APPENDICES TO THE MODEL DESCRIPTION DOCUMENT

FOR

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

BY

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ABSTRACT

A Model Description Document for the Emulation Simulation Computer Model was published previously. The model consisted of a detailed model (emulation) of a SAWD CO2 removal subsystem which operated with much less detailed (simulation) models of a cabin, crew, and condensing and sensible heat exchangers. The purpose was to explore the utility of such an emulation/simulation combination in the design, development, and test of a piece of ARS hardware - SAWD.

Extensions to this original effort are presented in the manual. The first extension is an update of the model to reflect changes in the SAWD control logic which resulted from test. In addition, slight changes were also made to the SAWD model to permit restarting and to improve the iteration technique. The second extension is the development of simulation models for more pieces of air and water processing equipment. Models are presented for: EDC, Molecular Sieve, Bosch, Sabatier, a new condensing heat exchanger, SPE, SFWES, Catalytic Oxidizer, and multifiltration. The third extension is to create two system simulations using these models. The first system presented consists of one air and one water processing system. The second system consists of a potential Space Station air revitalization system complete with a habitat, laboratory, four modes, and two crews.
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 NAS1-17397, "Development of an Emulation/Simulation Computer Model of a Space Station Environmental Control and Life Support System (ECLSS)". This manual describes the analytical models used in the three computer simulation programs developed under this contract.

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 written by Dr. James L. Yanosy, Program Engineer, with assistance from Mr. Stephen A. Giangrande. The extensions to the program presented in this manual were performed under the direction of Mr. John M. Neel, Program Manager. Thanks is given to Mr. Joseph M. Homa for his efforts in the development of the Space Station Model.
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1.0 INTRODUCTION

The purpose of the original ESCM program was to demonstrate the utility of an emulation simulation computer program in the design, development and test of a piece of life support equipment. The piece of life support equipment selected for emulation was the SAWD CO₂ removal subsystem. A continuation of the effort called for an update of the computer model following testing of the SAWD unit. In addition, extensions to the contract called for the development of "lightweight" or low fidelity simulation models of contending life support equipment and the configuring of this equipment into two different systems.

This document provides three appendices to the original model description document[1]*. The appendices are:

A. Emulation Simulation Computer Model Update
B. Life Support System Model
C. Space Station Model

The following errata were found in the original document:

(1) Cover page: Report number should be SVHSER 9504.
(2) Page 25, fifth line: Should be "HA = Total enthalpy of gas entering header, Btu"

*Numbers in brackets denote references listed in Section 2.0
2.0 REFERENCES


APPENDIX A

ESCM UPDATE
A.1 Introduction

The Space Station Environmental Control and Life Support System (ECLSS) Emulation/Simulation Computer Model (ESCM) has been updated to include: (1) the capability of restarting the SAWD CO₂ removal subsystem from a transient start-up, (2) placing clamps on the SAWD bed segment temperature when iterating the bed segment temperature during the energy balance of the bed segment, and (3) the addition of an energy balance control method where the amount of CO₂ on the bed is determined from the time for the CO₂ to begin coming off the bed as detected by the flow sensor. This latter change was made to reflect a change made to the control logic in the hardware. Each of these updates to ESCM as they pertain to the Model Description Document are presented in this Appendix.

A.2 SAWD Bed

The capability to start the SAWD subsystem without first running the steady state analysis was incorporated into the IR45 subroutine. The inlet and exit heater parameters, as well as SAWD bed segment parameters (i.e. temperature, pressure, molecular weight, and flow rates) were initialized in the IR45 subroutine; in a similar manner, they are initialized in the STEADY subroutine which is only called by IR45 in steady state. Therefore, the SAWD CO₂ removal subsystem can be started from a transient start-up as well as a steady state start-up.
Additional logic was also added to the IR45 BALANCE subroutine. Limits were placed on the SAWD bed segment temperature while iterating on the bed segment temperature for an energy balance of the segment. One of the limits employed was as follows: if the temperature entering the bed segment was greater than the SAWD bed temperature at the start of the time step, then the resulting bed segment temperature must increase.

A.3 SAWD Control Model

A new control method has been incorporated into the SAWD CO₂ removal subsystem model (IR45). This type of control uses an energy balance control scheme as opposed to the relative humidity method which was previously used. The energy balance method uses energy principles to determine the absorption time of the next cycle based on the bed's past desorb cycle. The total amount of energy for desorb can be calculated from the amount of steam added to the bed during desorb. The amount of CO₂ desorbed from the bed is known from techniques using the accumulator on the flow sensor; thus, the energy required to remove the CO₂ from the bed can be calculated. Also, the energy required to heat up the bed resins and canister before the desorption of CO₂ can be calculated. Therefore, from an energy balance, the amount of energy to heat the water which was on the bed at the start of the desorb can be calculated. Thus, the bed water loading at the start of the desorb can be determined. Knowing the amount of water on
the bed at the start of the desorb, the next absorption time can be determined. The following SAWD control logic has been incorporated in ESCM Subroutine GPOLY1 to determine the absorb time.

Control Constants (Set in subroutine GPOLY1):

\[
\begin{align*}
K_0 &= 1.11 & K_{42} &= 2.5 & K_{47} &= 7480.0 & K_{51} &= 1085 \\
K_1 &= 0.045 & K_{43} &= 60.0 & K_{48} &= 60.87 & K_{52} &= 157.37 \\
K_{16} &= 115.01 & K_{44} &= 3.808 & K_{49} &= 0.0028205 & K_{53} &= 4.3167 \\
K_{41} &= 0.25 & K_{46} &= 0.6996 & K_{50} &= 0.0034246 & K_{54} &= 0.040259
\end{align*}
\]

Input:

- \text{CO2TIME} = \text{Time } \text{CO}_2 \text{ goes to cabin during desorb, minutes}
- \text{DETIME} = \text{Time for desorption, minutes}
- \text{INT1} = \text{Previous } \text{INT1} \text{ value.}
- \text{NEWABTIME} = \text{Previous absorb cycle time, minutes.}
- \text{ONTIME} = \text{Time steam generator is on during desorption, sec.}
- \text{P} = \text{Accumulator pressure at end of desorption, sec.}
- \text{PH2OPAST} = \text{Past value of bed loading for this bed, } \text{%}.
- \text{TIN} = \text{Inlet temperature at end of desorbing bed's post absorb cycle, } ^\circ\text{F}
- \text{TOUT} = \text{Exit temperature at end of desorbing bed's past adsorbing cycle, } ^\circ\text{F}
All the following calculations are done at the end of desorption.

Calculate Bed $\text{CO}_2$ loading fraction which was at start of this desorb "FCO2".

\[
\text{Power} = \frac{\text{ONTIME}}{(0.05769 \times \text{DETIME})}
\]

\[
\text{Power} = \text{Clamp} (\text{Power}, 1, 1040)
\]

\[
\text{TSAT} = K54 \times \text{P}^2 + K53 \times \text{P} + K52
\]

\[
\text{T3} = K16 \times (\text{TSAT} - 212)/\text{Power}
\]

\[
\text{T3} = \text{Clamp} (\text{T3}, 0.0, 17.5)
\]

\[
\text{Ratio} = (\text{CO2 Time} - \text{T3})/\text{DETIME}
\]

\[
\text{FCO2} = K51 \times \text{RATIO}^2 + K50 \times \text{RATIO} - K49
\]

\[
\text{FCO2} = \text{Clamp} (\text{FCO2}, 0.0, 0.05)
\]

Calculate Bed $\text{H}_2\text{O}$ loading percent which was at start of this desorb "PCTH20".

\[
\text{WGTH20} = \frac{(K0 \times \text{ONTIME} - K46 \times (\text{TSAT}-\text{TIN}) - K47 \times \text{FCO2} - K48)}{(\text{TSAT}-\text{TOUT}) - K1 \times \text{DETIME} - K44}
\]

\[
\text{OCTH20} = 100.0 \times \text{WGTH20}
\]

\[
\text{IF}((\text{PCTH20} - \text{OCTH20PAST}).LT.-3.0) \text{ PCTH20} = \text{PCTH20PAST}-3.0
\]

\[
\text{IF}((\text{PCTH20}-\text{PCTH20PAST}).LT.-3.0) \text{ PCTH20} = \text{PCTH20PAST}-3.0
\]

\[
\text{PCTH20} = \text{Clamp} (\text{PCTH20}, 10.0, 40.0)
\]

Calculate new absorb cycle time, "NEWABTIME" in minutes.
The steam flow rate determines the desorption time. The control of the steam flow is not calculated based on the relative humidity in the cabin during the previous absorption cycle. The steam flow for the next desorption of the bed is based on the steam flow rate during the past desorb multiplied by the calculated steam generation power ratio.

\[ M_{SN} = M_{SO} \times PR \]

The steam generator power ratio is set equal to 1.0 for the first desorption of each SAWD bed. For all subsequent desorptions, the power ratio is calculated by squaring the actual time of the last desorption and dividing it by the product of the calculated time of the last desorption and the calculated time of the new desorption time.

\[ PR = \frac{t_a \times t_a}{t_{co} \times t_{cn}} \]
where:

\[
\begin{align*}
MSN & = \text{New bed desorb steam flow, pph} \\
MSO & = \text{Old bed desorb steam flow, pph} \\
PR & = \text{Steam generator power ratio} \\
t_a & = \text{Actual time of last bed desorb, sec} \\
t_{co} & = \text{Calculated time of last bed desorb, sec} \\
t_{cn} & = \text{Calculated time of next bed desorb, sec}
\end{align*}
\]
APPENDIX B

MODEL DESCRIPTION DOCUMENT FOR ECLSB MODEL
B.1 Introduction

An extension to the original ESCM program is to develop lightweight simulation models of various life support equipment and to combine them into a system. The utility of using all lightweight models to enhance system design could then be explored. This differs from the original program which was to investigate the utility of a combined emulation and simulation model.

This manual provides the model description for one of the systems simulated. This system consists of one air revitalization group of equipment working in conjunction with one group of waste water processing equipment. The principal pieces of equipment are:

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<td>Electrochemical Depolarized Concentrator</td>
</tr>
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<td>CO\textsubscript{2} Reduction</td>
<td>Sabatier</td>
</tr>
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<td>O\textsubscript{2} Generation</td>
<td>Static Feed Solid Polymer Electrolysis</td>
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<td>Trace Gas Removal</td>
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<td>Condensate Processing</td>
<td>Multifiltration</td>
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<tr>
<td>Urine Reclamation</td>
<td>Vapor Compression Distillation</td>
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</table>
B.2  Modelling of System

The life support system to be analyzed is shown in Figure B-1. The following discusses how this system represents real hardware.

The system shown in Figure B-1 consists of many components; however, some are the same. Therefore, models of only the following components are needed:

(1) Crew  (8) EDC Cells  
(2) Cabin  (9) Fan  
(3) Fan (10) Splitter  
(4) Heat Exchanger (11) Mixer  
(5) SPE Cells (12) All Purpose Component  
(6) Catalytic Oxidizer (13) VCD  
(7) Sabatier

These components are arranged as required for use with G189A. Accordingly, particular items are arranged for modelling purposes but do not represent their actual physical location. First of all, the crew which consumes oxygen and produces carbon dioxide and water vapor is placed in series with other components before the cabin. This was done to keep the schematic simple and to minimize the number of components required. In actuality, the crew is in the cabin.
FIGURE B-1
ECLSS SYSTEM B SCHEMATIC FOR G189 TYPE COMPUTER MODEL
In the model in Figure B-1, it appears that the cabin has only four ports for gas flows - two entry and two exit. This is a restriction of G189A and again does not represent actuality. Air for the condensing heat exchanger, Sabatier cooling and the EDC are all drawn directly from the cabin. Since G189A has a limited number of ports, one port is used and then splitters are used to direct flow to each of the components. The end result is the same.

B.3 Modelling of Components

As discussed in Section B.2, only thirteen component analytical models need be available to analyze the life support system. 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 G189A manual [2]. In those cases, the reader will be referred to the G189A manual for a description of the analytical model.

