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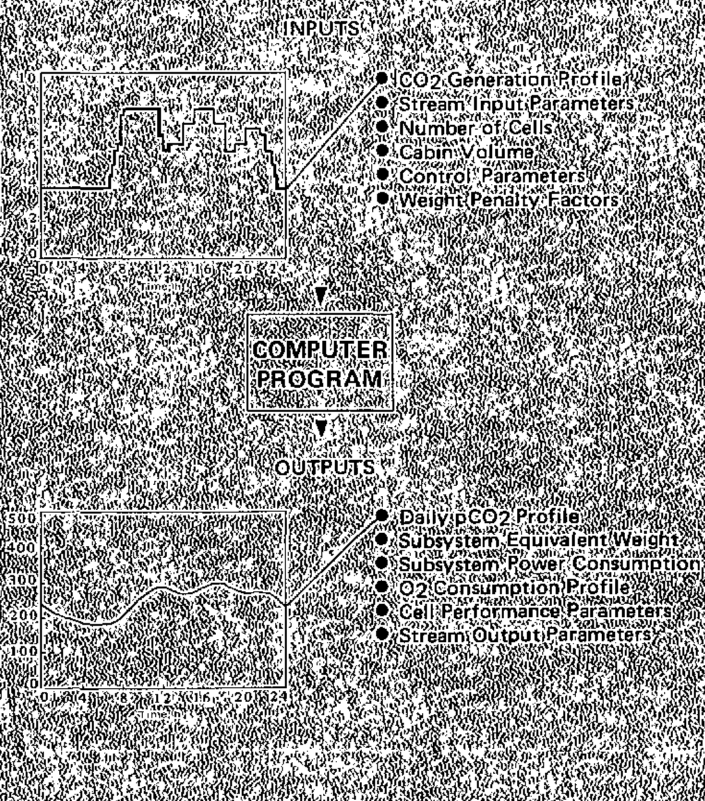
ELECTROCHEMICAL CARBON DIOXIDE CONCENTRATOR SUBSYSTEM MATH MODEL

FINAL REPORT

by
R.D. Marshall, J.N. Carlson
and F.H. Schubert

September, 1974

MATH MODEL SOLUTION SEQUENCE



Prepared Under Contract No. NAS2-6478

by

Life Systems, Inc.
Cleveland, Ohio 44122

for

AMES RESEARCH CENTER
National Aeronautics & Space Administration

ER-220-6

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FOREWORD

The development activity described herein was conducted by Life Systems during the period November, 1973 to September, 1974 as part of NASA Contract NAS2-6478. The Program Manager was Richard D. Marshall. Technical support was provided as follows:

Jan Carlson - Computer simulation model

Tim Hallick - Test program

Franz Schubert - Model analyses

Direct technical monitorship was provided at NASA Johnson Space Center, Houston, Texas, by Mr. W. E. Ellis, Chief, Environmental and Thermal Systems Section, Crew Systems Division, and Mr. L. D. Kissinger. The program Technical Monitor was P. D. Quattrone, Chief, Environmental Control Research Branch, NASA Ames Research Center, Moffett Field, California.

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SUMMARY

A steady-state computer simulation model has been developed to describe the performance of the total Six-Man, Self-Contained Electrochemical Carbon Dioxide Concentrator Subsystem, referred to as CS-6, as built for the Air Revitalization Group (ARG) of Space Station Prototype (SSP). The math model combines expressions describing the performance of the Electrochemical Depolarized Carbon Dioxide Concentrator (EDC) cells and modules previously developed with expressions describing the performance of the other major CS-6 components. The model is capable of accurately predicting CS-6 performance over EDC operating ranges and the computer simulation results agree with experimental data obtained over the prediction range.

Two computer programs were written utilizing the mathematical expressions developed to describe CS-6 performance. The first computer program, referred to as the CS-6 Base Program, calculates the steady-state performance characteristics of the CS-6 subsystem and its components, including intercomponent and subsystem fluid interface parameters, component and subsystem power and heat generation, and subsystem equivalent weight. The second program, referred to as the CS-6 Cabin pCO_2 Simulation Program, utilizes the CS-6 Base Program with minor modifications as a subroutine to describe the daily cabin partial pressure of carbon dioxide (pCO_2) profile that would result from using the CS-6 as the carbon dioxide (CO_2) removal subsystem in a simulated spacecraft air revitalization application. The program takes a daily CO_2 generation profile and cabin volume, and calculates and subtracts the CO_2 removal rate to arrive at the daily cabin pCO_2 profile.

Seven experiments were conducted in support of the math model to (1) establish the performance characteristics of the CS-6 and of the individual CS-6 subsystem components and (2) verify the predictability of the two computer programs. The experiments performed characterized the electrochemical modules, the process air blowers, the cooling air blowers, the hydrogen (H_2) flow sensor and distribution mountings, the primary controller, the emergency controller, and the steady-state CS-6 intercomponent interface parameters.

