following calculations:

$P_T = 14.7$ psia

$P_{O2} = 2.9$ psia

$P_{H2O} = 0.2$ psia

$P_{CO2} = 3.0$ mmHg $= 0.06$ psia

$P_{N2} = 14.7 - 2.9 - 0.2 - 0.06$
$= 11.54$ psia

From Section 3.3, the sensible and condensing heat exchanger fan flows are:

Sensible heat exchanger = 2100
Condensing heat exchanger = $\underline{300}$
2400 cfm

3.2 Cabin (Continued)

Gas	Mw	Press (psia)	Density* (pcf)	Flow, lbm/hr Primary	Secondary
Nitrogen	28.016	11.54	.0569	7169	1024
Oxygen	32	2.90	.0163	2054	293
Water vapor	18.016	0.20	.000634	80	11
Carbon dioxide	44.01	0.06	.000449	57	8

$$* \rho = \frac{144PM_w}{R\ T} \quad \text{where } T = 70°F = 530°R$$

The above values were used as the first guess. After having run the ESCM program, the program computes the actual steady state flows. These computed values can then be used as a better first guess for subsequent cases. These better first guesses are the values shown in Reference 4 Table 8 for the initial flows in the input specific to ESCM.

3.3 Fan

Three fans exist in the ARS subgroup modelled by ESCM. They are the sensible heat exchanger fan, condensing heat exchanger fan, and the SAWD carbon dioxide removal system fan. The G189A subroutine FAN is used to model the fans. Reference 3 gives a complete description of the analytical models used in the subroutine. Of the different analytical models available in that subroutine, the following is used for the sensible and condensing heat exchanger fans:

$$(m_T)_e = 60 * cfm * \rho$$

$$P_e = P_i$$

$$\dot{Q} = w * 3.413$$

$$T_e = T_i + \frac{\dot{Q}}{(m_T)_e\ c_p}$$

$$R = (m_T)_e/(m_T)_i$$

$$(m_{nc})_e = (m_{nc})_i * R$$

$$(m_v)_e = (m_v)_i * R$$

$$(m_l)_e = (m_l)_i * R$$

$$(m_{O2})_e = (m_{O2})_i * R$$

$$(m_{N2})_e = (m_{N2})_e * R$$

$$(m_{CO2})_e = (m_{CO2})_e * R$$

3.3 Fan (Continued)

Where:

m = mass flow, lbm/hr
cfm = fan volumetric flow, cfm
ρ = density of fan incoming gas, lbm/ft^3
w = fan power, watts
$\dot{Q}$ = fan heat added to gas stream, Btu/hr
cp = specific heat of incoming gas, Btu/lbm-°F
R = ratio of fan outlet to inlet flow

Subscripts:

T = total
e = outlet
i = inlet
nc = non-condensables
v = water vapor
l = entrained liquid
02 = oxygen
N2 = nitrogen
C02 = carbon dioxide

The only input needed is the fan cfm and power for each fan.

3.3.1 Condensing Heat Exchanger Fan

For the condensing heat exchanger fan, the following analysis was used to obtain the fan cfm and power:

Assume:

dry bulb temperature, $T_{db} = 70°F$
relative humidity, RH = 55%

Therefore:

P_{sat} @ 70°F = 0.3631 psia
P_v @ 70°F 55% RH = 0.55 * 0.3631 = 0.1997 psia

The corresponding dew point is obtained from the steam tables of Reference 5.

$$T_{dp} = T_{sat} \text{ @ } 0.1997 \text{ psia} = 53.1°F$$

$$\omega_i = \frac{M_v}{M_a}\frac{P_v}{P_a} = \frac{M_v}{M_a}\frac{P_v}{P_T - P_v}$$

3.3.1 Condensing Heat Exchanger Fan (Continued)

Where:

ω = specific or absolute humidity, lbm vapor/lbm air
M_v = molecular weight of the vapor, lbm/lb-mole
M_a = molecular weight of air, lbm/lb-mole
P_v = absolute pressure of vapor, psia
P_a = absolute pressure of air, psia

Therefore:

$$\omega_i = \frac{18.016}{28.95} * \frac{0.1997}{10-0.1997} = 0.01268$$

In the condensing heat exchanger, assume:

$(T_{H2O})_i = 45°F$

$(T_a)_i = 70°F$

Effectiveness, = 0.85

$(T_a)_e = 70 - 0.85\ (70 - 45) = 48.8°F$

Assume saturated conditions at exit. Therefore from Ref. 5:

$T_{sat} = 48.8°F \quad P_{sat} = (P_{H2O})_e = 0.1703$ psia

$$\omega_e = \frac{18 * 0.1703}{28.92 * (10-0.1703)} = 0.01078$$

$\Delta\omega = \omega_i - \omega_e = 0.01268 - 0.01078 = 0.00190$

The mass flow of dry air is determined from:

$$m_a = \frac{m_l}{\omega_{in} - \omega_{out}}$$

Where:

m_a = mass flow of dry air, lbm/hr
m_l = mass flow of condensed water, lbm/hr

The mass flow of water to be condensed is determined for a four man crew. From Reference 4 Table 1:

Load		
Sweat and Respiration	= 8 * 4.02 =	32.16 lbm/day
Hygiene Latent Load	= 8 * 0.96 =	7.68 lbm/day
Food Preparation	= 8 * 0.06 =	0.48 lbm/day
Experiments	= 1.00 =	1.00 lbm/day
Laundry	= 8 * 0.13 =	1.04 lbm/day
Average SAWD Load	= 8 * 4.88 =	39.04 lbm/day
Total		81.40 lbm/day

3.3.1 Condensing Heat Exchanger Fan (Continued)

For a 4 man system, the load is 40.7 lbm/day. Substituting this water condensation rate into the above equation for the mass flow of dry air yields:

$$m_a = \frac{40.7/24}{0.00190} = 892.5 \text{ lbm/hr}$$

The fan cfm then is:

$$cfm = \frac{m_a}{\rho\, 60}$$

Where:

cfm = fan flow, cfm

ρ = density of air, lbm/ft^3

$$cfm = \frac{892.5}{.051 * 60} = 292 \text{ cfm} \quad \text{Use 300 cfm}$$

To compute the fan power, the following equation and assumptions are used:

$$w = \frac{cfm * \Delta P}{8.5 * \eta}$$

Where:

w = fan power, watts
ΔP = fan head rise, In-H_2O
η = fan efficiency
cfm = fan volumetric flow, cfm

Assume:

ΔP = 2.0 In-H_2O

η = 0.5

$$w = \frac{292 * 2.0}{8.5 * 0.5} = 137 \text{ watts}$$

The condensing heat exchanger sensible heat load is:

$$\dot{Q} = m\, c_p \Delta T = 892.5 \times 0.24 \times (70 - 48.8) = 4541 \text{ Btu/hr} = 1330 \text{ watts}$$

3.3.2 Sensible Heat Exchanger Fan

The loads for the sensible heat exchanger are as follows:

Non-ECLSS loads = 5000 w/module

Modelled ECLSS loads:

CHX Fan	= 137 watts
SAWD Fan + Steam	= 86 watts
	223 watts

$$\text{For 4 man crew} = \frac{7000 * 4}{3.413 * 24} = 342$$

$$\Sigma w = 5000 + 223 + 342 - 1330 = 4235 \text{ watts}$$

The value of 1330 watts is subtracted in the above equation to account for the sensible heat removed by the condensing heat exchanger. For the sensible heat exchanger assume the following:

$(T_a)_i = 71.8°\text{F}$ (1.8°F additional for fan)

$(T_{H20})_i = 60°\text{F}$

effectiveness, $\epsilon = 0.80$

$$(T_a)_e = (T_a)_i - \epsilon[(T_a)_i - (T_{H20})_i]$$

$$= 71.8 - 0.80\ (71.8 - 60)$$

$$= 62.4°\text{F}$$

The flow of air is then given by:

$$= \frac{\dot{Q}}{cp\ \Delta T} = \frac{4235 * 3.413}{0.24 * (71.8 - 62.4)}$$

$$= 6407 \text{ lbm/hr}$$

$$\text{cfm} = \frac{m_a}{\rho 60} = \frac{6499}{.051 * 60} = 2093 \qquad \text{Use 2100 cfm}$$

3.3.2 Sensible Heat Exchanger Fan (Continued)

The fan power required is:

$$w = \frac{cfm * \Delta P}{8.5 * \eta}$$

Assume:

ΔP = 2 In-H_2O

η = 0.60

$$w = \frac{2093 * 2.0}{8.5 * 0.60} = 821 \text{ watts}$$

3.3.3 SAWD Fan

For the SAWD fan, the following analytical model is used:

$$(m_T)_e = (m_T)_i$$

$$P_e = P_i$$

$$\dot{Q} = w * 3.413$$

$$T_e = T_i + \frac{\dot{Q}}{(m_T)_e \ c_p}$$

$$(m_{nc})_e = (m_{nc})_i$$

$$(m_v)_e = (m_v)_i$$

$$(m_1)_e = (m_1)_i$$

$$(m_{O2})_e = (m_{O2})_i$$

$$(m_{N2})_e = (m_{N2})_i$$

$$(m_{CO2})_e = (m_{CO2})_i$$

The SAWD fan flow however is an input item which depends on the cycle phase and the time within that phase. During startup, the fan slowly builds in cfm as the air flows through the bed and the bed dries. The drier the bed, the less is the resistance to flow. During the energy transfer phase, air must pass through a wet bed and then into the second bed which is dry.

3.3.3 SAWD Fan (Continued)

The fan cfm is shown in Figure 6 as a function of time within a phase. During energy transfer where air is flowing through two beds, the fan flow follows the energy transfer phase curve shown in Figure 6. When the energy transfer phase is completed, the flow which existed at the end of the energy transfer phase is used as the starting point flow on the absorption phase curve and a pseudo-elapsed time is created. The fan cfm then increases along the absorption phase curve per this pseudo elapsed time.

For the SAWD fan power, assume:

cfm = 21

$\Delta P = 7$ In-H_2O

$\eta = 0.35$

$$\text{Power} = \frac{Q\ \Delta P}{8.5\,\eta} = \frac{21 * 7}{8.5 * 0.35} = 49.4 \text{ watts} \qquad \text{Use 50 watts}$$

3.4 Heat Exchangers

Two heat exchangers are in the ARS subgroup modelled by ESCM. They are the cabin air sensible heat exchanger and the cabin air humidity control heat exchanger. The subroutine used in ESCM to model the heat exchanger is called ANYHX and a complete description of all the equations and options used in the subroutine is given in Reference 3. The option used in the ESCM is to input the heat exchanger UA and then to use the standard steady state effectiveness - NTU relations for a counter flow heat exchanger to compute the heat exchanger performance and exit temperatures.