In addition to the thirteen components, the control of the cabin air conditions and the water tank levels are discussed.
Of the thirteen components, many were discussed previously in the ESCM Model Description Document [1]. The following are discussed here:

SPE Cells  Bacteria Filter
Catalytic Oxidizer  Charcoal Filter
Sabatier  Multifiltration
EDC Cells  Controls
VCD

B.3.1 SPE Cells

The solid polymer electrolysis cells convert water to hydrogen and oxygen and give off heat to a heat exchanger with the coolant being air. The following constants and operating conditions are used:

\[ A_c = \text{unit cell area} = 0.239 \text{ ft}^2 \]
\[ P_c = \text{cell operating pressure} = 200 \text{ psia} \]
\[ T_c = \text{cell operating temperature} = 155^\circ \text{F} \]
\[ N_c = \text{number of cells} = 20 \]

The cell current density is determined from:

\[ J_c = I/A_c \]

where \( I = \) cell current, amps
\( J_c = \) cell current density, amps/ft\(^2\)
A cell efficiency is then determined by linear interpolation of the tables in Table B-1 for the cell pressure $P_C$, current density $J_C$, and cell temperature $T_C$. In addition, the voltage $V_C$ across each cell is determined by linear interpolation of the tables in Table B-2 for the cell pressure $P_C$, current density $J_C$, and cell temperature $T_C$.

The total watts consumed by the cells becomes:

$$w_e = I \cdot V_C \cdot N_c$$

where $V_C$ = voltage across each cell, volts

$w_e$ = total electrical power of cells, watts

The amount of oxygen and hydrogen produced is given by:

$$m_{O_2} = 0.000659 \frac{I}{100} \cdot N_c$$

$$m_{H_2} = \frac{m_{O_2}}{8}$$

where: $m_{O_2}$ = mass flow of oxygen produced, lbm/hr

$m_{H_2}$ = mass flow of hydrogen produced, lbm/hr

The water consumed by electrolysis is given by:

$$m_{H_2O,E} = 1.125 \cdot m_{O_2}$$
<table>
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<td>450</td>
<td>99.1</td>
<td>97.8</td>
<td>96.7</td>
</tr>
<tr>
<td>500</td>
<td></td>
<td>98.1</td>
<td>97.0</td>
</tr>
</tbody>
</table>

Percent Efficiency at $T_c = 180^\circ$F

<table>
<thead>
<tr>
<th>$J_c$ (AMPS/FT²)</th>
<th>100</th>
<th>200</th>
<th>300</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>87.8</td>
<td>82.4</td>
<td>79.0</td>
</tr>
<tr>
<td>100</td>
<td>93.0</td>
<td>86.7</td>
<td>82.9</td>
</tr>
<tr>
<td>150</td>
<td>95.4</td>
<td>90.7</td>
<td>86.3</td>
</tr>
<tr>
<td>200</td>
<td>96.6</td>
<td>92.9</td>
<td>89.1</td>
</tr>
<tr>
<td>250</td>
<td>97.2</td>
<td>94.2</td>
<td>91.2</td>
</tr>
<tr>
<td>300</td>
<td>97.7</td>
<td>95.1</td>
<td>92.6</td>
</tr>
<tr>
<td>350</td>
<td>98.0</td>
<td>95.8</td>
<td>93.7</td>
</tr>
<tr>
<td>400</td>
<td>98.3</td>
<td>96.4</td>
<td>94.5</td>
</tr>
<tr>
<td>450</td>
<td>98.4</td>
<td>96.7</td>
<td>95.1</td>
</tr>
<tr>
<td>500</td>
<td>98.0</td>
<td>97.1</td>
<td>95.6</td>
</tr>
</tbody>
</table>
### TABLE B-2
SPE CELL VOLTAGE

<table>
<thead>
<tr>
<th>J_c (AMPS/FT^2)</th>
<th>100</th>
<th>200</th>
<th>300</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1.556</td>
<td>1.568</td>
<td>1.577</td>
</tr>
<tr>
<td>100</td>
<td>1.594</td>
<td>1.602</td>
<td>1.609</td>
</tr>
<tr>
<td>150</td>
<td>1.623</td>
<td>1.632</td>
<td>1.638</td>
</tr>
<tr>
<td>200</td>
<td>1.650</td>
<td>1.662</td>
<td>1.667</td>
</tr>
<tr>
<td>250</td>
<td>1.678</td>
<td>1.690</td>
<td>1.697</td>
</tr>
<tr>
<td>300</td>
<td>1.714</td>
<td>1.725</td>
<td>1.733</td>
</tr>
<tr>
<td>350</td>
<td>1.760</td>
<td>1.772</td>
<td>1.777</td>
</tr>
<tr>
<td>400</td>
<td>1.832</td>
<td>1.843</td>
<td>1.857</td>
</tr>
</tbody>
</table>

**Cell Voltage at T_c = 140°F**

<table>
<thead>
<tr>
<th>Cell Pressure (psia)</th>
<th>100</th>
<th>200</th>
<th>300</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>1.503</td>
<td>1.514</td>
<td>1.522</td>
</tr>
<tr>
<td>150</td>
<td>1.537</td>
<td>1.548</td>
<td>1.553</td>
</tr>
<tr>
<td>200</td>
<td>1.562</td>
<td>1.573</td>
<td>1.581</td>
</tr>
<tr>
<td>250</td>
<td>1.587</td>
<td>1.599</td>
<td>1.606</td>
</tr>
<tr>
<td>300</td>
<td>1.614</td>
<td>1.624</td>
<td>1.632</td>
</tr>
<tr>
<td>350</td>
<td>1.639</td>
<td>1.651</td>
<td>1.657</td>
</tr>
<tr>
<td>400</td>
<td>1.670</td>
<td>1.682</td>
<td>1.689</td>
</tr>
</tbody>
</table>

**Cell Voltage at T_c = 180°F**

<table>
<thead>
<tr>
<th>Cell Pressure (psia)</th>
<th>100</th>
<th>200</th>
<th>300</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>1.701</td>
<td>1.722</td>
<td>1.728</td>
</tr>
<tr>
<td>150</td>
<td>1.714</td>
<td>1.733</td>
<td>1.739</td>
</tr>
<tr>
<td>200</td>
<td>1.725</td>
<td>1.745</td>
<td>1.751</td>
</tr>
<tr>
<td>250</td>
<td>1.733</td>
<td>1.754</td>
<td>1.760</td>
</tr>
<tr>
<td>300</td>
<td>1.741</td>
<td>1.762</td>
<td>1.768</td>
</tr>
<tr>
<td>350</td>
<td>1.749</td>
<td>1.770</td>
<td>1.776</td>
</tr>
<tr>
<td>400</td>
<td>1.757</td>
<td>1.778</td>
<td>1.784</td>
</tr>
</tbody>
</table>
where: \( m_{H2O,E} \) = mass flow of water consumed by electrolysis, lbm/hr

Water is also present as saturated vapor in the oxygen and hydrogen gas flows.

The amount is determined from the following relation:

\[
Y_v = \frac{P_{sat}(T_c)}{P_c}
\]

\[
m_{H2O,02} = \frac{Y_v \cdot m_{O2}}{1-Y_v \cdot MW_{O2}} \cdot MW_{H20}
\]

\[
m_{H2O,H2} = \frac{Y_v \cdot m_{H2}}{1-Y_v \cdot MW_{H2}} \cdot MW_{H2}
\]

where: \( Y_v \) = mole fraction of water vapor

\( MW_{O2} \) = molecular weight of oxygen, lbm/mole

\( MW_{H2} \) = molecular weight of hydrogen, lbm/mole

\( P_{sat} \) = saturation pressure at given temp., psia

\( m_{H2O,02} \) = mass flow of water vapor in oxygen, lbm/hr

\( m_{H2O,H2} \) = mass flow of water vapor in hydrogen, lbm/hr

Therefore, the total water consumed becomes:

\[
m_{H2O,T} = m_{H2O,E} + m_{H2O,02} + m_{H2O,H2}
\]
The waste electrical power is given by:

\[ w_w = w_e (1 - 1.48 \frac{\eta}{V_c}) \]

The heat given off to the ambient is given by:

\[ Q = (w_w + 0.11 w_e + 27.3) 3.413 \]

where \( Q \) = heat lost to ambient, Btu/hr.

All this heat is transferred to a heat exchanger which is cooled by ambient air.

B.3.2 Catalytic Oxidizer

The model of the catalytic oxidizer is a simple model which computes the temperature of the air stream exiting the unit. The composition of the air remains unchanged. The following constants are used:

- \( w_{\text{htr}} \) = heater power = 28 watts
- \( M_c \) = mass of high temperature bed catalyst = 2.0 lbm
- \( T_c \) = operating temperature of high temp. catalyst = 600\(^{\circ}\)F
- \( s \) = fraction of air flow to high temp. catalyst = 0.1111
- \( \eta_{HX} \) = heat exchanger effectiveness = 0.9
- \( c_p \) = specific heat of air = 0.24 Btu/lbm-F

B-10
First the temperature leaving the high temperature bed is computed as:

\[ T_h = T_c - \eta_{HX} (T_c - T_i) \]

where
\( T_h \) = exit temp. from high temp. bed, °F
\( T_i \) = air inlet temp. to cat ox., °F

This high temperature air mixes with the air not going to the high temperature bed to give the resultant exit temperature.

\[ T_e = \frac{s m_1 T_h c_p + (1-S) m_1 T_i c_p}{m_1 c_p} \]

Figure B-2 shows a schematic of the catalytic oxidizer subsystem and the location of the above discussed temperatures and flows.

B.3.3 Sabatier CO\(_2\) Reduction Subsystem

The Sabatier CO\(_2\) reduction subsystem consists of the Sabatier reactor, a fan and a water separator as modeled for G189A.

A listing of the Sabatier subroutine SABHS is given in the ECLSB User's Manual [3]. The model is a simplified block box model which provides the gas composition exiting the reactor and the mixed temperature of the cooling air leaving the reactor and condensing heat exchanger.
FIGURE B-2
CATALYTIC OXIDIZER SUBSYSTEM SCHEMATIC
The Sabatier reaction is assumed to go to completion. First a test is made on the incoming gases to determine whether excess hydrogen or carbon dioxide exists. The reaction is:

$$\text{CO}_2 + 4 \text{H}_2 \rightarrow \text{CH}_4 + 2 \text{H}_2\text{O}$$

If \( \frac{m_{\text{H}_2,1}}{2.016} < \frac{4 m_{\text{CO}_2,1}}{44.01} \)

then excessive carbon dioxide exists and all the hydrogen is consumed. For this case, the following relations hold:

- \( m_{\text{CH}_4,e} = \frac{m_{\text{H}_2,1}}{4 \text{MWCH}_4} \)
- \( m_{\text{H}_2\text{O},e} = \frac{m_{\text{H}_2,1}}{4 \text{MWH}_2} \)
- \( m_{\text{H}_2,e} = 0.0 \)
- \( m_{\text{CO}_2,e} = m_{\text{CO}_2,1} - \frac{m_{\text{H}_2,1}}{4 \text{MWH}_2} \)
- \( Q_{\text{sen}} = 8864. \frac{m_{\text{H}_2,1}}{4 \text{MWH}_2} \)
where: 

\( m_{H_2, i} \) = mass flow of hydrogen entering reactor, lbm/hr \\
\( m_{H_2, e} \) = mass flow of hydrogen exiting reactor, lbm/hr \\
\( m_{CO_2, i} \) = mass flow of carbon dioxide entering reactor, lbm/hr \\
\( m_{CO_2, e} \) = mass flow of carbon dioxide exiting reactor, lbm/hr \\
\( m_{CH_4, e} \) = mass flow of methane exiting reactor, lbm/hr \\
\( m_{H_2O, e} \) = mass flow of water exiting reactor, lbm/hr \\
\( m_{H_2O, i} \) = mass flow of water entering reactor, lbm/hr \\
\( MW \) = molecular weight, lbm/mole \\
\( Q_{sens} \) = sensible heat produced by reaction, Btu/hr 