INTRODUCTION

In parallel to the development of an Electrochemical Carbon Dioxide Concentrator Subsystem, Life Systems, Inc. had developed a steady-state computer simulation model to predict the performance of the Electrochemical Depolarized Carbon Dioxide Concentrator (EDC) cells and modules over a wide range of operating conditions.[1] The objectives of the present program were to (1) expand this existing model to predict the performance characteristics of the total Six-Man, Self-Contained Electrochemical Carbon Dioxide Concentrator Subsystem, referred to as the CS-6, as built for the Air Revitalization Group (ARG) of Space Station Prototype (SSP), and (2) develop two computer programs using the expanded model to predict the steady-state performance characteristics of the CS-6 (first program) and to determine the daily partial pressure of carbon dioxide (pCO_2)

(1) All references cited are listed at the end of the report.

profile for a given spacecraft cabin volume and carbon dioxide (CO_2) generation profile (second program).

To accomplish the objectives of the program, the program was organized into three tasks and a program management function. The specific objectives of these tasks were to:

1. Perform supporting experimentation to characterize subsystem components and to verify the performance predictions of the expanded math model.

2. Prepare the CS-6 Base Program by expanding the EDC computer simulation model to enable predicting the steady-state performance characteristics of the CS-6 as a total subsystem.

3. Prepare the CS-6 Cabin pCO_2 Simulation Program to predict CS-6 response to a specified, repetitive CO_2 generation profile for a given time period and a specified cabin volume. The pCO_2 Simulation Program allows CS-6 performance to be characterized as a function of time for constant input parameters, current and process air flow rate (Control Mode A), and variable input control parameters for current and air flow rates as a function of cabin pCO_2 (Control Mode B).

The CS-6 Subsystem and component testing was completed and the results were used to develop the mathematical expressions describing CS-6 performance. These experimentally obtained correlations were then combined with subsystem and component mass and energy balances to write the CS-6 Base Program. The CS-6 Cabin pCO_2 Simulation Program was then prepared using the Base Program as a subroutine to calculate CS-6 performance parameters as a function of time.

CS-6 SUBSYSTEM

The CS-6 was designed specifically as the Carbon Dioxide Collection Subsystem (CCS) for the SSP program. The function of the CS-6 is to remove 6.0 kg (13.2 lb)/day) of CO_2 from the cabin atmosphere and deliver the CO_2 premixed with hydrogen (H_2) to the CO_2 Reduction Subsystem. The major components of the CS-6 are the electrochemical modules that actually perform the CO_2 removal function and the supporting hardware required to manifold the process gas streams (blowers, valves, ducting, etc.) and control the CO_2 removal process. The detailed schematic of the CS-6 subsystem is presented in Figure 1. The design specifications for the CS-6 are presented in Table 1. A detailed description of the operation and components of the CS-6 has been documented previously in literature.[2,3,4] The description of the CS-6 subsystem that follows details how the subsystem process streams and hardware were viewed for math modeling purposes.

Process Streams

A simplified functional schematic of the CS-6 subsystem is given in Figure 2. The actual arrangement of the CS-6 hardware is in two identical process loops.