The UA for the sensible heat exchanger is 6240 Btu/hr-°F and is calculated as follows:

$$(T_{H2O})_{out} = \frac{\dot{Q}}{m\ c_p} + (T_{H2O})_{in} = \frac{(4235 + 821) * 3.413}{1900} + 60$$

$$= 69.1°\text{F}$$

$$\frac{c_{min}}{c_{max}} = \frac{6500 * 0.24}{1900 * 1.0} = 0.821$$

For a counter flow heat exchanger with $\epsilon = 0.80$ and $c_{min}/c_{max} = 0.821$, NTU = 4.0.

Therefore:

$$UA = NTU * c_{min} = 4.0 * 6500 * 0.24 = 6240 \text{ Btu/hr-°F}$$

This is a constant UA for the the sensible heat exchanger.

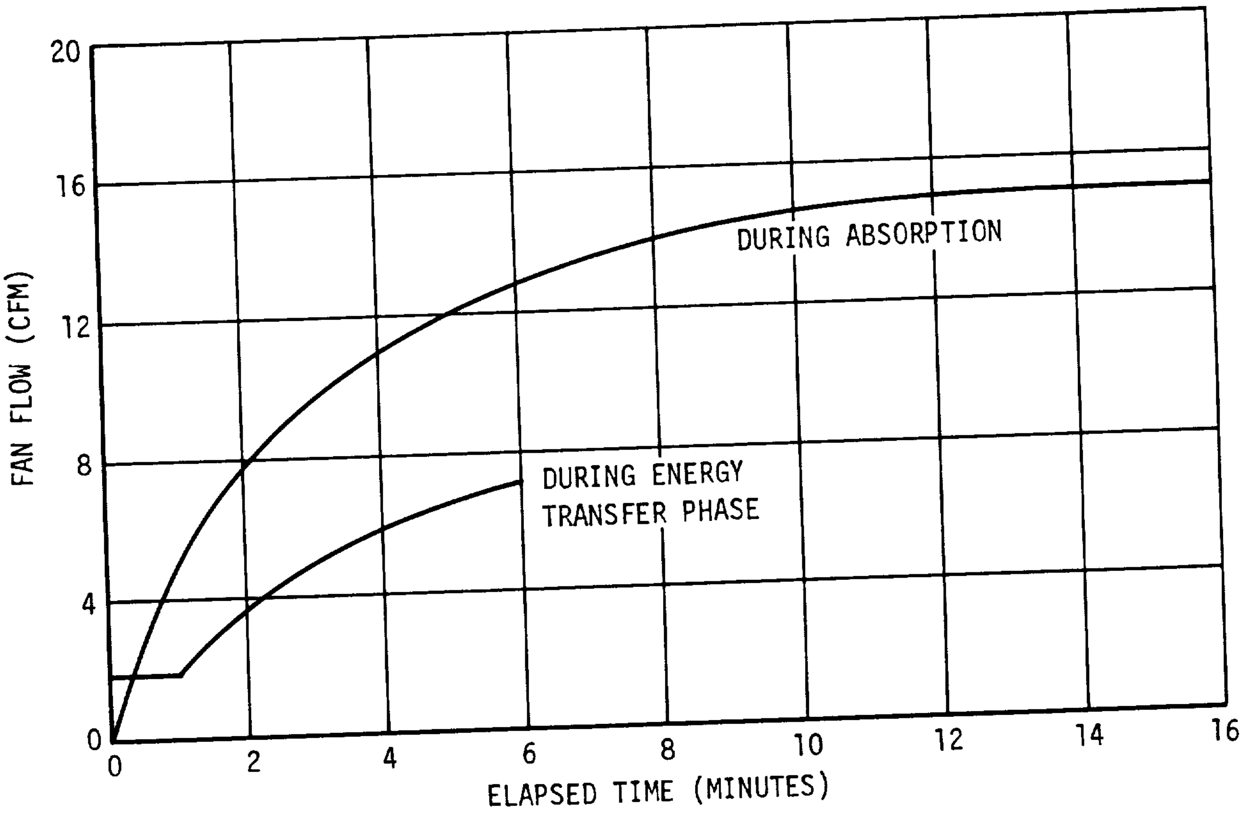

Figure 6
SAWD Fan Flow

3.4 Heat Exchangers (Continued)

The UA for the condensing heat exchanger is computed in subroutine GPOLY1 and the following relation is used:

$$UA = e^{(2.809 - .00169 * m_{H2O})} * m_{max}^{(0.52 + 0.00026 * m_{H2O})}$$

Where:

m_{max} is the maximum of the following:

(1) m_{air} = total air flow into heat exchanger including the vapor flow.

(2) $m_{eff} = m_{air} * \frac{(c_p)_{eff}}{(c_p)_{air}}$

The effective specific heat is defined in Reference 3 in the subroutine description for ANYHX.

3.5 SAWD Bed

The analysis of the SAWD bed is perfomed in subroutine IR45 which is the name of the resin used in the bed. This subroutine is newly written for ESCM and is not described in the Reference 3 G189A Manual. In this document is described the analysis modelled in subroutine IR45 to compute the carbon dioxide absorption and desorption from the resin.

As shown in Figure 2, the SAWD bed consists of inlet and outlet header volumes and a central volume consisting of foam impregnated with dry amine. In the computer model, this central volume is divided into five segments. Thus, as shown in Figure 7, the model of the SAWD canister consists of an inlet and exit header, five void volume segments and five corresponding resin plus foam plus can segments, and a temperature sensor. The air flows into the inlet header, through void segments one through five, out the outlet header, and lastly past the temperature sensor. In the void segments, water and carbon dioxide are exchanged with the corresponding resin segments. The following sections describe the equations which model the processes occurring in the headers, the bed void and resin segments, and the temperature sensor.

3.5.1 The Headers

The fundamental process modelled in the headers is the mixing of the incoming gas with the gas already residing in the header. This mixing process results in an equilibrium temperature and a required amount of exiting gas to maintain the pressure less than or equal to the downstream. If the mixed gas is a mixture of non-condensables and vapor, the following analysis is used:

SAWD canister is divided into seven segments including 5 bed segments

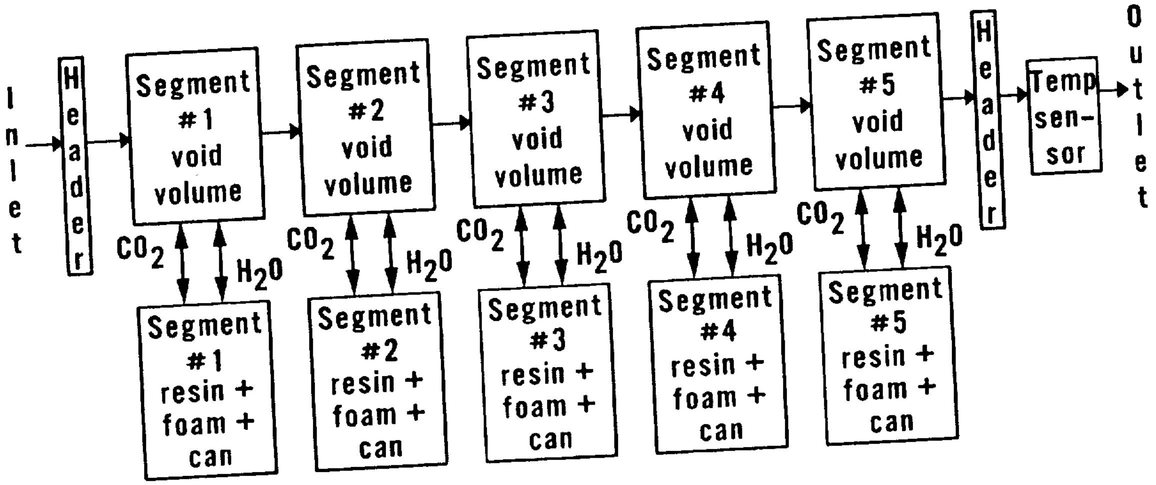

Figure 7
SAWD Canister Simulation

3.5.1 The Headers (Continued)

$$HA = (M_{nc}c_{p,nc})_i \; T_i + (M_v)_i \; h_{g,i} + (M_l)_i \; h_{l,i}$$

$$HS = (M_{nc}c_{p,nc})_{ST} \; T_{ST} + (M_v)_{ST} \; h_{g,ST} + (M_l)_{ST} \; h_{l,ST}$$

$$HMIX = HA + HS$$

Where:

HS = Total enthalpy of gas entering header, Btu
HS = Total enthalpy of gas already stored in header, Btu
HMIX = Total enthalpies of gases entering and stored, Btu

Subroutine HBALNC is called to establish the mixture temperature, mass of vapor, and mass of entrained liquid for an initial starting pressure equal to the downstream pressure. With this new mixture temperature, mass of vapor, and mass of entrained liquid, the pressure in the header is computed using the perfect gas law as follows:

$$M_T = (M_{nc} + M_v + M_l)_i + (M_{nc} + M_v + M_l)_{ST}$$

$$P = \frac{\bar{R} \; M_T \; T}{144 \; M_w V_o}$$

Where:

V_o = volume in header, ft^3

If the pressure P calculated is greater than the input downstream pressure, then iteration ceases and the mass of gas leaving the header is computed to make the mass of gas remaining give the downstream pressure. To do this the following relations are used:

$$M_e = M_T \; (1 - \frac{P_d}{P})$$

$$M_{ST} = M_T * \frac{P_d}{P}$$

On the other hand, if the pressure P calculated is less than the downstream pressure, the iteration is repeated with pressure P used in HBALNC instead of the downstream pressure. The iteration repeats until the pressure tried equals the pressure calculated using the perfect gas law. When this occurs, all the gas stays in the header. Therefore:

$$M_e = 0.0$$
$$M_{ST} = M_T$$

3.5.1 The Headers (Continued)

The case for the gas being a mixture of non-condensables and vapor was just described. The following describes the analyses for the case where the gas is all vapor. First, analyses are performed assuming all the steam will stay in the header because the downstream pressure is too great. In this case, temperature is iterated upon until the energy equation is balanced.