On the other hand, if excess hydrogen exists, the following relations hold:

\[
m_{CH_4, e} = \frac{m_{CO_2, i}}{MW_{CH_4}} \times \frac{MW_{CH_4}}{MW_{CO_2}}
\]

\[
m_{H_2O, e} = \frac{m_{CO_2, i}}{MW_{H_2O}} \times \frac{2MW_{H_2O} + m_{H_2O, i}}{MW_{CO_2}}
\]

\[
m_{CO_2, e} = 0.0
\]

\[
m_{H_2, e} = m_{H_2, i} - \frac{m_{CO_2, i}}{MW_{CO_2}} \times 4MW_{H_2}
\]
The latent heat load to condense the water produced is

\[ Q_{\text{LAT}} = 1050 \text{ m}^3\text{H}_2\text{O} \]

The temperature of the cooling air leaving the Sabatier is:

\[ T_{\text{air},e} = T_{\text{air},i} + \frac{(Q_{\text{LAT}} + Q_{\text{sens}})}{m_{\text{air}} \cdot c_p} \]

where: \( m_{\text{air}} \) = mass flow of air, lbm/hr

The fan draws air around the reactor for cooling and through a condensing heat exchanger to condense the product water. The fan operational characteristics are:

\[ \text{cfm} = 20.0 \]

\[ \text{power} = 34 \text{ watts} \]

The condensed water and product gases pass through a water separator which is modeled as an alternate component for use with G189A. All the water is separated from the product gases and 0.13 Btu/hr is added to the product gases in the form of heat.
The EDC CO$_2$ removal subsystem removes carbon dioxide from the air stream through a fuel cell type process which requires hydrogen and produces electricity. Heat is removed through a water cooled heat exchanger. Again, simple black box models are used. See Figure B-3 for a schematic representation.

A listing of the EDC subroutine EDCHS is contained in Appendix A of the ECLSB User's Manual [3]. The following constants are used:

- $J_d$ = design current density = 11 Amps/ft$^2$
- $R_{CO_{2}}$ = CO$_2$ transfer rate = 0.001736 lbm CO$_2$/amp-hr
- $A_c$ = area per cell = ft$^2$/cell
- $T_c$ = cell operating temperature = 70$^\circ$F
- $P_c$ = cell operating pressure = 14.7 psia
- $C_{PCO_{2}}$ = 0.211 Btu/lbm-F
- $C_{PH_{2}}$ = 3.437 Btu/lbm-F
- $C_{PO_{2}}$ = 0.221 Btu/lbm-F
- $N_c$ = number of cells = 30

First, the carbon dioxide removal at design conditions is calculated using the following:

$$m_{CO_{2},d} = R_{CO_{2}} J_d A_c N_c$$
FIGURE B-3
EDC CO₂ REMOVAL SUBSYSTEM
Then, a factor is computed for use in determining the actual CO₂ removed. This factor is given by:

$$J_{CO₂} = \left( \frac{J_A}{J_D} + 0.27 \right) \frac{1}{1.27}$$

The actual CO₂ removed becomes:

$$m_{CO₂,A} = m_{CO₂,i} - m_{CO₂,e}$$

where:

- $J_A$ = actual current density, amps/ft²
- $m_{CO₂,i}$ = mass flow of CO₂ into EDC, lbm/hr
- $m_{CO₂,e}$ = mass flow of CO₂ exiting EDC in air stream, lbm/hr

The actual electrical characteristics required are:

$$I = 1.27 K_{CO₂} J_D A_C$$

$$V = \frac{J_A}{0.5 N_c} \frac{\text{dividing line on separate half space}}{J_D}$$

$$w = I V$$
In the process, oxygen is consumed; the amount is given by the following relations:

\[
PCO2 = \frac{mCO2,1}{MWCO2} \frac{P_i}{\frac{760}{14.696}}
\]

\[
\eta = 1.02 + \frac{0.19}{PCO2} - \frac{0.718}{PCO2^2}
\]

\[
MCO2,c = \frac{MCO2,A}{2 MWCO2}
\]

\[
mO2,e = mO2,i - mO2,C
\]

where:
- \(P_i\) = inlet pressure of air to EDC, psia
- \(mCO2,1\) = inlet mass flow of CO\(_2\) into EDC, lbm/hr
- \(MWCO2\) = molecular weight of CO\(_2\) = 44.01 lbm/mole
- \(PCO2\) = partial pressure of CO\(_2\) in inlet air, mm Hg
- \(\eta\) = effectiveness of conversion
- \(MWO2\) = molecular weight of oxygen = 32 lbm/mole
- \(mO2,C\) = mass flow of oxygen consumed, lbm/hr
- \(mO2,i\) = mass flow of oxygen into EDC, lbm/hr
- \(mO2,e\) = mass flow of oxygen exiting EDC air stream, lbm/hr
The factor of 2 in the preceding equation arises from the overall reaction taking place in the EDC cells:

\[ \text{CO}_2 + \frac{1}{2} \text{O}_2 + \text{H}_2 \rightarrow \text{CO}_2 + \text{H}_2\text{O} + \text{electricity} + \text{heat} \]

Accordingly, the amount of hydrogen consumed is given by:

\[ m_{\text{H}_2,\text{C}} = 2 \frac{m_{\text{O}_2}}{MW_{\text{H}_2}} \]

The amount of water produced is:

\[ m_{\text{H}_2\text{O},\text{P}} = \frac{m_{\text{H}_2,\text{C}}}{MW_{\text{H}_2}} \cdot MW_{\text{H}_2\text{O}} \]

Some of the water available leaves with the hydrogen and carbon dioxide gases. It is assumed that the vapor is saturated and that the pressure in the H\text{H}_2-\text{CO}_2 exit port is 20 psia. The amount of water leaving with the H\text{H}_2-\text{CO}_2 mixture is given by the following:

\[
m_{\text{H}_2,e} = m_{\text{H}_2,i} - m_{\text{H}_2,\text{C}}
\]

\[
m_{\text{H}_2,\text{e} + \text{MCO}_2} = \frac{m_{\text{H}_2,e} + m_{\text{CO}_2}}{MW_{\text{H}_2\text{CO}_2}}
\]
\[ P_V = P_{sat(T_c)} \]

\[ = \frac{M_{H_2O}}{P_V} \frac{P_V}{P_T} \]

\[ m_{H_2O,VE} = \omega (m_{CO_2,a} + m_{H_2,e}) \]

\[ m_{H_2O,e} = m_{H_2O,p} + m_{H_2O,i} + m_{H_2O,vi} - m_{H_2O,ve} \]

where:
- \( m_{H_2,i} \) = mass flow of hydrogen into EDC, lbm/hr
- \( m_{H_2,e} \) = mass flow of hydrogen exiting EDC, lbm/hr
- \( M_{H_2} \) = molecular weight of hydrogen, lbm/moles
- \( M_{H_2O} \) = molecular weight of water, lbm/moles
- \( M_{W_{mix}} \) = molecular weight of \( H_2-CO_2 \) mix exiting EDC, lbm/moles
- \( P_V \) = vapor pressure of water in \( H_2-CO_2 \) stream, psia
- \( P_{sat} \) = saturation pressure for given temp, psia
- \( \omega \) = humidity ratio
- \( P_T \) = total pressure in \( H_2-CO_2 \) exit line, psia
- \( m_{H_2O,ve} \) = vapor leaving with \( H_2 \) and \( CO_2 \), lbm/hr
- \( m_{H_2O,i} \) = mass flow of water into EDC from air stream, lbm/hr
- \( m_{H_2O,vi} \) = mass flow of water into EDC with \( H_2 \) stream, lbm/hr
The total heat generated is given by:

\[ Q_d = 65.7 + 766.8 \cdot m_{CO_2, d} \]

\[ Q_{sens} = (1.06 \cdot K_{CO_2} - 0.06) \cdot Q_d \]

where:  
\( Q_d \) = design heat production, Btu/hr  
\( Q_{sens} \) = actual heat production, Btu/hr

Of this heat, 25\% is added to the air stream and 75\% must be removed by the heat exchanger. Accordingly, the exit air temperature is given by:

\[ T_e = T_i + \frac{0.25 \cdot Q_{sens}}{(m_{air,i} + m_{H2O,vi}) \cdot c_p} \]

where:  
\( T_i \) = inlet air temperature, F  
\( m_{air,i} \) = inlet air flow, lbm/hr  
\( c_p \) = specific heat of inlet air = 0.24 Btu/lbm-F

B.3.5 VCD Water Processing Subsystem

Vapor compression distillation process purifies water through a distillation type process. The model at present is simple and determines the amount of power consumed and the amounts of water and brine delivered. The following relations and constants are used:
\[ m_{H_2O,e} = 0.96 \, m_{H_2O,i} \]

\[ m_b = 0.04 \, m_{H_2O,i} \]

\[ w = \frac{m_{H_2O,e}}{40.1} \]

where:
- \( m_{H_2O,i} \) = mass flow of water into VCD, \( 2.30 \) lbm/hr for 3 man units or \( 2.73 \) lbm/hr for 6 man unit.
- \( m_{H_2O,e} \) = mass flow of clean water exiting VCD, lbm/hr
- \( m_b \) = mass flow of brine, lbm/hr
- \( w \) = power required, watts

### B.3.6 Filtration Models

Three filtration devices are modeled in ECLSB by the use of the Alternate Component subroutine. The three components are the bacteria filter, charcoal filter, and multifiltration. For each of these, the inlet flows and conditions pass through unchanged.

### B.3.7 Control

A variety of items require control to operate the system effectively. CO\(_2\) and O\(_2\) levels in the cabin atmosphere need to be maintained, and water levels in the various tanks need to be regulated. This control logic is contained in subroutines GPOLY1 and GPOLY2, and listings of these are contained in Table B-3 and Table B-4 respectively.
LISTING OF GPOLY1 FOR ECLSB MODEL

SUBROUTINE GPOLY1

THIS SUBROUTINE PROVIDES THE CONTROL LOGIC FOR SYSTEM "B" ECLS SIMULATION USING THE G189A COMPUTER PROGRAM.

TYPE STATEMENTS:

INTEGER ONCE
REAL MR,INOM
LOGICAL STEADY, CYCLIC, LTSIDE, OPEN, VCOND, MFTON

DIMENSION STATEMENTS:

DIMENSION V(1), K(1)
DIMENSION TURINE(8), THWASH(11), TSHOWR(2), TDRINK(8), TFOODP(5)

COMMON STATEMENTS:

COMMON /COMP/ DS(15), N, NA1, NB1, NC, NCAB, NCFL, NEXT, NEXV, NK,
1 NKEX, NKS, NKT, NLFL, NP, NPASS, NPF, NPFIT(6), NQ, NS, NSF, NSFT(6),
2 NSTR(18), NSUBR, NV, NVT, Y(12)
COMMON /RARRAY/ IMAXR, R(2560)
COMMON /ECLST1/ KCHOUT, KPRNT, KPTINV(4), KWIT, KWIT1, KWIT2,
1 KWIT3, KWIT4, NUFF, KSTDY
COMMON /KANDV/ K
COMMON /MISC/ DTIME, GRAV, KFLSYS, KOUTPT, KPDROP, KSYPS, KTRANS,
1 LPSUM(5), MAXC1, MAXLP, MAXSLP, MAXSSI, NCOMPS, NEWDT, NLAST, NPASPD,
2 MINSSI, PMIN, PLMIN, START, STEADY, TIME, TIMEMX, TMAX, TMIN, WTIME
COMMON /CASE/ NCASE, NRSCS, NRECS
COMMON /PROPTY/ COPO, CP(99), CPCONL, CPCONV, CPCO2, CPDIL, CPOXY, CPIC,
1 CAMGAS, RHOD, RHO(99), VISCO, VISC(99), VISMGAS, WTMG, WTM(99), WTMCON,
2 WTMDIL, WTMT, XKO, XK(99), XKGAS, XKLQ, VISLIQ
COMMON /SOURCE/ A(19), B(19), CPA, CPB, IA1, IB1, NA, NB, NPF, NPFST(6),
1 NSES, NSFST(6), ROH, ROB, VISCA, VISCA, WTMA, WTMB, XXA, XKB
COMMON /VLOC/ IP, IS, IC, IQ, IV, IVT, IEX, INEXK
COMMON /LRC/ IDATE(2), ISCHM

DATA INITIALIZATION:

DATA TURINE / 0.1, 3.0, 6.0, 9.0, 12.0, 15.0, 20.0, 25.0 /
DATA THWASH / 0.1, 3.0, 5.0, 6.0, 9.0, 10.0, 11.0, 12.0, 15.0, 20.0, 25.0 /
DATA TSHOWR / 15.0, 25.0 /
DATA TDRINK / 0.1, 3.0, 6.0, 9.0, 12.0, 15.0, 20.0, 25.0 /
DATA TFOODP / 0.1, 5.0, 10.0, 14.0, 25.0 /
DATA KU, KH, KS, KD, KF / 1, 1, 1, 1, 1 /

EQUIVALENCE (V(1), K(1))

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INITIALIZE AT START OF STEADY STATE SOLUTION. DONE ONLY ONCE.

IF(STEADY .AND. KSYPAS .LE. 1) THEN
  LSIDE = .TRUE.
  TCAB0 = 0.0
  TDESO = 0.0
  IFREQ = VV(2,184)
  NMEN = KK(1,16)
  H2OADD = VV(2,128)
  CYCLIC = VV(2,185) .GT. 0.9
END IF

IF(N .EQ. 1) THEN
  READ TABLE OF METABOLIC RATE VS MISSION TIME (24 HR CYCLE).
  TIMCYC = AMOD(TIME,86400.)
  MR = VALUE(1,TIMCYC,0.0)
  TCAB = VV(2,104)
  TCAB = 70.
  QL = MR-480.*(MR/1000.+ 10.)*(TCAB-60.0)
  QLMin = 0.22*MR+2.6*(TCAB-60.0)
  QL = AMAX1(QL,QLMin)
  QS = MR-QL
  R(66) = QS
  R(67) = QL
  R(82) = MR
END IF

IF(N .NE. 2) THEN
  IF(KSTEADY .OR. MOD(KSYPAS,IFREQ) .EQ. 0) ISCM = 1
  R(181) = DTIME
  R(182) = DTIME/60.
END IF

LIGHTSIDE - DARKSIDE?

IF(CYCLIC) THEN
  TIMORB = AMOD(TIME,5400.)
  LTSIDE = TIMORB .LE. 2700.
END IF

NITROGEN ADDITION RATE

R(166) = 0.0
WCN = 0.0
PT = R(4)
P02 = R(94)
IF(PT .GE. 14.819) GO TO 220
IF (PT .GE. 14.818 .AND. P02 .GE. 8.28) GO TO 220
IF (P02 .LT. 8.09) GO TO 220
REGULATOR LOGIC.

IF(OPEN) GO TO 210

N2 OPENING CURVES.

WCN = VALUE(22,PT,0.0)
OPEN = .TRUE.
GO TO 220

N2 CLOSING CURVES.

WCN = VALUE(28,PT,0.0)
IF(WCN .LE. 0.0) OPEN = .FALSE.

OXYGEN AND H2O VAPOR ADDITION FROM SPE, LBM/HR

R(128) = H2OADD+VV(20,68)
R(165) = V(VIV+2)

TRACE CONTAMINANTS ADDITION

END IF

IF(N .EQ. 8) THEN
IF(.NOT. STEADY .OR. KSYPAS .GE. 4) THEN
WSEC = VV(7,1)
WPRI = VV(5,1)
WTOT = WSEC+WPRI
SR = WSEC/WTOT
R(65) = SR
END IF
END IF

IF(N .EQ. 6) THEN
R(84) = 0.0
IF(VV(7,68) .GE. 660.) R(84) = 1.0
END IF

IF(N .EQ. 9) THEN
IF(.NOT. STEADY .OR. KSYPAS .GE. 4) THEN
WSEC = VV(14,1)
WPRI = VV(16,1)+VV(28,1)+VV(21,1)
WTOT = WSEC+WPRI
SR = WSEC/WTOT
R(65) = SR
END IF
END IF

C
IF(N .EQ. 11) THEN
  W8 = A(1)*R(72)/CPA
  W8 = AMAX1(W8,A(1))
  R(66) = EXP(2.809-0.00169*B(1))*W8*(0.52+0.00026*B(1))
END IF

C
C
EXTRACT CONDENSATE WATER.

C
IF(N .EQ. 18) THEN
  R(67) = A(7)
  A(1) = A(1)-A(7)
  A(7) = 0.0
  CPA = (A(5)*A(8)+A(6)*CPCONV)/A(1)
END IF

C
IF(N .EQ. 15) THEN
  IF(.NOT. STEADY .OR. KSYPAS .GE. 4) THEN
    WSEC = VV(16,1)
    WPRI = VV(28,1)+VV(21,1)
    WTOT = WSEC+WPRI
    SR = WSEC/WTOT
    R(65) = SR
  END IF
END IF

C
IF(N .EQ. 16) THEN
  R(84) = 1.0
  IF(.NOT. LTSIDE) R(84) = 0.0
END IF

C
17 IF(N .NE. 17) GO TO 1799
IF(STEADY .AND. KSYPAS .LT. 4) GO TO 1799
WSEC = VV(21,1)
WPRI = VV(28,1)
WTOT = WSEC+WPRI
SR = WSEC/WTOT
R(65) = SR
1799 CONTINUE

C
18 IF(N .NE. 18) GO TO 1899
R(84) = 1.0
IF(.NOT. LTSIDE) R(84) = 0.0
1899 CONTINUE

C
19 IF(N .NE. 19) GO TO 1999
R(84) = 1.0
IF(.NOT. LTSIDE) R(84) = 0.0
1999 CONTINUE
C
20 IF(N .NE. 20) GO TO 2099
INOM = R(72)
PO2 = VV(2,94)
R(69) = INOM
IF(PO2 .GE. 8.1) R(69) = 0.9*INOM
IF(PO2 .LE. 2.9) R(69) = 1.1*INOM
CALL SK(1,20,16)
IF(LTSIDE) GO TO 2099
R(69) = 0.0
CALL SK(0,20,16)
2099 CONTINUE
C
21 IF(N .NE. 21) GO TO 2199
R(65) = VV(20,65)
2199 CONTINUE
C
28 IF(N .NE. 28) GO TO 2899
PCO2 = VV(2,100)
R(68) = R(69)
IF(PCO2 .GT. 8.0) R(68) = R(69)
IF(PCO2 .LT. 2.0) R(68) = R(69)
IF(LTSIDE) GO TO 2899
R(68) = 0.0
2899 CONTINUE
C
24 IF(N .NE. 24) GO TO 2499
R(65) = VV(28,65)
2499 CONTINUE
C
28 IF(N .NE. 28) GO TO 2899
C
C EXTRACT CONDENSATE WATER.
C
R(67) = A(7)
A(1) = A(1)-A(7)
A(7) = 0.0
CPA = (A(5)*A(8)+A(6)*CPCONV)/A(1)
2899 CONTINUE
C
82 IF(N .NE. 82) GO TO 8299
CPA = CPCONL
RHOA = RHO(1)
CPB = CPCONL
RHOB = RHO(1)
WTMA = WTM(1)
WTMB = WTM(1)
VISCA = VISC(1)
VISCB = VISC(1)
XKA = XK(1)
8299 CONTINUE
IF(N .NE. 85) GO TO 8599

URINE DUMP TO STORAGE TANK, LBM/HR

A(1) = 0.0
IF (NMEN .EQ. 6) WDMP = 17./7.
IF (NMEN .EQ. 8) WDMP = 26.28/7.
TIMCYC = AMOD(TIME,86400.)
IF(TIMCYC .LT. TURINE(7)*8600. .AND. KU .EQ. 8) KU = 1
IF(TIMCYC .LT. TURINE(KU)*8600.) GO TO 8510
KU = KU+1
KU = MINO(KU,8)
A(1) = WDMP/DTIME*8600.

WASTE HAND WASH WATER DUMP TO STORAGE TANK, LBM/HR

WHWASH = 0.0
IF(TIMCYC .LT. TWHASH(10)*8600. .AND. KH .EQ. 11) KH = 1
IF(TIMCYC .LT. TWHASH(KH)*8600.) GO TO 8520
KH = KH+1
KH = MINO(KH,11)
WHWASH = 11.5/10.
A(1) = A(1)+WHWASH/DTIME*8600.

WASTE SHOWER WATER DUMP TO STORAGE TANK, LBM/HR

WSHOWR = 0.0
IF(TIMCYC .LT. TSHOWR(1)*8600. .AND. KS .EQ. 2) KS = 1
IF(TIMCYC .LT. TSHOWR(KS)*8600.) GO TO 8580
KS = KS+1
KS = MINO(KS,2)
WSHOWR = 22.5
A(1) = A(1)+WSHOWR/DTIME*8600.

FLOW EXITING URINE WASH WATER STORAGE TANK, LBM/HR

R(1) = 0.0
IF(R(69) .LE. 80.) GO TO 8540
VCDON = .TRUE.
GO TO 8550
8540 IF(R(69) .GE. 27.) GO TO 8550
VCDON = .FALSE.
8550 IF(.NOT. VCDON) GO TO 8599
IF(NMEN .EQ. 8) R(1) = 2.80
IF(NMEN .EQ. 6) R(1) = 2.78
8599 CONTINUE
41  IF(N .NE. 41) GO TO 4199
    H2OSPE = VV(20,67)
    R(1) = (WHWASH+WSHOWR)/DTIME*3600.+H2OSPE*WMFLT
4199 CONTINUE

42  IF(N .NE. 42) GO TO 4299
    WSEC = (H2OSPE+WMFLT)*DTIME/3600.
    WTOT = WSEC+WHWASH+WSHOWR  
    IF(WTOT .LE. 0.0) GO TO 4299
    SR = WSEC/WTOT
    R(65) = SR
4299 CONTINUE

46  IF(N .NE. 46) GO TO 4699
    R(1) = 0.0
    WDRINK = 0.0
    TIMCYC = AMOD(TIME,86400.)
    IF(TIMCYC .LT. TDRINK(7)*8600. .AND. KD .EQ. 8) KD = 1
    IF(TIMCYC .LT. TDRINK(KD)*8600.) GO TO 4610
    IF (NMEN .EQ. 8) WDRINK = 19.56/7.
    IF (NMEN .EQ. 6) WDRINK = 31.82/7.
    KD = KD+1
    KD = MINO(KD,8)
    R(1) = WDRINK/DTIME*3600.
4699 CONTINUE

C  FOOD PREPARATION WATER DUMP TO STORAGE TANK, LBM/HR

4610 WFOODP = 0.0
    IF(TIMCYC .LT. TFOODP(4)*8600. .AND. KF .EQ. 5) KF = 1
    IF(TIMCYC .LT. TFOODP(KF)*8600.) GO TO 4699
    KF = KF+1
    KF = MINO(KF,5)
    IF (NMEN .EQ. 8) WFOODP = 4.74/4.
    R(1) = R(1)+WFOODP/DTIME*3600.
4699 CONTINUE

56  IF(N .NE. 56) GO TO 5699
    WSEC = WMFLT
    WTOT = WSEC+H2OSPE
    IF(WTOT .LE. 0.0) GO TO 5699
    SR = WSEC/WTOT
    R(65) = SR
5699 CONTINUE