Energy In + (Energy Stored)$_1$ = (Energy Stored)$_2$

$$H_i = M_i\, h_{g,i} \tag{1}$$

$$H_{ST,1} = M_{ST,1}\left[h_{g,ST} - \frac{\bar{R}\,(T_{ST} + 460)}{(M_W)_v\, J}\right] \tag{2}$$

$$M_T = M_{ST,1} + M_i$$

$$H_{ST,2} = M_T\left[h_{g,TRY} - \frac{\bar{R}\,(T_{TRY} + 460)}{(M_W)_v\, J}\right] \tag{3}$$

$$H_{ST,2} = H_{ST,1} + H_i \tag{4}$$

Temperature T_{TRY} is iterated upon until equation (4) is satisfied. At this point, the pressure in the header is computed assuming all the vapor stays in the header and using the new temperature of stored vapor in the header.

$$T_{ST,2} = T_{TRY}$$

$$P = \frac{M_T\,\bar{R}\,(T_{ST,2} + 460)}{144\,(M_W)_v\, V_o}$$

If this pressure is indeed less than the downstream pressure, then all the steam does stay in the header. If this pressure is greater than the downstream pressure, then the energy balance must be repeated with an exiting enthalpy term added.

Energy In + (Energy Stored)$_1$ = Energy Out + (Energy Stored)$_2$

$$M_{ST,2} = \frac{144\, P_d\, (M_W)_v\, V_o}{\bar{R}\,(T_{TRY} + 460)} \tag{5}$$

$$M_e = M_T - M_{ST,2} \tag{6}$$

$$H_{ST,2} = M_{ST,2}\left[h_{g,TRY} - \frac{\bar{R}\,(T_{TRY} + 460)}{(M_W)_v\, J}\right] \tag{7}$$

$$H_e = M_e\, h_{g,TRY} \tag{8}$$

$$H_e + H_{ST,2} = H_i + H_{ST,1} \tag{9}$$

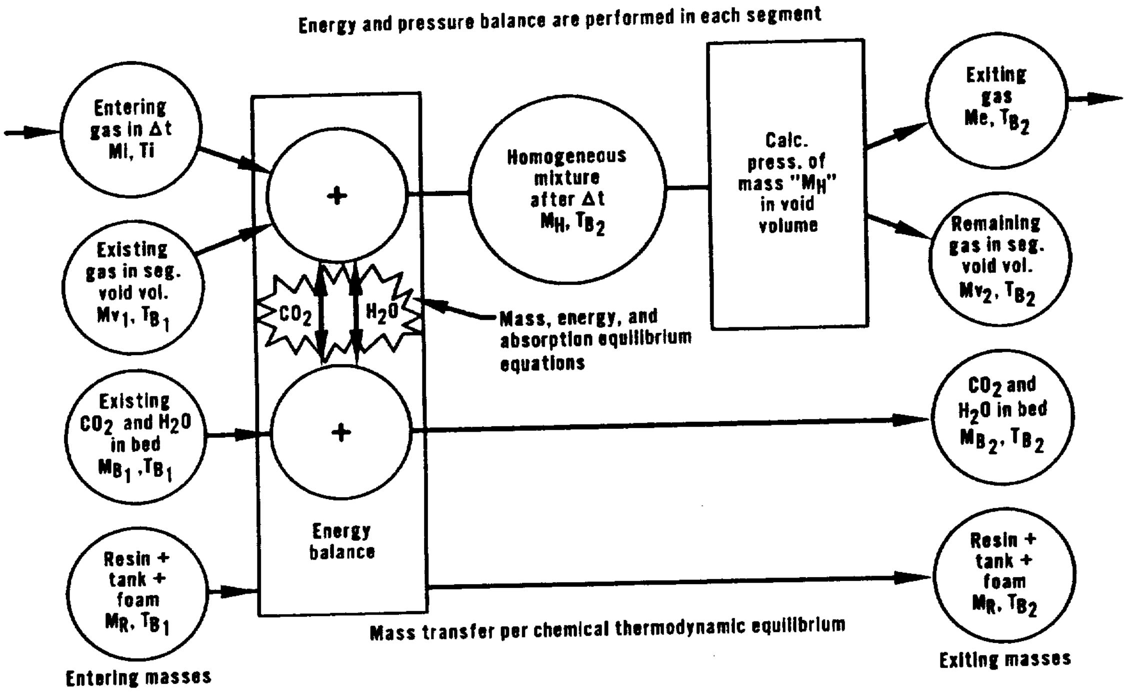

Figure 8

SAWD Bed Energy Balance

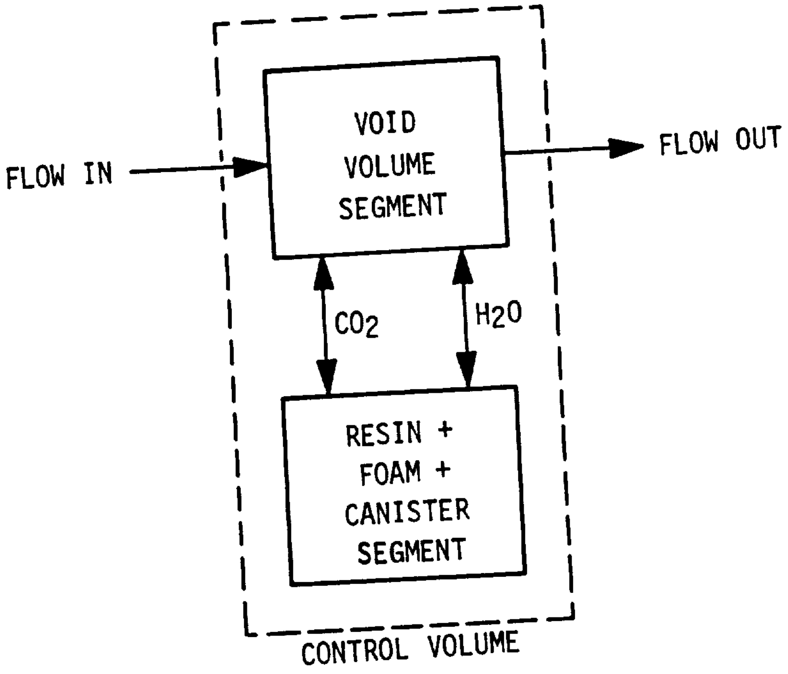

Figure 9

Control Volume Around Bed Segments

3.5.1 The Headers (Continued)

Temperature T_{TRY} is iterated upon in equations (5) through (9) until equation (9) is satisfied. At that point, the exiting gas temperature and temperature of gas left in the header are set equal to T_{TRY}. The pressure in the header is set equal to the downstream pressure.

3.5.2 The Resin Plus Void Plus Canister

The SAWD bed is divided axially into five void volume segments and five resin plus foam plus canister segments as shown in Figure 7. For each combination of matching void volume and resin segments, a mass and energy balance is performed as pictorially illustrated in Figure 8.

A mass of gas M_i enters the void volume at temperature T_i during a time step t. This mass of gas is assumed to mix with the existing gas M_V, in the void volume which is at a temperature T_{B1}. In the matching numbered segments is a mass of water and carbon dioxide M_{B1} resident on the resin at a temperature T_{B1}. Also in this matching numbered segment is a mass of resin, foam, and tank M_R which remains constant and which is at a temperature T_{B1} too. A mass and energy balance is performed between the void and resin segments to determine the exchange of water and carbon dioxide between the void volume and the resin and to determine the new temperature of the gas mixture and the bed T_{B2}. The new mass of gas in the void volume M_H and its temperature T_{B2} are used in the perfect gas law to calculate the pressure in the segment void volume if all the gas were to remain in the segment. Gas M_e not needed to maintain the pressure is permitted to leave with the same properties and constituent mass fractions as the mixture. The remaining gas M_{V2}, the carbon dioxide and water in the resin M_{B2}, and the resin plus tank plus foam M_R are all at the final temperature T_{B2}.

The energy balance equation begins with the uniform state uniform flow form of the first law of thermodynamics as presented in Reference 6 by Van Wylen and Sonntag:

$$Q + \sum M_i \left(h_i + \frac{V_i^2}{2gc} + Z_i \frac{g}{gc}\right) = W + \sum M_e \left(h_e + \frac{V_e^2}{2gc} + Z_e \frac{g}{gc}\right)$$

$$+ \sum M_2 \left(u_2 + \frac{V_2^2}{2gc} + Z_2 \frac{g}{gc}\right) - \sum M_1 \left(u_1 + \frac{V_1^2}{2gc} + Z_1 \frac{g}{gc}\right)$$

This form of the first law is applied to a control volume around the void volume segment and the corresponding numbered resin segment as shown in Figure 9. The assumptions in applying this first law are:

3.5.2 The Resin Plus Void Plus Canister (Continued)

1) The control volume remains constant relative to the coordinate system.

2) The state of the mass crossing the control surface is constant with time and uniform over the various areas of the control surface where flow occurs.

3) The state of the mass within the control volume may change with time; but, at any instant of time, the state is uniform over the entire control volume (or over several identifiable regions that make up the entire control volume).

For the SAWD control volume, as presently modelled:

$$W = 0.0 \qquad V_2 = V_1 = 0.0$$

$$Q = 0.0 \qquad Z_2 = Z_1 = Z_e = Z_i = 0.0$$

Also, it is assumed that changes in kinetic energy are negligible compared with the other changes. The first law will now be expanded to itemize each of the constituents and then rearranged to a form suitable for the computer. The first law can be expanded to:

$$\begin{aligned}0 = {} & (M_{v,e}\, h_{v,e} - M_{v,i}\, h_{v,i}) + (M_{nc,e}\, h_{nc,e} - M_{nc,i}\, h_{nc,i}) + \\ & (M_{cg,e}\, h_{cg,e} - M_{cg,i}\, h_{cg,i}) + (M_{v,2}\, u_{v,2} - M_{v,i}\, u_{v,i}) + \\ & (M_{nc,2}\, u_{nc,2} - M_{nc,1}\, u_{nc,1}) + (M_{cg,2}\, u_{cg,2} - M_{cg,1}\, M_{cg,1}\, u_{cg,1}) + \\ & (M_{w,2}\, u_{w,2} - M_{w,1}\, u_{w1}) + (M_{cl,2}\, u_{cl,2} - M_{cl,1}\, u_{cl,1}) + \\ & (M_{r,2}\, u_{r,2} - M_{r,1}\, u_{r,1}) + (M_{t,2}\, u_{t,2} - M_{t,1}\, u_{t,1} + \\ & (M_{f,2}\, u_{f,2} - M_{f,1}\, u_{f,1})\end{aligned}$$