58  IF(N .NE. 58) GO TO 5899
    WMFLT = 0.0
    R(1) = 0.0
    WPOT = VV(46,69)
    IF(WPOT .GE. 40.) GO TO 5810

B-24f
MFTON = .TRUE.
GO TO 5820

5810 IF(WPOT .LE. 45.) GO TO 5820
MFTON = .FALSE.

5820 IF(.NOT. MFTON) GO TO 5899
IF(R(100)*DTIME/8600. .LE. R(69)) GO TO 5880
R(1) = 0.0
WMTLT = R(100)
GO TO 5899

5880 R(1) = R(100)

5899 CONTINUE

C

61 IF(N .NE. 61) GO TO 6199
IF(STEADY .AND. KSYPAS < 4) GO TO 6199
TCAB = VV(2,104)
TDES = V(IV+28)
TTOL = 0.1
IF(ABS(TCAB-TDES) < TTOL) GO TO 6199
A1 = 0.025
ITER = 1
CALL ESTIM(R(65),TCAB,TDES,R650D,TCABO,TDESO,A1,ITER,NSTR(1))
R(65) = AMAX1(R(65),0.0)
R(65) = AMIN1(R(65),0.9)

6199 CONTINUE

C

RETURN

END
LISTING OF GPOLY2 FOR ECLSB MODEL

SUBROUTINE GPOLY2

COMMON /COMP/ DS(15), N, NA1, NB1, NC, NCAB, NCFL, NEXT, NEXV, NK,
1 NKEX, NKS, NKT, NLFL, NP, NPASS, NPF, NPFT(6), NQ, NS, NSF, NSFT(6),
2 NSTR(18), NSUBR, NV, NVT, Y(12)
COMMON /RARRAY/ IMAXR, R(0:250)
COMMON /ECLST1/ KCHOUT, KPRNT, KPTINV(4), KWIT, KWIT1, KWIT2,
1 KWIT3, KWIT4, NUFF, KSTEADY
COMMON /KANDV/ K
COMMON /MISC/ DTIME, GRAV, KFLSYS, KOUTPT, KPDROP, KSYPAS, KTRANS,
1 LPSUM(6), MAXI, MAXLP, MAXSLP, MAXSSI, NCOMPS, NEWDI, NLAST, NPASPD,
2 MINSSI, PGMIN, PLMIN, START, STEADY, TIME, TIMEMX, TMAX, TMIN, TMAX
COMMON /CASE/ NCASE, NRSCS, NRECS
COMMON /PROPT/ CP0, CP(99), CPCONL, CPCONV, CPCO2, CPDIL, CPoxy, CPIC,
1 GAMGAS, RH00, RHO(99), VISCO, VISC(99), VISGAS, WTMO, WTM(99), WTMCON,
2 WTMDIL, WTMTC, XK0, XK(99), XKGAS, XKLIQ, VISLIQ
COMMON /SOURCE/ A(19), B(19), CPA, CPB, IA1, IB1, NA, NB, NPFS, NPFT(6),
1 NSF, NSFST(6), RHOA, RHOB, VISCA, VISCB, WIMA, WMTB, XKA, XKB
COMMON /VLOC/ IP, IS, IC, IQ, IV, IVT, IEX, INEXK

DIMENSION V(1), K(1)

EQUIVALENCE (V(1), K(1))

LOGICAL STEADY

IF(N.NE.1) GO TO 199

CALC NET FLOWS DUE TO CABIN PRI & SEC FLOW LOOPS

SBC02 = 0.0
SBH20 = 0.0

CALC NET H2O VAPOR CHANGE

125 XH20 = R(70) - SBE20 + VV(18,67) + VV(23,75) + VV(20,68)
CALL SV(XH20,2,187)

CALC NET O2 CHANGE

XO2 = -R(68) - VV(23,78) + VV(20,66)
CALL SV(XO2,2,176)

CALC NET CO2 CHANGE

XCO2 = R(69) - SBC02 + VV(28,79)
CALL SV(XCO2,2,177)

CONTINUE

IF (N .NE. 2) GO TO 299
R(2) = 70.
R(21) = 70.
R(89) = 0.42
R(98) = 46.
R(104) = 70.

CONTINUE

C

18 IF(N.NE. 13) GO TO 1899
R(20) = R(67)
R(21) = R(2)
R(22) = 24.7
R(28) = 24.7

1899 CONTINUE

C

28 IF(N.NE. 28) GO TO 2899
R(20) = R(67)
R(21) = R(2)
R(22) = 24.7
R(28) = 24.7
R(68) = VV(26,68)

2899 CONTINUE

C

RETURN

END
B.3.7.1 **Nitrogen Addition Control**

Nitrogen is added to maintain the total pressure in the cabin at a level of 14.813 psia. The same control as used and described in the ESCM Model Description Document [1] is used in the ECLSB model.

B.3.7.2 **Oxygen Production Control**

The oxygen level is controlled by adjusting the electrical current to the SPE cells according to the following:

\[
\begin{align*}
P_{O2} & \geq 3.1 \text{ psia} & I &= 0.9 \text{ INOM} \\
P_{O2} & \leq 2.9 \text{ psia} & I &= 1.1 \text{ INOM}
\end{align*}
\]

where:  
\( P_{O2} \) = partial pressure of \( O_2 \) in cabin, psia  
\( I \) = current to SPE cells, amps  
\( \text{INOM} \) = nominal current to cells = 22 amps

This nominal electrical current corresponds to a nominal oxygen consumption rate for three men at 0.255 lbm/hr.
B.3.7.3 CO₂ Partial Pressure Control

At present, the EDC production current is not adjusted in response to changes in the CO₂ partial pressure in the cabin. The current density is maintained at a constant 11.0 amps per square foot. The user may change this control logic by making desired changes in the GPOLY1 subroutine.

B.3.7.4 Cabin Temperature and Humidity Control

Control of cabin temperature and humidity is accomplished by regulating the fraction of air flow from the cabin which passes through the condensing heat exchanger. The more air through the heat exchanger, the cooler the cabin should become. The technique to regulate the fraction to the heat exchanger is described by the following relations:

For \( |T_1 - T_s| < 0.1^\circ F \)

the fraction remains unchanged. Otherwise;

\[
f = f_1 + 0.025 \frac{f_2 - f_1}{T_1 - T_2} \frac{T_1 - T_s}{T_1 - T_2}
\]

and \( f \) is clamped between 0 and 0.9.
Where:  
\( f \) = new flow fraction bypassing heat exchanger  
\( f_1 \) = last flow fraction  
\( f_2 \) = flow fraction prior to \( f_1 \)  
\( T_1 \) = last cabin temperature, °F  
\( T_2 \) = cabin temperature prior to \( T_1 \), °F  
\( T_s \) = set point cabin temperature, °F

This is tantamount to a straight integral control technique with a varying integration gain constant.

The effects of this control on cabin temperature and humidity are negated, however, by the logic in GPOLY2. GPOLY2 simply sets the cabin temperature to 70°F, the humidity to 42%, and the dew point to 46°F. This was done to give reasonable temperatures until a new control low can be developed.

B.3.7.5 Water Tank Level Control

Four water tanks are used for storage of clean and waste water; they are:

1. Urine and Wash Water Storage Tank  
2. Clean Hygiene Water Storage Tank  
3. Potable Water Storage Tank  
4. Condensate Water Storage Tank
For each of these tanks, the calculations for the entering and exiting water flows are presented in the following paragraphs.

B.3.7.5.1 Urine and Wash Water Storage Tank

The Urine and Wash Water Storage Tank receives water from crew urination, hand washing, and showering. The amount of water for each of these activities is considered to be dumped into the tank over a period of one time step which is currently 120 seconds or two minutes. Table B-5 gives the amount and time of day at which water is dumped into the tank for each of these activities. This table, of course, may be altered by the user by appropriate changes to the logic in GPOLY1.

Flow will exit the tank only if the VCD unit is on. The VCD unit turns on whenever the tank level is greater than 30 percent full and turns off if the tank level falls below 27 percent full. When the VCD is on, it draws water at 2.3 lbm/hr for a three man unit and 2.73 lbm/hr for a six man unit.

B.3.7.5.2 Clean Hygiene Water Storage Tank

The Clean Hygiene Water Storage Tank receives water from the VCD unit at the rate processed by the VCD. Water is used from this tank for handwashing and showers and to supply the needs of the SPE and Multifiltration units. Accordingly, water for handwashing and
<table>
<thead>
<tr>
<th>Time of Day</th>
<th>Urine 3 Men</th>
<th>Urine 6 Men</th>
<th>Handwash</th>
<th>Shower</th>
</tr>
</thead>
<tbody>
<tr>
<td>8:06 AM</td>
<td>2.429</td>
<td>3.754</td>
<td>1.15</td>
<td></td>
</tr>
<tr>
<td>9:00</td>
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<tr>
<td>10:00</td>
<td>2.429</td>
<td>3.754</td>
<td>1.15</td>
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</tr>
<tr>
<td>11:00</td>
<td>2.429</td>
<td>3.754</td>
<td>1.15</td>
<td></td>
</tr>
<tr>
<td>12:00</td>
<td>2.429</td>
<td>3.754</td>
<td>1.15</td>
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<tr>
<td>1:00 PM</td>
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<tr>
<td>2:00</td>
<td>2.429</td>
<td>3.754</td>
<td>1.15</td>
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<tr>
<td>4:00</td>
<td>2.429</td>
<td>3.754</td>
<td>1.15</td>
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<tr>
<td>5:00</td>
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<td>3.754</td>
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</tr>
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<td>6:00</td>
<td>2.429</td>
<td>3.754</td>
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<td>2.429</td>
<td>3.754</td>
<td>1.15</td>
<td>22.5</td>
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<tr>
<td>1:00 AM</td>
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<tr>
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<td>2.429</td>
<td>3.754</td>
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<tr>
<td>8:00</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17.00</td>
<td>26.28</td>
<td>11.5</td>
<td>22.5</td>
<td></td>
</tr>
</tbody>
</table>
showers is drawn from the tank according to the schedule in Table B-5. Again, all the water for a given time in the table is presumed to be drawn over one time step, i.e., two minutes.

The water required by the SPE unit is given in Section B.3.1 by the relation for $m_{H2O,t}$. The water required for the multifiltration unit is 2.55 lbm/hr. However, water is drawn from the Hygiene Tank only if the condensate tank is unable to supply the multifiltration needs.

B.3.7.5.3 Potable Water Storage Tank

The potable water storage tank receives water from the multifiltration unit. The multifiltration unit is supplied by a water pump which draws water from the condensate storage tank or the clean hygiene water storage tank if the condensate tank has insufficient water. The pump draws water at 2.55 lbm/hr. The multifiltration unit pump turns on when the tank level falls below 90% full and turns off if the level rises above 45%.

Water is drawn from the tank for drinking and food preparation. Again, the amount of water drawn for each of these activities is considered to be drawn from the tank over a period of one time step which is currently two minutes. Table B-6 gives the amount and time of day for each of these activities.
### TABLE B-6
**USAGE SCHEDULE FOR POTABLE WATER TANK**

<table>
<thead>
<tr>
<th>Time of Day</th>
<th>Drinking (l)</th>
<th>Food Preparation (l)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3 Men</td>
<td>6 Men</td>
</tr>
<tr>
<td>8:06 AM</td>
<td>2.794</td>
<td>4.474</td>
</tr>
<tr>
<td>9:00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10:00</td>
<td>2.794</td>
<td>4.474</td>
</tr>
<tr>
<td>11:00</td>
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<td>4.474</td>
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<tr>
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<tr>
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<td>4.474</td>
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<td>6:00</td>
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<tr>
<td>7:00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8:00</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
B.3.7.5.4 Condensate Water Storage Tank

The condensate water storage tank receives condensate water from the condensing heat exchanger and the Sabatier reactor water separator. Water is drawn from the condensate tank as required by the multifiltration unit to supply the potable water needs. When water is drawn, it is drawn at 2.55 lbm/hr.
APPENDIX C

SPACE STATION MODEL
C.1 Introduction

This manual provides the model description document for a Space Station model which includes a habitat, laboratory, and four nodes. Only the air revitalization equipment is modelled; waste water management tanks and processing equipment are not included in the model. The principal pieces of equipment are:

<table>
<thead>
<tr>
<th>Function</th>
<th>Subsystem Option Available</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{CO}_2$ Removal</td>
<td>EDC, Molecular Sieve</td>
</tr>
<tr>
<td>$\text{CO}_2$ Reduction</td>
<td>Bosch, Sabatier</td>
</tr>
<tr>
<td>$\text{O}_2$ Generation</td>
<td>SPE, KOH</td>
</tr>
<tr>
<td>Trace Gas Removal</td>
<td>Catalytic Oxidizer</td>
</tr>
<tr>
<td>Condensate Processing</td>
<td>Plate-fin shuttle type heat exchanger</td>
</tr>
</tbody>
</table>

Options are also available for hydrogen or $\text{CO}_2$ bussing.
C.2 Modelling of System

Figures C-1 through C-14 present the schematics of the system as modeled using G189A. The following discusses how this system represents real hardware. Further descriptions of the system can be found in the User's Manual [4].