The following mass balance relations are invoked for the noncondensables:

$$M_{nc,i} + M_{nc,1} = M_{nc,e} + M_{nc,2}$$

$$\Delta M_{nc} = M_{nc,2} - M_{nc,1}$$

$$M_{nc,e} = M_{nc,i} - \Delta M_{nc}$$

The following mass balance relations are invoked for water:

$$M_{v,i} + M_{v,1} + M_{w,1} = M_{v,e} + M_{v,2} + M_{w,2}$$

$$\Delta M_w = M_{w,2} - M_{w,1}$$

$$\Delta M_v = M_{v,2} - M_{v,1}$$

$$M_{v,e} = M_{v,i} - \Delta M_w - \Delta M_v$$

3.5.2 The Resin Plus Void Plus Canister (Continued)

The following mass balance relations are invoked for carbon dioxide:

$$M_{cg,i} + M_{cg,1} + M_{cl,1} = M_{cg,e} + M_{cg,2} + M_{cl,2}$$

$$\Delta M_{cl} = M_{cl,2} - M_{cl,1}$$

$$\Delta M_{cg} = M_{cg,2} - M_{cg,1}$$

$$M_{cg,e} = M_{cg,i} - \Delta M_{cl} - \Delta M_{cg}$$

The following mass balance relations are invoked for the resin, tank, and foam:

$$M_{r,2} = M_{r,1} = M_r$$

$$M_{t,2} = M_{t,1} = M_t$$

$$M_{f,2} = M_{f,1} = M_f$$

Invoking these mass relations yields:

$$\begin{aligned}0 = {} & M_{v,i} (h_{v,e} - h_{v,i}) + M_{nc,i} (h_{nc,e} - h_{nc,i}) + \\ & M_{cg,i} (h_{cg,e} - h_{cg,i}) + M_{v,1} (u_{v,2} - u_{v,1}) + \\ & M_{nc,1} (u_{nc,2} - u_{nc,1}) + M_{cg,1} (u_{cg,2} - u_{cg,1}) + \\ & M_{w,1} (u_{w,2} - u_{w,1}) + M_{cl,1} (u_{cl,2} - u_{cl,1}) + \\ & M_r (u_{r,2} - u_{r,1}) + M_t (u_{t,2} - u_{t,1}) + M_f (u_{f,2} - u_{f,1}) - \\ & \Delta M_w (h_{v,e} - u_{w,2}) - \Delta M_{cl} (h_{cg,e} - u_{cl,2}) - \\ & \Delta M_v (h_{v,e} - u_{v,2}) - \Delta M_{cg} (h_{cg,e} - u_{cg,2}) - \\ & \Delta M_{nc} (h_{nc,e} - u_{nc,2})\end{aligned}$$

Now specific heats and temperatures are introduced where:

$$T_{v,e} = T_{nc,e} = T_{cg,e} = T_e$$

$$T_{v,i} = T_{nc,i} = T_{cg,i} = T_i$$

$$T_{v,2} = T_{nc,2} = T_{cg,2} = T_2$$

$$T_{v,1} = T_{nc,1} = T_{cg,1} = T_1$$

$$T_{w,2} = T_{cl,2} = T_{r,2} = T_{t,2} = T_{f,2} = T_{b,2}$$

$$T_{w,1} = T_{cl,1} = T_{r,1} = T_{t,1} = T_{f,1} = T_{b,1}$$

3.5.2 The Resin Plus Void Plus Canister (Continued)

Substituting temperatures and specific heats yields:

$$\begin{aligned} 0 = {} & M_{v,i}\, c_{p,v}\, (T_e - T_i) + M_{nc,i}\, c_{p,nc}\, (T_e - T_i) + \\ & M_{cg,i}\, c_{p,cg}\, (T_e - T_i) + M_{v,1}\, c_{v,v}\, (T_2 - T_1) + \\ & M_{nc,1}\, c_{v,nc}\, (T_2 - T_1) + M_{cg,1}\, c_{v,cg}\, (T_2 - T_1) + \\ & M_{w,1}\, c_w\, (T_{b,2} - T_{b,1}) + M_{cl,1}\, c_{cl}\, (T_{b,2} - T_{b,1}) + \\ & M_r\, c_r\, (T_{b,2} - T_{b,1}) + M_t\, c_t\, (T_{b,2} - T_{b,1}) + \\ & M_f\, c_f\, (T_{b,2} - T_{b,1}) - \Delta M_w\, (h_{v,e} - u_{w,2}) - \\ & \Delta M_{cl}\, (h_{cg,e} - u_{cl,2}) - \Delta M_v\, (h_{v,e} - u_{v,2}) - \\ & \Delta M_{cg}\, (h_{cg,e} - u_{cg,2}) - \Delta M_{nc}\, (h_{nc,e} - u_{nc,2}) \end{aligned}$$

For solution, it is assumed that the exiting conditions from the void segment equal the final conditions in the void segment. Therefore:

$T_2 = T_e$ $\quad u_{v,e} = u_{v,2}$

$h_{v,e} = h_{v,2}$ $\quad u_{nc,e} = u_{nc,2}$

$h_{nc,e} = h_{nc,2}$ $\quad u_{cg,e} = u_{cg,2}$

$h_{cg,e} = h_{cg,2}$

Substituting:

$$\begin{aligned} 0 = {} & (M_{v,i}\, c_{p,v} + M_{nc,i}\, c_{p,nc} + M_{cg,i}\, c_{p,cg})\, (T_e - T_i) + \\ & (M_{v,1}\, c_{v,v} + M_{nc,1}\, c_{v,nc} + M_{cg,1}\, c_{v,cg})\, (T_e - T_1) + \\ & (M_{w,1}\, c_w + M_{cl,1}\, c_{cl})\, (T_{b,2} - T_{b,1}) + \\ & (M_r\, c_r + M_t\, c_t + M_f\, c_f)\, (T_{b,2} - T_{b,1}) - \\ & \Delta M_w\, (h_{v,e} - u_{w,2}) - \Delta M_{cl}\, (h_{cg,e} - u_{cl,2}) - \\ & \Delta M_v\, (h_{v,e} - u_{v,e}) - \Delta M_{cg}\, (h_{cg,e} - u_{cg,e}) - \\ & \Delta M_{nc}\, (h_{nc,e} - u_{nc,e}) \end{aligned}$$

But:

$$h - u = \frac{144\, P_v}{J} = \frac{\bar{R}T}{M_w}$$

3.5.2 The Resin Plus Void Plus Canister (Continued)

$$0 = (M_{v,i}\ c_{p,v} + M_{nc,i}\ c_{p,nc} + M_{cg,i}\ c_{p,cg})\ (T_e - T_i) +$$
$$(M_{v,1}\ c_{v,v} + M_{nc,1}\ c_{v,nc} + M_{cg,1}\ c_{v,cg})\ (T_e - T_i) +$$
$$(M_{w,1}\ c_w + M_{cl,1}\ c_{cl})\ (T_{b,2} - T_{b,1}) +$$
$$(M_r c_r + M_t c_t + M_f c_f)\ (T_{b,2} - T_{b,1}) -$$
$$\Delta M_w\ (h_{v,e} - u_{w,2}) - \Delta M_{cl}\ (h_{cg,e} - u_{cl,2}) -$$
$$(\Delta M_v/Mw_v + \Delta M_{cg}/Mw_{cg} + \Delta M_{nc}/Mw_{nc})\ \bar{R}\ T_e$$

But:

$$h_{v,e} - u_{w,2} = h_{fg} + \Delta h_{wa}$$

Where:

Δh_{wa} = heat released during water absorption, Btu/lbm

It is assumed that Δh_{wa} is insignificant compared to h_{fg} and is therefore ignored. Therefore:

$$h_{v,e} - u_{w,2} = h_{fg}$$

Also:

$$h_{cg,e} - u_{cl,2} = \Delta h_{cr}$$

Where Δh_{cr} is the heat released during carbon dioxide absorption. This h_{cr} is determined experimentally and has the value of 1270 Btu/lbm. See Reference 8.

Substituting these two relations yields:

$$0 = (M_{v,i}\ c_{p,v} + M_{nc,i}\ c_{p,nc} + M_{cg,i}\ c_{p,cg})\ (T_e - T_i) +$$
$$(M_{v,1}\ c_{v,v} + M_{nc,1}\ c_{v,nc} + M_{cg,1}\ c_{v,cg})\ (T_e - T_i) +$$
$$(M_{w,1}\ c_w + M_{cl,1}\ c_{cl})\ (T_{b,2} - T_{b,1}) +$$
$$(M_r\ c_r + M_t\ c_t + M_f\ c_f)\ (T_{b,2} - T_{b,1}) -$$
$$\Delta M_w\ h_{fg} - \Delta M_{cl}\ \Delta h_{cr} -$$
$$(\Delta M_v/Mw_v + \Delta M_{cg}/Mw_{cg} + \Delta M_{nc}/Mw_{nc})\ \bar{R}\ T_e$$

3.5.2 The Resin Plus Void Plus Canister (Continued)

Lastly, it is assumed that:

$T_e = T_{b,2}$

$T_1 = T_{b,1}$

$$\begin{aligned} 0 = {} & (M_{v,i}\, c_{p,v} + M_{nc,i}\, c_{p,nc} + M_{cg,i}\, c_{p,cg})\, (T_e - T_i) + \\ & (M_{v,1}\, c_{v,v} + M_{nc,1}\, c_{v,nc} + M_{cg,1}\, c_{v,cg})\, (T_e - T_i) + \\ & (M_{w,1}\, c_w + M_{cl,1}\, c_{cl})\, (T_e - T_i) + \\ & (M_r\, c_r + M_t\, c_t + M_f\, c_f)\, (T_e - T_i) - \\ & \Delta M_w\, h_{fg} - \Delta M_{cl}\, \Delta h_{cr} - \\ & (\Delta M_v/Mw_v + \Delta M_{cg}/Mw_{cg} + \Delta M_{nc}/Mw_{nc})\, \bar{R}\, T_e \end{aligned}$$

In this equation, there are six unknowns:

T_e = gas exit and final bed temperature, °F

ΔM_w = change in the mass of absorbed water on the bed, lbm

ΔM_{cl} = change in the mass of absorbed carbon dioxide on the bed, lbm

ΔM_v = change in the mass of vapor in the void volume segment, lbm

ΔM_{nc} = change in the mass of non-condensables in the void volume segment, lbm

ΔM_{cg} = change in the mass of carbon dioxide gas in the void volume segment, lbm

The procedure to solve for these unknowns is to iterate on temperature T_e until the energy equation just derived is balanced. For a trial temperature, the following equations are used to solve for ΔM_w, ΔM_{cl}, ΔM_v, ΔM_{nc}, and ΔM_{cg}.