In these schematics, extra lines, mixers, and splitters are inserted to provide the user with flexibility to select various options without having to rewrite the programs. These lines do not represent actual plumbing arrangements of a Space Station. For example, a duct does not exit the habitat then tee to two modes as shown in Figure C-1. In actuality, a node is adjacent to the habitat and a fan draws air directly from the habitat into the node. Therefore, these are functional schematics and do not represent actual plumbing.
FIGURE C-1
SPACE STATION MODEL OVERVIEW

C-3
FIGURE C-2
SPACE STATION NODES
FIGURE C-3
OVERVIEW OF HABITAT ARS
FIGURE C-4
OVERVIEW OF LABORATORY ARS
FROM CABIN

FROM CO₂ REMOVAL AND CAT. OX

TO CO₂ REMOVAL AND CAT. OX.

FIGURE C-5
HABITAT COOLING PACKAGES

C-7
FIGURE C-6
LABORATORY COOLING PACKAGES

FROM CO₂ REMOVAL AND CAT. OX.

TO CO₂ REMOVAL AND CAT. OX.

FROM CABIN

TO CABIN

COOLANT

FAN

H₂O SEP

CONDENSATE
FIGURE C-7
HABITAT OXYGEN GENERATORS
FIGURE C-8
LABORATORY OXYGEN GENERATORS
FIGURE C-9
HABITAT CO₂ REMOVAL UNITS

C-11
FIGURE C-10
LABORATORY CO₂ REMOVAL UNITS
FIGURE C-11
HABITAT $\text{CO}_2$ REDUCTION UNITS

C-13
FIGURE C-12
LABORATORY CO₂ REDUCTION UNITS
FIGURE C-14
LABORATORY CATALYTIC OXIDIZERS
C.3 Modelling of Components

The following sections discuss the analytical models of the components available in this Space Station model. Some of these have been described elsewhere. The following lists the subsystems and where they have been discussed.

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPE</td>
<td>Appendix B</td>
</tr>
<tr>
<td>Catalytic Oxidizer</td>
<td>Appendix B</td>
</tr>
<tr>
<td>Sabatier</td>
<td>Appendix B</td>
</tr>
<tr>
<td>EDC</td>
<td>Appendix B</td>
</tr>
</tbody>
</table>

The following subsystems are discussed below:

Molecular Sieve
Bosch
KCH
Plate Fin Heat Exchanger
Control Logic
C.3.1 **Molecular Sieve**

*Molecular Sieve* removes carbon dioxide from incoming air. Some constants are:

- $t_h$ = half cycle time = 60 minutes
- $P_{min}$ = min. pressure of desorbing mole sieve bed = 1.0 psia
- $T_{MS}$ = max. temperature of desorbing mole sieve bed = 360°F
- $T_{MSG}$ = max. temperature of desorbing silica gel bed = 180°F
- $cfm$ = fan cfm = 23.25
- $\Delta P_{fan}$ = 11 in H$_2$O
- $\Delta H_{SG}$ = enthalpy change for adsorbing silica gel bed = 1400 Btu/1b H$_2$O
- $\Delta H_{MS}$ = enthalpy change for adsorbing mol sieve bed = 1800 Btu/1b CO$_2$
- $C_{FM_c}$ = compressor cfm = 1.05

In order to understand the analytical description, the schematic of the molecular sieve subsystem shown in Figure C-15 should be reviewed.
FIGURE C-15
MOLECULAR SIEVE SUBSYSTEM SCHEMATIC
First, the temperature leaving the fan is computed by the following:

\[ T_2 = T_1 + \frac{Q_{FAN}}{m_a C_p} \]

where: \( T_2 \) = temperatures leaving fan, F  
\( T_1 \) = temperature entering fan, F  
\( Q_{FAN} \) = fan power, Btu/lb

\[ Q_{FAN} = \frac{\text{cfm} \Delta P_{FAN} \times 3.413}{8.5 \gamma} \]

\( m_a \) = air inlet mass flow to fan, lbm/hr  
\( C_p \) = specific heat of air, Btu/lbm-F

Next, the temperature of the process air leaving the adsorbing silica gel bed is calculated from the following:

\[ T_{3\text{MAX}} = T_2 + \frac{\omega \Delta h_{sg}}{C_p} \]

\[ m_{sg} = \frac{T_{3\text{MAX}} - T_3}{600 - t_h} \]

\( T_3 = T_3 + m_{sg} \Delta t \)

where: \( \omega \) = absolute humidity of air entering molecular sieve  
\( T_{3\text{MAX}} \) = maximum temperature of air leaving the adsorbing silica gel bed, F  
\( m_{sg} \) = change of air temperature leaving silica gel bed with time, F/sec
\[ \Delta t = \text{simulation time step, sec} \]
\[ t_h = \text{time into half cycle, sec} \]

After 10 minutes into the half cycle, the temperature of the air leaving the silica gel bed is limited to \( T_{3\text{max}} \).

The water removed by the silica gel bed is:

\[ M_{\text{H}_2\text{O}} = M_{\text{H}_2\text{O}} + (M_{\text{H}_2\text{O},\text{in}}) \Delta t \]

where:

- \( M_{\text{H}_2\text{O}} \) = mass of water removed by silica gel bed during half cycle, lbm
- \( M_{\text{H}_2\text{O},\text{in}} \) = flow of vapor and entrained liquid entering system, lbm/hr

Thus the assumption is that all the moisture entering the system is adsorbed onto the silica gel bed. Now, the temperature and mass flow of cool dry air leaving the heat exchanger is:

\[ T_4 = T_{\text{cool}} + 50^\circ F \]

where:
- \( T_{\text{cool}} \) = temperature of coolant water entering HX, F
- \( T_4 \) = temperature of air leaving HX, F
The heat transferred by the heat exchanger to the water is:

\[ Q_{HX} = m_d \, c_p \, (T_3 - T_4) \]

where: \( m_d \) = mass flow of dry air which entered molecular sieve subsystem, lbm/hr

The air flows next to the CO\(_2\) adsorbing molecular sieve bed. The temperature of the air leaving that bed is given by the following calculations:

\[ m_{CO2,a} = m_{CO2,i} \, \xi \, CO2 \]

\[ M_{CO2,a} = M_{CO2,a} + m_{CO2,A} \, \Delta t \]

\[ P_{CO2,e} = P_{CO2,i} \, (1 - \xi \, CO2) \]

\[ m_{CO2,e} = m_{CO2,i} \, (1 - \xi \, CO2) \]

\[ T_{5,MIN} = T_4 + \frac{M_{CO2,a} \, \Delta h_{ms}}{m_d \, c_p} \]

\[ m_{ms} = \frac{T_{5,\text{min}} - T_5}{1800 - t_h} \]

\[ T_5 = T_5 + m_{ms} \, \Delta t \]
where: \( m_{CO2,i} \) = inlet CO\(_2\) mass flow into molecular sieve bed, pph
\( \xi \) = CO\(_2\) removal efficiency of molecular sieve bed
\( m_{CO2,a} \) = rate of CO\(_2\) adsorption, lbm/hr
\( M_{CO2,a} \) = total mass of CO\(_2\) present on bed, lbm
\( P_{CO2,i} \) = partial pressure of CO\(_2\) in inlet air, psia
\( P_{CO2,e} \) = partial pressure of CO\(_2\) in molecular sieve exit bed, psia
\( m_{CO2,e} \) = exit CO\(_2\) mass flow out of molecular sieve bed, pph
\( T_{5,\text{min}} \) = minimum temp. exiting molecular sieve bed, F

After 1,800 seconds into the half cycle, the exit temperature cannot be less than \( T_{5,\text{min}} \).

The process air then flows to the desorbing silica gel bed. The temperature of the bed rises for the first 17 minutes, peaks, then falls for 17 minutes until the temperature reaches a minimum \( T_{5,\text{min}} \). The equations are:

For the first 17 minutes:

\[
M_{sgd} = \frac{T_{MSG} - T_6}{1020 - t_h}
\]

\[
T_6 = T_6 + M_{sgd} \Delta t
\]

where: \( t_6 \) = temperature leaving, desorbing silica gel bed, F
\( M_{sgd} \) = temperature change with time of air leaving desorbing silica gel bed, F/sec
This temperature $T_G$ cannot exceed $T_{msg}$.

For the next 17 minutes:

$$T_{5,\text{min}} - T_6$$

$$M_{sgd} = \frac{2040 - t_h}{\Delta t}$$

$$T_6 = T_6 + M_{sgd} \Delta t$$

For these 17 minutes, the air temperature is limited to a minimum of $T_{5,\text{min}}$. From 34 minutes into the half cycle to the end of the half cycle, the temperature exiting the desorbing silica gel bed is set to $T_{5,\text{min}}$.

The properties of the air leaving this silica gel bed are:

$$P_{H_2O} = P_{SAT}(T_6)$$

$$\frac{MW_{H_2O}}{m_{H_2O}} = \frac{P_{H_2O}}{MW_d \cdot P_T - P_{H_2O}}$$

$$M_{sgd} = M_{sgd} + m_{HSO} \Delta t$$

where:

- $P_{HSO}$ = partial pressure of water vapor in air, psia
- $m_{H_2O}$ = mass flow of water leaving silica gel bed, pph
- $M_{sgd}$ = mass of water desorbed from bed this half cycle, lbm

Of course, the mass desorbed is limited to the mass adsorbed from the previous cycle.
The electrical power to the desorbing silica gel bed is given by:

For $t_h < 240$ seconds  \( W_{htr} = 0 \) watts

$t_h \geq 240$ seconds \( W_{htr} = 657 \) watts

The average heat given up by the desorbing silica gel bed to the cabin is:

\[
Q_{sg} = \frac{46}{290} (T_{msg} - T_{cab})
\]

where:  \( T_{cab} \) = cabin air temperature, F

The final calculation is that for the mass of CO₂ desorbed from the molecular sieve bed. The following equations are used for $t_h > 480$ seconds.

\[
U_7 = \frac{R \left( T_4 + 460 \right)}{144 \; P_{min} \; MW_{CO₂}}
\]

\[
M_{CO₂,d} = \left[ 1.01 + 0.01 \left( \frac{P_8}{P_{min}} \right)^{0.769} \right] \frac{cfm_C}{U_7}
\]

where:
- \( R \) = Universal gas constant = 1545 ft-lbf/mole R
- \( MW_{CO₂} \) = Molecular weight of CO₂ = 44 lbm/mole
- \( P_{min} \) = Minimum pressure of desorbing molecular sieve, psia
- \( P_8 \) = Accumulator pressure, psia
- \( cfm_C \) = Compressor cfm
- \( m_{CO₂,d} \) = Mass flow of CO₂ desorbed, lbm/hr
For $t_h < 480$ seconds, $m_{CO2,d} = 0$.

The total carbon dioxide desorbed during the present half cycle is given by:

$$m_{CO2,d} = m_{CO2,d} + m_{CO2,d} \Delta t$$

Of course, the total amount desorbed is limited to the amount of CO$_2$ that was originally present on the bed.

C.3.2 Bosch

The Bosch is a process that reduces carbon dioxide and hydrogen to carbon and water while giving off heat. The model used here is based on the one described in the G189A Manual [2]. A functional schematic of the process is shown in Figure C-16. The chemical reaction is described by:

$$2H_2 + CO_2 \rightarrow C + 2H_2O$$

A listing of the program is provided in the User's Manual Appendices [4].

First the molecular weight of bone dry condenser exit gas and the inlet molar flows of H$_2$ and CO$_2$ are computed.
FIGURE C-16
BOSCH PROCESS SUBSYSTEM SCHEMATIC
\[ n_{\text{H}_2,i} = \frac{m_{\text{H}_2,i}}{2.016} \]

\[ n_{\text{CO}_2,i} = \frac{m_{\text{CO}_2,i}}{44.011} \]

\[ \text{MWBDG} = 16.043 \ Y_{\text{CH}_4} + 44.011 \ Y_{\text{CO}_2} + 2.016 \ Y_{\text{H}_2} + 28.011 \ Y_{\text{CO}} \]

where:
- \( m_{\text{H}_2,i} \) = Mass flow of \( \text{H}_2 \) entering Bosch system, pph
- \( n_{\text{H}_2,i} \) = molar flow of \( \text{H}_2 \) entering Bosch system, moles/hr
- \( m_{\text{CO}_2,i} \) = mass flow of \( \text{CO}_2 \) entering Bosch system, pph
- \( n_{\text{CO}_2,i} \) = molar flow of \( \text{CO}_2 \) entering Bosch system, pph
- \( Y_{\text{CH}_4} \) = mole fraction of methane in dry cond. exit gas = .235
- \( Y_{\text{CO}_2} \) = mole fraction of \( \text{CO}_2 \) in dry cond. exit gas = .163
- \( Y_{\text{H}_2} \) = mole fraction of \( \text{H}_2 \) in dry cond. exit gas = .327
- \( Y_{\text{CO}} \) = mole fraction of \( \text{CO} \) in dry cond. exit gas = .275
- \( \text{MWBDG} \) = molecular weight of bone dry cond. exit gas

The amount of carbon processed and water produced for a quasi-equilibrium assumption is given by the following which is based on the reaction formula:

If \( \text{CO}_2 \) limiting:

\[ m_{\text{C},p} = m_{\text{CO}_2,i} \times \text{MW}_\text{C} \]

\[ m_{\text{H}_2\text{O},p} = 2 \times m_{\text{CO}_2,i} \times \text{MW}_{\text{H}_2\text{O}} + m_{\text{H}_2\text{O},i} \]
If H₂ limiting:

\[ m_{c,p} = m_{H2,i} \frac{M_W}{2} \]

\[ m_{H2O,p} = m_{H2,i} M_{H2O} + m_{H2O,i} \]

where:

- \( M_W \) = molecular weight of carbon = 12.011 lbm/mole
- \( M_{H2O} \) = molecular weight of water = 18.016 lbm/mole
- \( m_{H2O,i} \) = mass flow of vapor and entrained liquid entering Bosch system, lbm/hr
- \( m_{c,p} \) = mass rate of carbon production, lbm/hr
- \( m_{H2O,p} \) = mass rate of water production, lbm/hr

Therefore, flow out of condenser is:

\[ m_3 = m_r - m_{c,p} - m_{H2O,p} \]

where:

- \( m_r \) = recycle flow rate on more specifically the mass flow at the compressor = 6.80 lbm/hr

The temperature at the condenser exit is iterated upon. Its initial value is assumed to be 20°F hotter than the inlet coolant temperature:

\[ T_3 = T_{cool} + 20 \]
The iteration begins with the calculation of the flow rate of bine dry condenser exit gas

\[
\frac{m_{\text{BDG}}}{\text{m}^3} = \frac{m_{\text{pH2O}}}{\text{MW}_{\text{H2O}}} \frac{P_{\text{H2O}}}{1 + \frac{m_{\text{BDG}}}{\text{MW}_{\text{BDG}}} \left( \frac{P_{\text{COND}} - P_{\text{H2O}}}{P_{\text{sat}}(T_3)} \right)}
\]

where:
- \( P_{\text{H2O}} \) = partial pressure of vapor leaving condenser, psia
- \( P_{\text{COND}} \) = total pressure of recycle gas in condenser = 16.9 psia
- \( m_{\text{BDG}} \) = mass flow of bone dry gas leaving condenser, pph

Accordingly, the flows out of the condenser and compressor are:

\[
\frac{n_{\text{BDG}}}{\text{m}^3} = \frac{m_{\text{BDG}}}{\text{MW}_{\text{BDG}}}
\]

\[
m_{\text{H2O}, 3} = \frac{m_{\text{BDG}}}{n_{\text{BDG}}} \frac{P_{\text{H2O}}}{\text{MW}_{\text{H2O}}}
\]

\[
m_{\text{H2O}, 4} = m_{\text{H2O}, 3} + m_{\text{H2O}, 2}
\]

\[
m_{\text{H2}, 3} = n_{\text{BDG}} \frac{Y_{\text{H2}}}{\text{MW}_{\text{H2}}}
\]

\[
m_{\text{H2}, 4} = m_{\text{H2}, 3} + m_{\text{H2}, 4}
\]

\[
m_{\text{CO2}, 3} = m_{\text{BDG}} \frac{Y_{\text{CO2}}}{\text{MW}_{\text{CO2}}}
\]

\[
m_{\text{CO2}, 4} = m_{\text{CO2}, 3} + m_{\text{CO2}, 4}
\]

\[
m_{\text{CH4}, 3} = m_{\text{BDG}} \frac{Y_{\text{CH4}}}{\text{MW}_{\text{CH4}}}
\]

\[
m_{\text{CH4}, 4} = m_{\text{CH4}, 3}
\]

\[
m_{\text{CO}, 3} = m_{\text{BDG}} \frac{Y_{\text{CO}}}{\text{MW}_{\text{CO}}}
\]

\[
m_{\text{CO}, 4} = m_{\text{CO}, 3}
\]

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The properties of the flow exiting the compressor are:

\[
C_p^4 = (3.42 \, m_{H2,4} + 0.21 \, m_{CO2,4} + 0.55 \, m_{CH4,4} + 0.25 \, m_{CO,4} \\
+ 0.49 \, m_{H2O,4} + 0.22 \, m_{O2} + 0.299 \, m_{N2}) / m_r
\]

\[
MW_4 = m_r / (m_{H2,4}/2.016 + m_{CO2,4}/44.011 + m_{CH4,4}/16.043 \\
+ m_{CO,4}/28.011 + m_{H2O,4}/18.06 + m_{O2}/32 \\
+ m_{N2}/28.088)
\]

\[
\gamma_4 = \frac{C_p^4}{MW_4}
\]

where:
- \(C_p^4\) = Specific heat of gas at compressor exit, BTU/lbm-F
- \(MW_4\) = Molecular weight of gas at compressive exit, lbm/mole
- \(\gamma_4\) = Ratio of constant pressure to constant volume specific heats
- \(m_{O2}\) = Mass flow of oxygen in recycle gas = 0.0 lbm/hr
- \(m_{N2}\) = Mass flow of nitrogen in recycle gas = 0.0 lbm/hr
The mixed temperature of inlet gases and the recycle gases exiting condenser is given by:

\[ T_6 = \frac{\left( m_{BDG} \cdot C_{PBDG} + 0.49 \cdot m_{H2O,iv} + 0.21 \cdot m_{CO_2,iv} + 3.42 \cdot m_{H2,i} + 0.49 \cdot m_{H2O,ie} + 1.0 \cdot m_{H2O,ie} \right) \cdot T_3 + 0.21 \cdot m_{CO_2,ie} + 3.42 \cdot m_{H2,i} + 0.49 \cdot m_{H2O,ie} + 1.0 \cdot m_{H2O,ie}}{m_{r} \cdot C_{P4}} \]

\[ C_{PBDG} = \frac{[3.42 \cdot m_{H2,3} + 0.21 \cdot m_{CO_2,3} + 0.55 \cdot m_{CH4,3} + 0.25 \cdot m_{CO,3} + 0.22 \cdot m_{O2} + 0.299 \cdot m_{N2}]}{m_{BDG}} \]

where:
- \( T_6 \) = Mixed temperature of gases entering, compressor, °F
- \( m_{H2O,iv} \) = Mass flow of vapor entering system, pph
- \( m_{H2O,ie} \) = Mass flow of entrained liquid entering system, pph
- \( C_{PBDG} \) = Specific heat of dry gas exiting condenser, Btu/lbm-°F

The energy required to raise the pressure of the recycle flow gases across the compressor is given by:

\[ Q_c = m_r \cdot R \cdot (T_G + 460) \gamma_4 \left[ \frac{P_r}{P_{cond}} \right]^\frac{\gamma_4-1}{\gamma_4} \]

\[ \frac{778 \text{ MW}_4 (\gamma_4-1) \eta_a}{\gamma_4} \]

where:
- \( R \) = Universal gas constant = 1545 ft-lbf/mole-R
- \( P_r \) = Reactor pressure = 24.3 psia
- \( \eta_a \) = Aerodynamic efficiency of compressor = 1.0
- \( Q_c \) = Compressor energy into recycle gas, Btu/hr
The total power consumed by the compressor is given by:

\[ W_c = \frac{Q_c}{\epsilon_c \times 3.41} \]

where: \( W_c \) = Power to run compressor, watts
\( \epsilon_c \) = Motor efficiency of compressor

Therefore, the heat lost to the ambient is:

\[ Q_a = 3.41 W_c - Q_c \]

The heat of reaction in the reactor is:

\[ Q_r = 973 \times m_{CO2,i} \]

Essentially, it is assumed that the input gases are stoichiometric in ratio which then causes the mole fractions of the gases to remain constant in the recycle loop. The temperature out of the compressor is:

\[ T_4 = T_6 + \frac{Q_c}{m_r \times C_{P4}} \]
The temperature out of the reactor is:

\[ T_1 = T_r - \frac{Q_{LR}}{m_r C_{p4}} \]

where: \( Q_{LR} \) = Heat loss from reactor = 0.0 Btu/hr

The temperature into the condenser is:

\[ T_2 = T_1 - \varepsilon_{HX} (T_1 - T_4) \]

where: \( \varepsilon_{HX} \) = Heat exchanger efficiency = 0.85

Finally, the temperature of the gases leaving the condenser is:

\[ T_3 = T_2 - \varepsilon_c (T_2 - T_{cool}) \]

where: \( \varepsilon_c \) = Condenser efficiency = 0.90

This \( T_3 \) is compared with the original guessed \( T_3 \). If they agree within 0.3 F, the iteration is complete; otherwise, this \( T_3 \) is tried as the next guess.

C.3.3 Static Feed Water Vapor Electrolysis (KOH)

The Static Feed Water Vapor Electrolysis subsystem uses KOH as the medium for electrolysis to produce oxygen. This model is based on the ELCELL subroutine in GI89A [2]. The following assumptions are used:

(1) The unit is isothermal within the cells.
(2) Product gas streams exit at the prevailing cell temperature.

(3) The cell Faradaic efficiency is 100%; the cells are voltage inefficient only.

(4) All cells are connected in series, i.e., the same input current passes through each cell.

(5) The thermoneutral voltage is 1.48 volts; the voltage efficiency is equal to the thermoneutral voltage divided by the actual voltage.