First of all, the change in the mass of carbon dioxide in the resin (i.e., the mass of carbon dioxide absorbed or desorbed) is determined from the following equations:

$$M_{cl} = r\, M_r \left[(P_{CO2})_{i1} - (P_{CO2})_{eq} \right] \Delta t/3600$$

3.5.2 The Resin Plus Void Plus Canister (Continued)

The absorption/desorption rate r is calculated from the following equation:

$$r = r_0 (1 - 0.9\, L_{H2O})$$

Where:

r_0 = baseline absorption/desorption rate = 1.5 pph/ lb IR45/psid

L_{H2O} = bed water loading, lb of H_2O per lb of dry amine.

The equilibrium partial pressure of carbon dioxide $(P_{CO2})_{eq}$ is calculated from the following equations:

$$(P_{CO2})_{eq} = Y_{CO2}\, P_T$$

Where Y_{CO2} is a function of equivalent carbon dioxide loading. This function is derived from data in Reference 7 and Hamilton Standard's own experimental data.

The equivalent carbon dioxide loading is determined from the actual carbon dioxide loading and two adjustment factors as follows:

$$(L_{CO2})_{eq} = \frac{L_{CO2}}{WFACT * TFACT}$$

WFACT represents the effect of water loading on the carbon dioxide loading. The effect is determined from Hamilton Standard test results and shows that actual CO_2 loading L_{CO2} increases with water loading and reaches a maximum around 20 to 30% water loading. This agrees with conclusions reached by P. Mignon in Reference 7 where he states:

> "Below 10 percent, water deficiency reduces the possibility of reaction between amine and dissolved CO_2. Above 30 percent, the water layer is too important and limits the CO_2 diffusion toward aminated molecules."

TFACT represents the effect of temperature on the carbon dioxide loading. The effect is determined from Hamilton Standard test results and shows that actual CO_2 loading L_{CO2} decreases significantly with increases in temperature. This agrees with data by P. Mignon in Reference 7 and data presented by A. Boehm in Reference 9.

Therefore, to determine the mass of carbon dioxide absorbed or desorbed, the parameters that need to be known are:

3.5.2 The Resin Plus Void Plus Canister (Continued)

T_e = gas exit and final bed temperature, °F

M_r = mass of dry resin, lbm

$(P_{CO2})_{i1}$ = partial pressure of carbon dioxide in the total of the inlet and state 1 gases.

Δt = time step, seconds

L_{H2O} = water loading

P_T = total pressure, psia

r_o = baseline absorption desorption rate, pph/lb dry amine/psid

Of these, the only unknown is T_e. Therefore, during a given time step:

$$\Delta M_{c1} = f\ (T_e)$$

$$(M_{cg})_{e2} = (M_{cg})_{i1} - \Delta M_{c1}$$

The amount of carbon dioxide absorbed is limited to the amount of carbon dioxide available from the void and the incoming gas; while the amount of carbon dioxide desorbed is limited to the amount of carbon dioxide already residing in the resin. Lastly, the following minimum is placed on the carbon dioxide left in the void segment after absorption but before any flow is calculated to leave the void:

$$(M_{cg})_{e2,min} = \frac{144\ (P_{CO2})_{eq}\ Mw_{CO2}\ Vo_{seg}}{\bar{R}\ (T_e + 460)}$$

After solving the above equations for the change in the mass of absorbed carbon dioxide in the bed ΔM_{c1}, the following equations are solved to determine the change in the mass of absorbed water on the bed ΔMw:

$$\Delta Mw = (M_v)_{i1} - (M_v)_{e2}$$

The total mass of vapor $(M_v)_{e2}$ to be left in the void segment and to exit the void segment is determined from the following:

$$(M_v)_{e2} = Mw_v\ [n_{nc,i} + n_{nc,1} + (M_{cg})_{e2}/Mw_{cg}]\ \frac{P_{H2O,eq}}{P_T - P_{H2O,eq}}$$

3.5.2 The Resin Plus Void Plus Canister (Continued)

In this equation, $(M_{cg})_{e2}$ is known from the previous calculations on carbon dioxide. The only unknown is the partial pressure of the water, $P_{H2O,eq}$. This partial pressure is determined from:

$$(P_{H2O})_{eq} = P_{sat}\ (T_e) \quad \text{if } (P_{H2O})_{i1} \geq P_{sat}\ (T_e)$$

$$(P_{H2O})_{eq} = RH_{eq} \times P_{sat}\ (T_e) \quad \text{if } (P_{H2O})_{i1} \leq RH_{eq} \times P_{sat}\ (T_e)$$

$$(P_{H2O})_{eq} = (P_{H2O})_{i1} \quad \text{if } RH_{eq} \times P_{sat}\ (T_e) < (P_{H2O})_{i1} < P_{sat}\ (T_e)$$

Where the equilibrium relative humidity RH_{eq} is determined from the difference in water and carbon dioxide loadings. The relationship comes from Hamilton Standard non-cyclic equilibrium testing. The model assumes that the relative humidity of the exiting gas is in equilibrium with the bed water and carbon dioxide loadings. In addition by assuming that the loadings are constant over a time step, the partial pressure and therefore the amount of water leaving the control volume can be determined as a function of only the final bed temperature.

The total mass of vapor $(M_v)_{e2}$ to be left in the void segment and to exit the void segment is limited to the total mass of vapor $(M_v)_{i1}$ entering the void segment plus that originally in the void segment plus the mass $M_{w,1}$ originally in the dry resin itself. In other words:

$$(M_v)_{e2} \leq M_{v,i} + M_{v,1} + M_{w,1}$$

Like ΔM_{c1}, the only unknown to determine ΔM_w is the temperature T_e.

$$\Delta M_w = f\ (T_e)$$

$$M_{nc,2} = (M_{nc})_{e2}$$

$$M_{v,2} = (M_v)_{e2}$$

$$M_{cg,2} = (M_{cg})_{e2}$$

$$\Delta M_{nc} = M_{nc,2} - M_{nc,1}$$

$$\Delta M_v = M_{v,2} - M_{v,1}$$

$$\Delta M_{cg} = M_{cg,2} - M_{cg,1}$$

3.5.2 The Resin Plus Void Plus Canister (Continued)

However, if $P_T < P_d$ and $P_T < P_u$, then a pressure collapse situation has occurred. This is not a possible situation in reality. In this event, the following logic is used to adjust the changes in the masses (ΔM_{cl} and ΔM_w) of carbon dioxide and water on the resin. Essentially, too much carbon dioxide or water was absorbed onto the bed than was physically possible because pressure had to be maintained in the void volume. Therefore if only water was absorbed, then the mass of water absorbed is limited to that which would just make the pressure equal to the smaller of the upstream or downstream pressures.

$$N_{min} = \frac{144\ P_{min}\ Vo}{\bar{R}\ (T_e + 460)}$$

$$(M_v)_{e2} = M_{v,2}\ [N_{min} - (M_{nc})_{e2}/Mw_{nc} - (M_{cg})_{e2}/Mw_{cg}]\ Mw_v$$

At this point in the analysis, the changes in the masses of water and carbon dioxide on the bed have been determined. Therefore, the total masses which remain in the void segment plus those which exit are determined and are:

$$(M_{nc})_{e2} = M_{nc,2} + M_{nc,e} = M_{nc,1} + M_{nc,i}$$

$$(M_v)_{e2} = M_{v,2} + M_{v,e} = M_{v,1} + M_{v,i} - \Delta M_w$$

$$(M_{cg})_{e2} = M_{cg,2} + M_{cg,e} = M_{cg,1} + M_{cg,i} - \Delta M_{cl}$$

What remains to be determined is the split between the mass of substance which remains in the void segment and the mass which exits. Then when this split is known, the remaining terms ΔM_v, ΔM_{nc}, and ΔM_{cg} can be calculated to solve the energy equation. The split between the mass remaining in the void segment and that which exits is determined by the mass required to maintain the pressure greater than the downstream pressure. The pressure that would exist in the void segment if $(M_{nc})_{e2}$, $(M_v)_{e2}$, and the $(M_{cg})_{e2}$ remained in the segment is given by:

$$P_T = \frac{M_T\ \bar{R}\ (T_e + 460)}{144\ Mw_T\ Vo}$$

Where:

M_T = $(M_{nc})_{e2} + (M_{cg})_{e2} + (M_v)_{e2}$, lbm

Mw_T = molecular weight of M_T

Vo = segment void volume, ft^3

P_T = hypothetical pressure in void volume, psia

3.5.2 The Resin Plus Void Plus Canister (Continued)

If the pressure $P_T > P_d$, then the splits are given by:

$$M_{nc,e} = (M_{nc})_{e2} \times (1 - P_d/P_T)$$

$$M_{v,e} = (M_v)_{e2} \times (1 - P_d/P_T)$$

$$M_{cg,e} = (M_{cg})_{e2} \times (1 - P_d/P_T)$$

$$M_{nc,2} = (M_{nc})_{e2} \times P_d/P_T$$

$$M_{v,2} = (M_v)_{e2} \times P_d/P_T$$

$$M_{cg,2} = (M_{cg})_{e2} \times P_d/P_T$$

$$\Delta M_{nc} = M_{nc,2} - M_{nc,1}$$

$$\Delta M_v = M_{v,2} - M_{v,1}$$

$$\Delta M_{cg} = M_{cg,2} - M_{cg,1}$$

If the pressure $P_T \leq P_d$ but $P_T \geq P_u$, then all the mass stays in the void segment and:

$$M_{nc,e} = M_{v,e} = M_{cg,e} = 0.0$$

$$\Delta M_v = M_{v,2} - M_{v,1}$$

$$\Delta M_w = (M_v)_{i1} - (M_v)_{e2}$$

If only carbon dioxide were absorbed, then:

$$(M_{cg})_{e2} = M_{cg,2} = [N_{min} - (M_{nc})_{e2}/Mw_{nc} - (M_v)_{e2}/Mw_v]\ Mw_g$$

$$\Delta M_{cg} = M_{cg,2} - M_{cg,1}$$

$$\Delta M_{cl} = (M_{cg})_{i1} - (M_{cg})_{e2}$$

If both carbon dioxide and water were absorbed, then:

$$F = \frac{N_{min} - (M_{nc})_{e2}/Mw_{nc}}{(M_v)_{i1}/Mw_v + (M_{cg})_{i1}/Mw_{cg}}$$

$$(M_t)_{e2} = F * (M_v)_{i1}$$

$$(M_{cg})_{e2} = F * (M_{cg})_{i1}$$

$$\Delta M_v = M_{v,2} - M_{v,1}$$

$$\Delta M_{cg} = M_{cg,2} - M_{cg,1}$$

$$\Delta M_{cl} = (M_{cg})_{i1} - (M_{cg})_{e2}$$

$$\Delta M_w = (M_v)_{i1} - (M_v)_{e2}$$

3.5.2 The Resin Plus Void Plus Canister (Continued)

Now the values for ΔM_v, ΔM_w, ΔM_{cg}, ΔM_{cl}, ΔM_{nc}, and T_e are substituted into the energy equation. If the sum is less than 0.1, the energy equation is assumed to be balanced. If not, temperature is iterated upon using the standard Newton-Raphson technique. However, if the next trial temperature is greater than or equal to the saturation temperature for the downstream pressure, the temperature to try will be permitted to approach the saturation temperature in 25 increments from the initial temperature to the saturation temperature.

$$T_e = \frac{T_1\ (25 - I) + T_{sat} * I}{25}$$

Thus when I = 25, $T_e = T_{sat}$. Once the temperature T_e reaches T_{sat}, then temperature is no longer iterated upon but instead the mass of vapor $(M_v)_{e2}$ remaining in the void segment plus exiting is iterated upon.

3.5.3 The Temperature Sensor

The temperature sensor is at the exit of the SAWD bed and has a characteristic time constant. The standard differential equation for the response of a temperature sensor to a fluid temperature is:

$$\frac{dT}{dt} = \frac{1}{\tau}\ (T_a - T)$$

Where:

= temperature sensor time constant, sec

T_a = ambient temperature of fluid surrounding the temperature, F

T = temperature sensor temperature, F

In difference form the differential equation becomes:

$$T_2 - T_1 = \frac{T_a - T_1}{\tau} \times \Delta t$$

Or:

$$T_2 = T_1 + \frac{T_a - T_1}{\tau}\ \Delta t$$

This equation is used to determine the temperature as indicated by the temperature sensor. Currently, the time constant has a value of 240 seconds.

3.6 Tanks

The TANKG subroutine is used for analyzing the water supply tank as well as the carbon dioxide accumulator tank. A complete description of the subroutine is given in Reference 3 for all the analytical options.

For the water supply tank, the following options are selected:

1) The outlet flow during steady state is determined by a GPOLY1 statement or the previous value if no GPOLY1 statement changes it. The ESCM program sets the outlet flow during steady state to:

   m_e = 2.55 lbm/hr

2) In steady state, the tank fluid temperature is specified in the input as 70°F and the heating and cooling load required to offset ambient heat losses and fluid expansion is calculated for steady state operation.

3) No transient heat balance is performed; instead, the steady state heat balance equations are used.

4) The initial mass, pressure, and temperature inputs are taken as correct data. Volume is calculated and used in transient runs.

   Initial mass = 168.3 lb
   Initial pressure = 30.0 psia
   Initial temperature = 70°F

5) No provision for heat rejection/addition through use of secondary flow as heat transport medium exists.

During transient operation, the flow out of the tank is determined in GPOLY1. This logic is the logic to determine the mass of flow of steam for desorption of a SAWD bed. This will be described in Section 3.12.3 for SAWD Control.

For the carbon dioxide accumulator tank, the following options are selected:

1) In steady state calculations, the outlet flow is set equal to the inlet flow despite any coding in GPOLY1. In transient, the GPOLY1 coding will be executed.

2) In steady state, the tank fluid temperature is specified in the input as 70°F and the heating and cooling load required to offset ambient heat losses and fluid expansion is calculated for steady state operation.

3.6 Tanks (Continued)

3) No transient heat balance is performed; instead, the steady state heat balance equations are used.

4) Initial volume, pressure, and temperature inputs are used to calculate the initial mass.

Initial volume = 2.0 ft^3
Initial pressure = 30 psia
Initial temperature = 70°F

5) No provision for heat rejection/addition through use of secondary flow as heat transport medium exists.

During transient operation, the flow out the tank is regulated by orifices, valves, and pressure regulators as shown in Figure 2. If the tank pressure ever exceeds 30 psia, the back pressure regulator opens to vent the excess pressure to the overboard vent. Below 30 psia, the flow from the carbon dioxide tank can be directed to the overboard vent or to a carbon dioxide reduction process. If directed overboard, the solenoid valve opens at 30 psia and closes at 24 psia. The pressure in the tank will therefore oscillate up and down between 24 and 30 psia. If directed to a carbon dioxide reduction process, the corresponding solenoid valve is opened at 24 psia and the flow is regulated to exit at 0.275 lbm/hr by the downstream pressure regulator and orifice combination. Below 24 psia, no flow exits the tank and tank pressure is allowed to build. This exit flow logic is represented mathematically by the following equations:

For $P > 30$ psia:

$$m_e = m_i + \frac{144\ Mw\ Vo\ (P - 30)\ 3600}{\bar{R}\ (T + 460)\ \Delta t}$$

Where:

$Mw = 44.01$ for carbon dioxide

m_e = exiting mass flow, lbm/hr

m_i = inlet mass flow, lbm/hr

The above equation is designed to permit sufficient exit flow during the time step Δt to return the tank pressure to 30 psia.

For:

$P < 24$ psia:

3.6 Tanks (Continued)

$$m_e = m_i - \frac{144 \; Mw \; Vo \; (30 - P) \; 3600}{R \; (T + 460) \; \Delta t}$$

If:

$m_e < 0.0$, $m_e = 0.0$

The above equations are designed to permit no exit flow if there is no inlet flow and also to cause the exit flow to be sufficiently large so as to prevent the pressure from ever building up past 30 psia in one time step. This restriction simulates the 30 psia back pressure regulator.

For pressures between 24 and 30 psia and flow directed to a carbon dioxide reduction process.

$m_e = 0.275$ lbm/hr

For pressures between 24 and 30 psia and flow directed to an overboard vent:

$m_e = 0.2316 \times P$

This relation is derived from a solenoid valve flow coefficient of 0.065 and the following flow equation:

$$SCFM = 13.61 \; P \; C_v \sqrt{\frac{1}{SG \times (T + 460)}}$$

Where:

P = pressure

C_v = valve flow coefficient = 0.065

SG = specific gravity = 1.529

T = temperature = 70°F

SCFM = flow at standard temperature (70°F) and pressure (14.7 psia), cfm

$$m_e = \frac{SCFM}{386.73} \times M_w \times 60 \times P$$

Substituting all the appropriate values yields:

$m_e = 0.2316 \; P$

3.6 Tanks (Continued)

Now, both expressions for the exit flow for the tank pressure between 24 and 30 psia are restricted so as not to permit the pressure from exceeding 30 psia or falling below 24 psia in one time step.

The minimum exit flow for pressures between 24 and 30 psia is given by:

$$m_{e,min} = m_i - \frac{144\ Mw\ Vo\ (30 - P)\ 3600}{1545\ (T + 460)\ \Delta t}$$

The maximum exit flow for pressures between 24 and 30 psia is given by:

$$m_{e,max} = m_i + \frac{144\ Mw\ Vo\ (P - 24)\ 3600}{1545\ (T + 460)\ \Delta t}$$

3.7 Pumps

The PUMP subroutine is used to analyze component 28 the water supply pump. A complete description of the subroutine is given in Reference 3 for all the analytical options.

For the water supply pump, the only calculation performed is to add the input pump heat to the fluid stream. No head rise or other pump performance calculations are performed. The exiting temperature is given by:

$$T_e = T_i + \frac{\dot{Q}}{m_T\ c_p}$$

Where $\dot{Q}$ is the heat input to the fluid stream by the pump. The pump heat addition used in ESCM is 10.0 watts.

3.8 Steam Generator

The SMGEN subroutine is used to analyze the component 29 steam generator. A complete description of the subroutine is given in Reference 3 for all the analytical options.

For the steam generator in ESCM, heat is supplied by electrical heating, and the subroutine computes the amount of electrical energy required to vaporize the entering fluid and to superheat it to a user specified amount. The amount of electrical power required is calculated as follows:

$$\dot{Q} = m_i\ (h_e - h_i)$$

3.8 Steam Generator (Continued)

Where:

m_i = incoming mass flow, lbm/hr
h_e = exiting enthalpy, Btu/lbm
h_i = inlet enthalpy, Btu/lbm

$$h_i = h_l\ (T_i)$$

Where:

$h_l\ (T_i)$ = enthalpy of saturated liquid at temperature T_i, Btu/lbm

$$h_e = h_g\ (T_e)$$

Where:

$h_g\ (T_e)$ = enthalpy of saturated vapor at temperature T_e, Btu/lbm

$$T_e = T_{sat}\ (P) + \Delta T_{spht}$$

Where:

$T_{sat}\ (P)$ = saturation temperature at pressure P, °F

ΔT_{spht} = desired degrees of superheat, °F

To convert the required heat to electrical power, the following relation is used:

$$w = Q/3.413$$

3.9 Splitters

The SPLIT subroutine is used to split incoming flow to two separate exit paths; it represents a tee in a plumbing line. As seen in Figure 3 and Table 1, the SPLIT subroutine is used as follows:

Component No.	Component Description
3	Cabin secondary flow splits to SAWD and humidity control heat exchanger.
9	Humidity control heat exchanger primary flow splits to water separator and water separator bypass.

3.9 Splitters (Continued)

Component No.	Component Description
14	Cabin secondary flow splits to SAWD bed #1 and to SAWD bed #2.
17	SAWD bed #1 exit flow splits to SAWD fan and to CO_2 accumulator or bed #2.
22	SAWD bed #2 exit flow splits to SAWD fan and to CO_2 accumulator or bed #1.
24	SAWD bed #1 or #2 exit flow splits to CO_2 accumulator or cabin and to the opposite numbered bed.
26	Steam generator or SAWD bed #1 or #2 exit flow splits to SAWD bed #1 and #2 inlets.
30	SAWD bed #1 or #2 exit flow splits to cabin and CO_2 accumulator.

A complete description of the subroutine is given in Reference 3. For all components, the split ratio is determined in GPOLY1. The split ratio is defined as the ratio of the splitter's exit secondary flow to the splitter's inlet flow. Splitters 14, 17, 22, 24, 26, and 30 are controlled by the SAWD controller logic in GPOLY1. This logic is described later in Section 3.12.2. Here, the relations to determine the split ratios for components 3 and 9 are given.