The gas production is calculated as follows:

\[ J = \frac{I}{A} \]

\[ m_{H_2O,e} = N_c \frac{I}{1350} \]

\[ m_{H_2,p} = \frac{m_{H_2O,e}}{M_{H_2O}} \]

\[ n_{O_2,p} = \frac{n_{H_2,p}}{2} \]
where:  
I = Input current to cells, amps  
A = Area of one cell, ft²  
N_c = Number of cells  
m_{H2O, e} = Mass flow of O₂ consumed by electrolysis lbm/hr  
J = Cell current density, amps/ft²  
n_{H2, p} = Molar flow of hydrogen produced, moles/hr  
n_{O2, p} = Molar flow of oxygen produced, moles/hr

The details of the analytical method are described fully in the G189A manual for the subroutine ELCELL. However, the calculation of the energy required for electrolysis is computed according to the following equations and tables:

First, the cell voltage at 150 amps/sq. ft. current density for any cell temperature is determined by interpolation of the following table:

<table>
<thead>
<tr>
<th>T_c (F)</th>
<th>V_0 (Volts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>110</td>
<td>1.660</td>
</tr>
<tr>
<td>120</td>
<td>1.620</td>
</tr>
<tr>
<td>130</td>
<td>1.575</td>
</tr>
<tr>
<td>140</td>
<td>1.550</td>
</tr>
<tr>
<td>150</td>
<td>1.530</td>
</tr>
<tr>
<td>160</td>
<td>1.500</td>
</tr>
<tr>
<td>170</td>
<td>1.475</td>
</tr>
<tr>
<td>180</td>
<td>1.465</td>
</tr>
<tr>
<td>190</td>
<td>1.450</td>
</tr>
</tbody>
</table>

C-36
For cell temperatures less than 110 °F, the voltage is set to 1.70 volts.

Next, the effect of a current density different from 150 amps/sq. ft. is found by interpolating the following table:

<table>
<thead>
<tr>
<th>J (amps/ft)</th>
<th>Delta V/Delta J (Volts/ASF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.01460</td>
</tr>
<tr>
<td>100</td>
<td>0.00060</td>
</tr>
<tr>
<td>200</td>
<td>0.00055</td>
</tr>
<tr>
<td>300</td>
<td>0.00050</td>
</tr>
<tr>
<td>400</td>
<td>0.00050</td>
</tr>
<tr>
<td>500</td>
<td>0.00045</td>
</tr>
<tr>
<td>600</td>
<td>0.00045</td>
</tr>
</tbody>
</table>

Then the following is used to calculate the cell voltage:

\[ V_c = V_o + \frac{V}{J} (J-150) \]

The cell efficiency is:

\[ \eta = \frac{1.48}{V_c} \times 100 \]

and is limited to a peak value of 99%.

Lastly, the energy required for electrolysis is given by:

\[ Q = N_c I V_c \times 3.413 \]

**C.3.4 Plate Fin Condensing Heat Exchanger**

This subroutine models the performance for a plate fin condensing heat exchanger. Basically, the program iterates on the condenser
outlet temperature until the outlet temperature does not change from iteration to iteration.

First, the inlet dew point is calculated:

\[ \omega_i = \frac{m_{v,i}}{m_{o,i}} \]

\[ P_{v,i} = \frac{\omega_i P_{t,i}}{\omega_i + 0.622} \]

\[ T_{dp,i} = T_{sat}(P_{v,i}) \]

where:
- \( m_{v,i} \) = Mass flow of inlet vapor, pph
- \( m_{da,i} \) = Mass flow of dry air, pph
- \( \omega_i \) = Inlet absolute humidity
- \( P_{t,i} \) = Inlet air total pressure, psia
- \( P_{v,i} \) = Inlet air partial pressure of water, psia

The initial guess at the exit temperature is one quarter of the way from the coolant inlet temperature to the air inlet temperature:

\[ T_{a,e} = T_{c,i} + \frac{1}{4}(T_{c,i} + T_{a,i}) \]

From the exit temperature, the outlet absolute humidity and vapor pressure are calculated:
\[ P_{v,e} = P_{\text{sat}} (T_{a,e}) \]

\[ \omega_{e} = 0.622 \frac{P_{v,e}}{P_{T} - P_{v,e}} \]

The heat loads are then:

\[ Q_L = M_{d,a,i} (\omega_i - \omega_e) h_{fg} \]

\[ Q_S = m_{a,i} C_{p,a} (T_{a,i} - T_{a,e}) \]

\[ Q_t = Q_S + Q_L \]

where:  
- \( h_{fg} \) = Heat of vaporization, Btu/lbm  
- \( Q_L \) = Latent heat, Btu/hr  
- \( Q_S \) = Sensible heat, Btu/hr  
- \( Q_t \) = Total heat loss, Btu/hr  
- \( m_{a,i} \) = Total mass flow of air into Hx, lbm/hr

The coolant exit temperature is:

\[ T_{c,e} = T_{c,i} + \frac{Q_t}{m_c C_{p,c}} \]

where:  
- \( m_c \) = Coolant flow, pph  
- \( C_{p,c} \) = Specific heat of water, Btu/lbm-F

From here, various properties of the air and coolant are calculated as a function of the average temperature. The properties and nondimensional numbers calculated are:
The conditions are shown in the listing presented in the User's Manual [4]. Also shown there are various geometric dimensions such as fin height.

The film coefficient is chosen as the maximum of the following two equations:

\[ h = 3.65 \frac{K}{D_h} \]

\[ h = C_{\text{mod}} C_p G \frac{Pr^{-0.6667}}{K} \]

Overall fin efficiency is then computed from the following fin equations:

\[ \eta = \sqrt{\frac{2h}{KW}} \]
where:  

\[ h = \text{Film coefficient} \]

\[ k = \text{Thermal conductivity of fin} \]

\[ W = \text{Fin thickness} \]

\[ L = \text{Fin length} \]

\[ k = \frac{\tanh mL}{mL} \]

\[ \eta = 1 - \frac{A_f (1-k)}{A} \]

where:

\[ A_f = \text{Surface area of fins only, ft}^2 \]

\[ A = \text{Total exposed surface area, including the fins and the unfinned primary surface, ft}^2 \]

\[ k = \text{Fin effectiveness} \]

\[ \eta = \text{Total surface temperature effectiveness or overall fin efficiency} \]

The effective UA becomes:

\[ UA = \eta hA \]

The total effective dry UA is calculated as:

\[ UA_{dry} = \frac{1}{\frac{1}{UA_c} + \frac{1}{UA_a}} \]
where: $UA_c$ = Cold side effective UA, Btu/hr-F

$UA_a$ = Hot or air side effective UA, Btu/hr-F

The pinch point temperatures for the air side and coolant side are given by:

$$T_{pp,a} = \frac{UA_a}{UA_c} \left( T_{dp,i} + T_{dp,i} - T_{c,e} \right) Cp_c \frac{m_c + m_{a,i} Cp_a T_{a,i}}{m_{a,i} Cp_a + m_c Cp_c UA_a \frac{UA_a}{UA_c}}$$

The pinch point temperatures for the air and the coolant are those which occur at the location where the wall temperature equals the inlet dew point temperature:

$$T_{pp,c} = T_{dp,i} - \frac{UA_a (T_{pp,a} - T_{dp,i})}{UA_c}$$

These above equations can be derived from the simultaneous solution of the following two energy balances:

$$UA_a (T_{pp,a} - T_{dp,i}) = UA_c (T_{dp,i} - T_{pp,c})$$

$$m_{a,i} Cp_a (T_{pp,a} - T_{a,i}) = M_c Cp_c (T_{pp,c} - T_{c,e})$$

The wet side and dry side log mean temperature differences are:
\[ T_{w,lm} = \ln \left( \frac{\left( T_{a,e} - T_{c,i} \right) - \left( T_{pp,a} - T_{pp,c} \right)}{\left( T_{pp,a} - T_{pp,c} \right)} \right) \]

\[ T_{d,lm} = \ln \left( \frac{\left( T_{pp,a} - T_{pp,c} \right) - \left( T_{a,i} - T_{c,e} \right)}{\left( T_{a,i} - T_{c,e} \right)} \right) \]

Now, the wet and dry section dry UA's are:

\[ UA_{d,ws} = \frac{m_c \left( T_{pp,c} - T_{c,i} \right) \frac{UA_c}{UA_h} + \frac{Q_t}{Q_s}}{T_{w,lm}} \]

\[ UA_{d,ds} = \frac{m_c \left( T_{c,e} - T_{pp,c} \right)}{T_{d,lm}} \]

The total effective dry UA is:

\[ UA_{d,\text{tot}} = UA_{d,ws} + UA_{d,ds} \]

The air exit temperature is iterated upon until:

\[ UA_{d,\text{tot}} = UA_{d\text{dry}} \]

C.3.5 Control

The control of the Space Station model is done in subroutine GPOLY1. The following paragraphs describe the control laws used to control:
(a) Oxygen partial pressure
(b) Total cabin pressure
(c) Oxygen accumulator pressure
(d) Temperature control
(e) CO₂ accumulator exit flow control
(f) H₂-CO₂ mix to CO₂ reduction unit

Oxygen partial pressure is controlled by using the same technique as described in the original ESCM Model Description Document [1]. The controller maintains oxygen partial pressure between 3.09 and 3.23 psia.

Total cabin pressure is maintained by the addition of nitrogen. The controller admits nitrogen to bring the pressure up to 14.813 psia only after the oxygen pressure is above 3.09 psia. The original Model Description Document [1] should be seen for more detail.

The oxygen accumulator pressure is maintained by addition of oxygen from the oxygen generators as oxygen is drawn from the accumulators to maintain cabin O₂ partial pressure. The current to the oxygen generators is regulated to each of the generators according to the following law:
For \( P_{O2} \geq 1050 \) \hspace{1cm} I = 0.9 \, I_{nom} \\
For \( P_{O2} \leq 950 \) \hspace{1cm} I = 1.1 \, I_{nom} \\
For 950 < \( P_{O2} < 1050 \) \hspace{1cm} I = I_{nom} \\

As the current is increased, the oxygen generation by the electrolysis unit increases.

For temperature control, the bypass flow around the condensing heat exchanger is regulated. A proportional plus integral scheme is used:

\[
R = 0.05 \, E + \int 0.0001 \, E \, dt
\]

where: \( R = \) Fraction of flow to bypass Hx. \\
\( E = \) Temperature error = \( T_{set} - T_{act} \)

As more flow bypasses the Hx, the mixed flow after the Hx is hotter.

Carbon dioxide removed from the air is sent to an accumulator. Each CO2 removal unit has its own accumulator in a nonbussed system. The flow out of the accumulator is regulated to maintain pressure in the accumulator above 21 psia. Essentially, the average CO2 removal rate during the past molecular sieve cycle is used as the flow out of the accumulator for the present cycle.
Lastly, the H₂-CO₂ mixture into the CO₂ Reduction unit is regulated to be stoichiometric by venting excess hydrogen after being produced by the oxygen generators. The required H₂ flow and the amount to be vented is given by:

\[
\begin{align*}
    m_{H₂} &= 2 \frac{m_{CO₂} \cdot MW_{H₂}}{MW_{CO₂}} \\
    R &= m_i - \frac{m_i - m_{H₂}}{m_i}
\end{align*}
\]

where:
- \( m_{CO₂} \) = Flow of CO₂ to reduction, pph
- \( m_{H₂} \) = Stoichiometric flow of H₂ to reduction, pph
- \( m_i \) = Inlet flow to splitter, pph
- \( R \) = Fraction of H₂ inlet flow to be vented
Appendices to the Model Description Document for A Computer Program for the Emulation/Simulation of a Space Station Environmental Control and Life Support System

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A Model Description Document for the Emulation Simulation Computer Model was published previously. The model consisted of a detailed model (emulation) of a SAWD CO₂ removal subsystem which operated with much less detailed (simulation) models of a cabin, crew, and condensing and sensible heat exchangers. The purpose was to explore the utility of such an emulation/simulation combination in the design, development, and test of a piece of ARS hardware - SAWD.

Extensions to this original effort are presented in the manual. The first extension is an update of the model to reflect changes in the SAWD control logic which resulted from test. In addition, slight changes were also made to the SAWD model to permit restarting and to improve the iteration technique. The second extension is the development of simulation models for more pieces of air and water processing equipment. Models are presented for: EDC, Molecular Sieve, Bosch, Sabatier, a new condensing heat exchanger, SPE, SPWES, Catalytic Oxidizer, and multifiltration. The third extension is to create two system simulations using these models. The first system presented consists of one air and one water processing system. The second system consists of a potential Space Station air revitalization system complete with a habitat, laboratory, four modes, and two crews.
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