The split ratio for component number 3 is determined from the resulting secondary and total flows:

$$m_{sec} = (m_e)_{19} + (m_e)_{24p}$$

$$m_T = (m_e)_{12} + (m_e)_{10_s} + (m_e)_{24_p}$$

$$SR = m_{sec}/m_T$$

Where:

$(m_e)_{19}$ = SAWD fan exit flow, lbm/hr

$(m_e)_{24_p}$ = splitter #24 exit primary flow, lbm/hr

$(m_e)_{12}$ = humidity control heat exchanger fan exit flow, lbm/hr

$(m_e)_{10_s}$ = water separator water flow, lbm/hr

SR = split ratio

3.9 Splitters (Continued)

This adjustment of the split ratio prior to solving component number 3 provides a constant update of the cabin secondary flow split to the cabin humidity control heat exchanger and to the SAWD carbon dioxide removal subsystem.

The split ratio for component number 9 is different for each constituent of the flow exiting the humidity control heat exchanger. The values are constant throughout the analyses and are part of the input data set. The values used in ESCM are:

$SR_V = 0.03$ $SR_{CO2} = 0.03$

$SR_1 = 1.00$ $SR_{TC} = 0.03$

$SR_{O2} = 0.03$ $SR_{SF\#1} = 0.03$

$SR_{N2} = 0.03$

3.10 Mixer

The GASMIX subroutine is used to mix incoming primary and secondary flows together and to arrive at a mixed exit temperature. As seen in Figure 3 and Table 1, the GASMIX subroutine is used as follows:

Component No.	Component Description
11	Flows from the water separator and the water separator bypass line mix.
13	Flows from the humidity control heat exchanger fan and the SAWD desorption flow sensor mix.
15	Flows from the cabin and the steam generator or bed #2 mix before entering SAWD bed #1.
18	Flows from SAWD beds #1 and #2 mix before going to the SAWD fan.
20	Flows from the cabin and the steam generator or bed #1 mix before entering SAWD bed #2.
23	Desorption flows from SAWD beds #1 and #2 mix before going to the opposite bed, back to the cabin, or to the CO_2 accumulator.
25	Steam generator flow and flow from SAWD beds #1 or #2 mix before going to the inlet of one of the SAWD beds.
31	Flow from the cabin mixes with returning flow from the SAWD before entering the humidity control heat exchanger.

3.10 Mixer (Continued)

A complete description of the subroutine GASMIX is given in Reference 3. An adiabatic mixing process is assumed and the temperature, dew point, pressure, and constituent flows of the mixed stream are calculated. In all instances except for components 15 and 20, the pressure is taken as the minimum value of the primary or secondary source pressure or as the pressure from the source which has a non-zero flow. Components 15 and 20 always take the pressure of the secondary side. This is to maintain pressure in the SAWD bed after desorption flow ends and before absorption begins.

3.11 All Purpose Components

The ALTCOM subroutine is used to handle the secondary source flows for the cabin sensible and humidity control heat exchangers and to analyze the water separator. A complete description of ALTCOM is given in Reference 3.

When used as secondary source flows for the cabin sensible and humidity control heat exchangers, the subroutine is never called or executed. The component is simply a repository for the cooling flow, temperature, and pressure to the heat exchanger. The humidity control cooling flow, temperature, and pressure are constant at input values specified by the user. For ESCM, the values are:

Flow = 950 lbm/hr
Temperature = 45°F
Pressure = 50 psia

The sensible heat exchanger cooling flow is varied to control cabin temperature. The logic is discussed in Section 3.12.2. However, the coolant temperature and pressure are constant for ESCM at 60°F and 50 psia respectively.

The water separator is analyzed using option no. 2 whereby the heat load is specified and the exiting temperature is calculated. Prior to analyzing the water separator via ALTCOM, the following is performed in GPOLY1:

1) Any entrained liquid from the condensing heat exchanger is removed from the primary flow.

2) The separator heat load is added to the flow stream.

$\dot{Q} = 3.84 \times 3.413 = 13.1$ Btu/hr

In ALTCOM, the new exit temperature, mass flow of vapor, and mass flow of entrained liquid are computed assuming an adiabatic mixing. See a description of subroutine HBALNC in Reference 3.

The essential fact is that all the entrained liquid entering the water separator is removed by the water separator.

3.12 Control

Three items are controlled in the ARS subgroup analyzed by ESCM. They are the cabin temperature, the cabin oxygen and total pressures, and the SAWD carbon dioxide removal subsystem. The control logic is written in subroutine GPOLY1. Here will be presented the control logic for each item.

3.12.1 Two Gas Controller

The two gas controller for ESCM controls the entering flow of oxygen and nitrogen into the cabin to maintain the desired oxygen pressure from 3.09 to 3.23 psia. The controller admits nitrogen to bring the pressure up to 14.813 psia only after the oxygen partial pressure has been brought above 3.09 psia. The logic is shown in Table 2 while the opening and closing flow schedules for oxygen and nitrogen are shown in Figures 10 and 11, respectively. These curves are based on July 1980 Pressure Control Subsystem testing at Johnson Space Center.

3.12.2 Cabin Temperature Control

The cabin temperature is controlled by the cabin sensible heat exchanger. To remove more heat, the cooling flow to the heat exchanger is increased; and conversely to remove less heat, the cooling flow is decreased. The calculation of the proper cooling flow is done in GPOLY1 using a Newton-Raphson iteration technique described in Reference 3 in the subroutine ESTIM. The basic equation is:

$$m = m_1 + A \frac{m_2 - m_1}{T_1 - T_2} (T_1 - T_{set})$$

Where:

m = new cooling flow, lbm/hr

m_1 = flow at state 1, lbm/hr

T_1 = temperature at state 1, °F

m_2 = flow at state 2, lbm/hr

T_2 = temperature at state 2, °F

A = iteration constant = 0.025

The minimum flow is limited to 950 lbm/hr while the maximum flow is limited to 1900 lbm/hr.

Table 2

Two Gas Controller Logic For 14.5 psi Controller

Condition					Action			
Initial Oxygen Valve Status	Initial Nitrogen Valve Status	Last Valve Opened	PT (psia)	PO_2 (psia)	Oxygen Valve Status	Nitrogen Valve Status	O_2 Flow Per Opening Or Closing Curve	N_2 Flow Per Opening Or Closing Curve
N/A	N/A	N/A	≥ 14.819	---	Closed	Closed	---	---
N/A	N/A	N/A	≥ 14.813	≥ 3.23	Closed	Closed	---	---
Closed	N/A	N/A	<14.819	<3.09	Open	Closed	Opening	---
Open	N/A	N/A	<14.819	<3.09	Open	Closed	Closing[1]	---
Closed	N/A	Oxygen	<14.819	$3.09 \leq PO_2 < 3.23$	Open	Closed	Opening	---
Open	N/A	Oxygen	<14.819	$3.09 \leq PO_2 < 3.23$	Open	Closed	Closing[1]	---
N/A	Closed	Nitrogen	<14.819	$3.09 \leq PO_2 < 3.23$	Closed	Open	---	Opening
N/A	Open	Nitrogen	<14.819	$3.09 \leq PO_2 < 3.23$	Closed	Open	---	Closing[1]
N/A	Closed	N/A	<14.813	≥ 3.23	Closed	Open	---	Opening
N/A	Open	N/A	<14.813	≥ 3.23	Closed	Open	---	Closing[1]

---

[1] When flow calculated by closing curve = 0.0, valve closes.

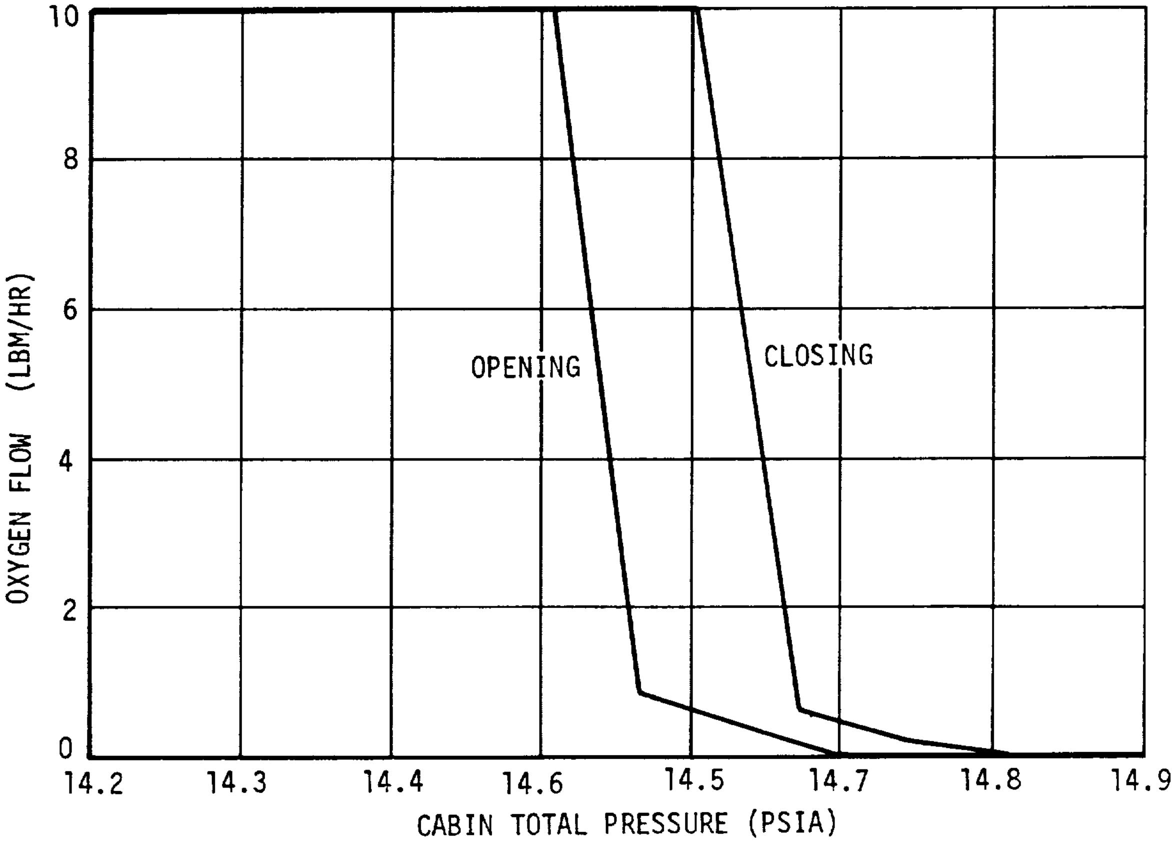

Figure 10

Oxygen Opening And Closing Flow Schedules

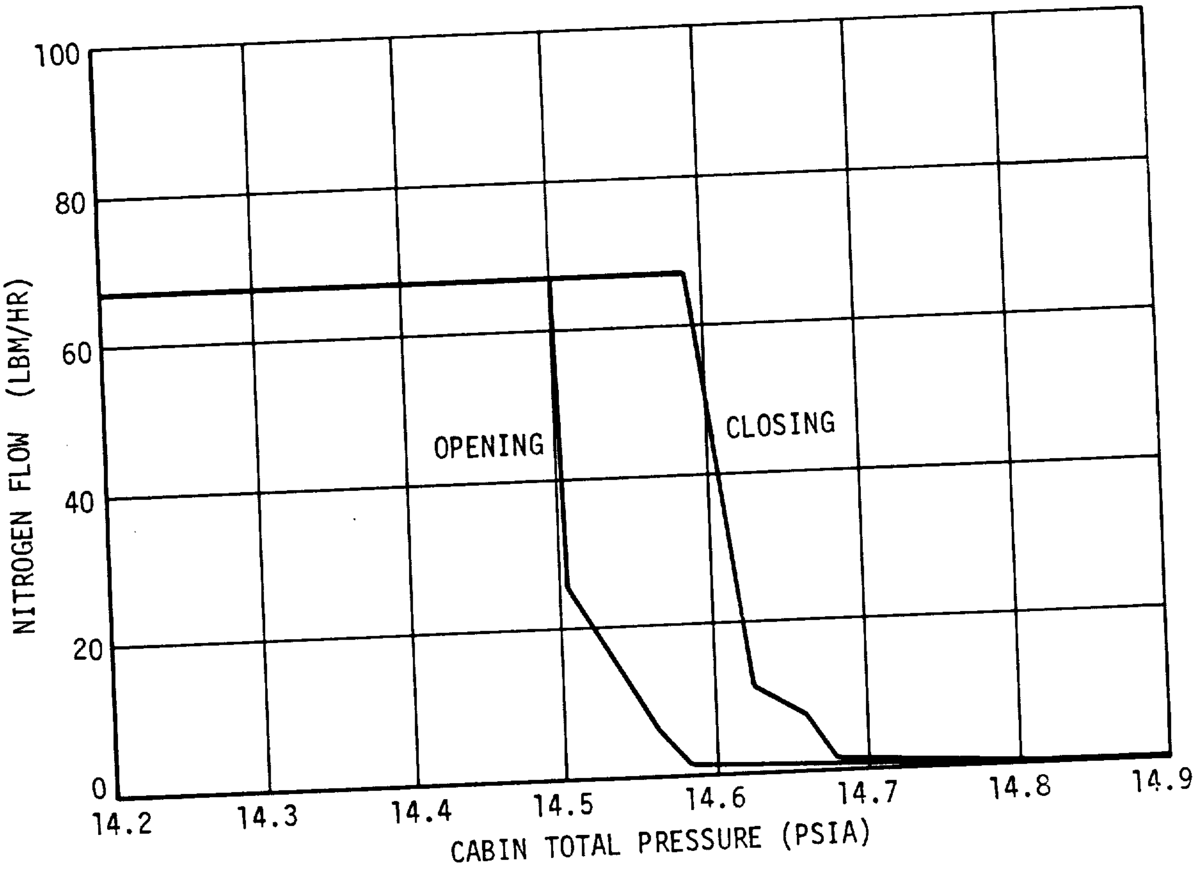

Figure 11

Nitrogen Opening And Closing Flow Schedules

3.12.3 SAWD Control

The sequence of operation is described for the startup cycle and the first full cycle. At startup, bed #2 desorbs while bed #1 is on standby. During standby, neither air nor steam flows through the bed. Initial flow from the desorbing bed #2 is directed first to the cabin to prevent contamination to the CO_2 accumulator with oxygen. When the flow reaches 0.01 cfm as detected by the flow sensor, the flow, almost totally CO_2 at this point, is directed to the accumulator. Pressure builds in the accumulator until 24 psia is reached. At this pressure, flow is permitted to leave at a controlled rate to a CO_2 reduction process. If pressure builds beyond 30 psia, CO_2 is dumped overboard to lower the pressure below 30 psia. During desorption, the pressure in the accumulator back pressures the desorbing bed, but a check valve prevents any back flow from the accumulator to the beds.

Desorbing in bed #2 continues until its exit temperature reaches 180°F, which indicates most CO_2 has been driven from the bed and flow consists mostly of steam. At that point, steam flow ceases and appropriate valves are switched to allow the pressure in bed #2 to bleed slowly to bed #1 for 120 seconds. Then, the fan starts pulling cabin air through bed #2 to bed #1 and then to the humidity control heat exchanger inlet. As the air passes through bed #2, it pushes the steam in bed #2 ahead to bed #1, and thereby heats bed #1. This energy transfer continues for five minutes or until the bed #1 exit temperature reaches 130°F, whichever occurs first.

After energy transfer is completed, steam flow is started and directed to bed #1 to desorb it while bed #2 begins absorption. Valve positions are changed to direct air flow into bed #2 and air exiting the bed flows to the humidity control heat exchanger inlet. Desorbing continues in bed #1 with any flow directed back to the cabin via the flow sensor until the flow reaches 0.01 cfm. Then, the desorb flow is directed to the accumulator. The process continues as described previously, but with bed #1 desorbing and bed #2 absorbing. For only this startup cycle, absorbing in bed #2 continues for a time which is determined directly from the average cabin relative humidity measured during the past desorption of bed #2. The time for all other absorption cycles is determined from the average cabin relative humidity measured during the previous absorption cycle. The beds then alternate through this sequence as directed by the SAWD controller.

One aspect that needs elaboration is the steam flow for desorption. The desorption steam flow changes from cycle to cycle depending on the average relative humidity in the cabin during the past absorption cycle. The flow is given by the following relation:

$$m = 0.0396\ (49 + 0.32857\ RH_{\%} - 0.008571\ RH_{\%}^{2})$$

3.12.3 SAWD Control (Continued)

Where:

$RH_{\%}$ = average cabin relative humidity in percent

4.0 NOMENCLATURE

Document Symbol	Description
C_v	Valve flow coefficient
H	Total enthalpy, Btu
J	Joule's constant = 778.26 ft-lbf/Btu
L	Bed loading, lb/lb-dry amine
M	Mass of substance, lbm
MR	Per man metabolic heat load, Btu/man-hr
Mw	Molecular weight, lbm/lb-mole
N	Number of people in crew
P	Pressure, psia
Q	Heat transferred to system, Btu
$\dot{Q}$	Rate of heat transfer, Btu/hr
QL	Latent heat added to gas stream per man, Btu/man-hr
QLMIN	Minimum latent heat added to the gas stream per man, Btu/man-hr
QS	Sensible heat added to the gas stream per man, Btu/man-hr
QT	Total gas stream heat load from the crew, Btu/hr
$\bar{R}$	Universal gas constant = 1545 ft-lbf/mole-R
RH	Relative humidity
SCFM	Volumetric flow at standard temperature (70°F) and pressure (14.7 psia), cfm

4.0 NOMENCLATURE (Continued)

Document Symbol	Description
SG	Specific gravity with respect to air at 70°F and 14.7 psia
SR	Split ratio in SPLIT subroutine
T	Temperature, °F
TCAB	Cabin air temperature, °F
U	Total internal energy, Btu
V	Velocity, ft/sec
Vo	Volume, ft^3
W	Work done by system, Btu
WCO2	Total crew carbon dioxide generation rate, lbm/hr
WH20	Crew water vapor generation rate, lbm/hr
WO2	Crew oxygen gas usage, lbm/hr
Z	Elevation of system, ft
cfm	Volumetric flow, cubic feet per minute
c_p	Constant pressure specific heat, Btu/lbm
c_v	Constant volume specific heat, Btu/lbm
h	Specific enthalpy, Btu/lbm
m	Mass flow, lbm/hr
n	Lb-moles
r	Reaction rate constant for absorption of carbon dioxide, pph of CO_2 per lb of dry resin per psi difference between pressure of CO_2 in void segment and equilibrium pressure in void segment.
r_o	Base reaction rate constant at zero water loading, pph of CO_2 per lb of dry resin per psi difference between pressure of CO_2 in void segment and equilibrium pressure in void segment.

4.0 NOMENCLATURE (Continued)

Document Symbol	Description
u	Specific internal energy, Btu/lbm
w	Power, watts
y	Mole fraction

Greek Letters:

Document Symbol	Description
ΔM_{cg}	Change in mass of carbon dioxide gas in segment void volume, lbm
ΔM_{cl}	Change in mass of carbon dioxide in resin, lbm
ΔM_{nc}	Change in mass of non-condensables in segment void volume, lbm
ΔM_{v}	Change in mass of vapor in segment void volume, lbm
ΔM_{w}	Change in mass of water stored in resin, lbm
ΔP	Pressure difference, psid
ΔT	Temperature difference, °F
Δh_{cr}	Heat released during carbon dioxide absorption, Btu/lbm
Δh_{wa}	Heat released during water absorption, Btu/lbm
Δt	Time step, seconds
ϵ	Heat exchanger effectiveness
η	Fan efficiency
ρ	Density, lbm/ft^3
τ	Time constant, seconds
ω	Absolute humidity

Subscripts:

Document Symbol	Description
CO2	Carbon dioxide
H2O	Water

4.0 NOMENCLATURE (Continued)

Document Symbol	Description
Subscripts:	
02	Oxygen
N2	Nitrogen
SF#1	Special flow #1
ST	stored
T	Total
TC	Trace contaminants
TRY	Trial value during iteration
a	Ambient or air
b	Bed
cg	Carbon dioxide gas
cl	Carbon dioxide stored in resin
d	Downstream
db	Dry bulb
dp	Dew point
e	Exit
eq	Equilibrium
e2	Sum of exit plus state 2 conditions in void segment
g	Gas or saturated vapor
i	Inlet
i1	Sum of inlet plus state 1 conditions in void segment
l	Entrained liquid or saturated liquid
min	Minimum

4.0 NOMENCLATURE (Continued)

Document Symbol	Description
nc	Non-condensables
r	Resin
sat	Saturation condition
spht	Superheat
t	Tank or metal canister around SAWD resin
u	Upstream
v	Water vapor
w	Water stored in resin
1	State in control volume at start of time step
2	State in control volume at end of time step

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16. Abstract

ESCM computes the transient performance of a Space Station air revitalization subsystem with carbon dioxide removal provided by a solid amine water desorbed subsystem called SAWD.

This manual describes the mathematical modelling and equations used in the Emulation/Simulation Computer Model. For the system as a whole and for each individual component, the fundamental physical and chemical laws which govern their operations are presented. Assumptions are stated; and when necessary, data is presented to support empirically developed relationships.

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