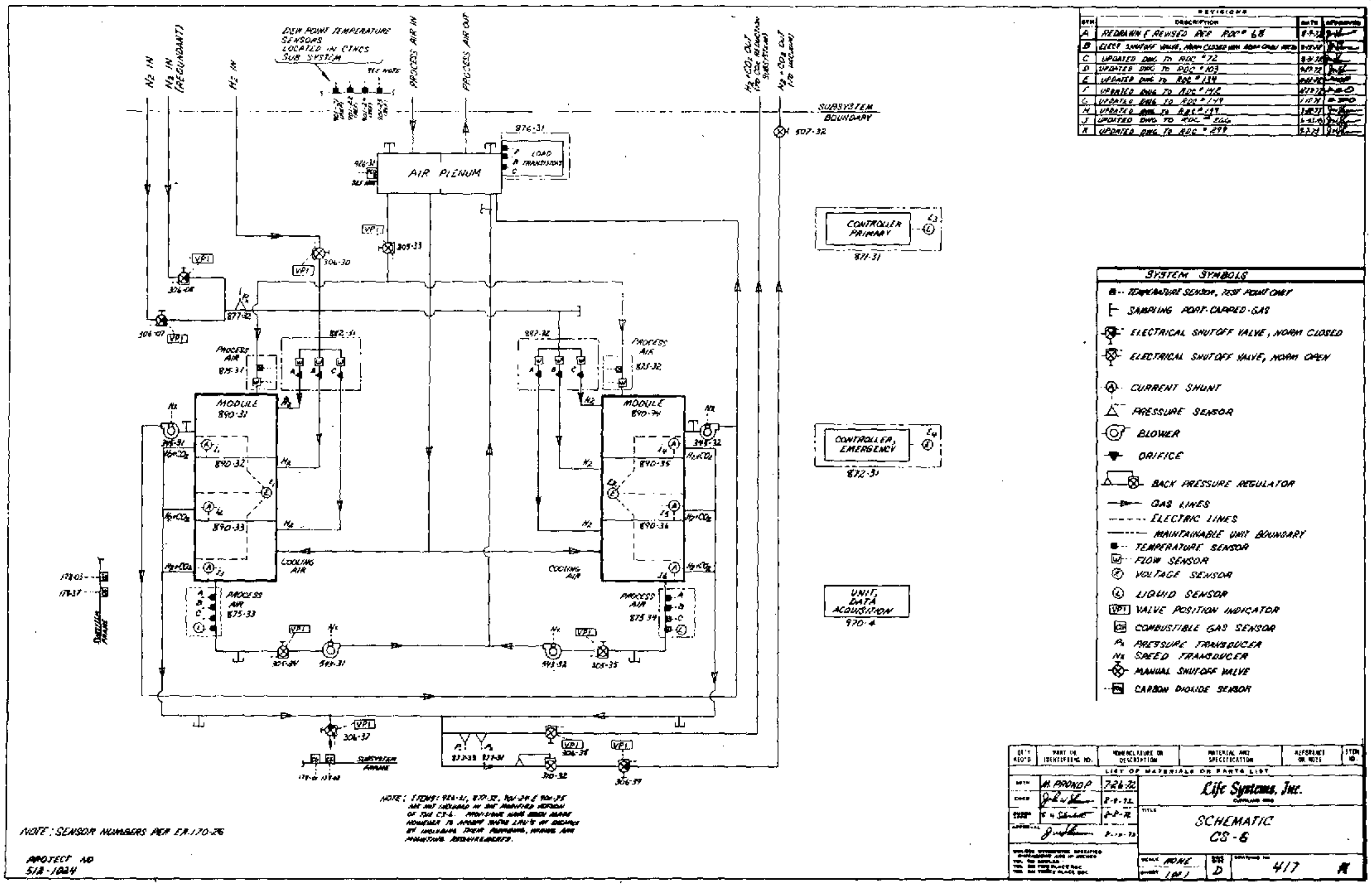

FIGURE 1 CS-6 SCHEMATIC

TABLE 1 CS-6 DESIGN SPECIFICATIONS

Number of Crew (Continuous)	6
CO_2 Removal Requirements	
Nominal (48-Hr Average), kg/d (Lb/Day)	6.0 (13.2)
Maximum (4-Hr Duration), kg/d (Lb/Day)	9.3 (20.4)
Cabin Atmosphere	
Total Pressure, kN/m^2 (Psia)	101-105 (14.7-15.2)
Temperature, K (F)	291-297 (65-75)
Dew Point Temperature, K (F)	281-287 (46-57)
O_2 Partial Pressure, kN/m^2 (Psia)	21.0-22.6 (3.04-3.28)
CO_2 Partial Pressure	
Nominal, N/m^2 (mm Hg)	<400 (<3)
Operating Range, N/m^2 (mm Hg)	200-400 (1.5-3)
Diluent	Air Constituents
Process Air	
Total Pressure, N/m^2 (Inch Water)	Ambient + 1495 (+ 6)
Temperature, K (F)	Dew Point + 3.34 (+ 6)
Dew Point Temperature, K (F)	281-283 (46-50)
O_2 Partial Pressure, kN/m^2 (Psia)	21.0-22.6 (3.04-3.28)
CO_2 Partial Pressure	
Nominal, N/m^2 (mm Hg)	381 (2.86)
Operating Range, N/m^2 (mm Hg)	200-385 (1.5-2.89)
Diluent	Air Constituents
Cooling Air	
Total Pressure, N/m^2 (Inch Water)	Ambient + 1495 (+ 6)
Temperature, K (F)	Process Air Dew Point + 3.34 (+ 6)
H_2 Supply	
Total Pressure, kN/m^2 (Psia)	<138 (<20)
Temperature, K (F)	291-297 (65-75)
Dew Point Temperature, K (F)	283-289 (50-60)
H_2 + CO_2 Exhaust	
Total Pressure	Ambient
Electrical Power	106-122 VRMS, 400 ±40 Hz, 3Ø, 5 Wire
Purge Supply	
Type Gas	N_2
Pressure, kN/m^2 (Psia)	310 (45)
Packaging	Self-Contained
Gravity	0-1 g
Allowable Downtime	8-12 Hr
Duty Cycle	Variable[a]

(a) The SSP Specification cites potential orbital On/Off cyclic operation.

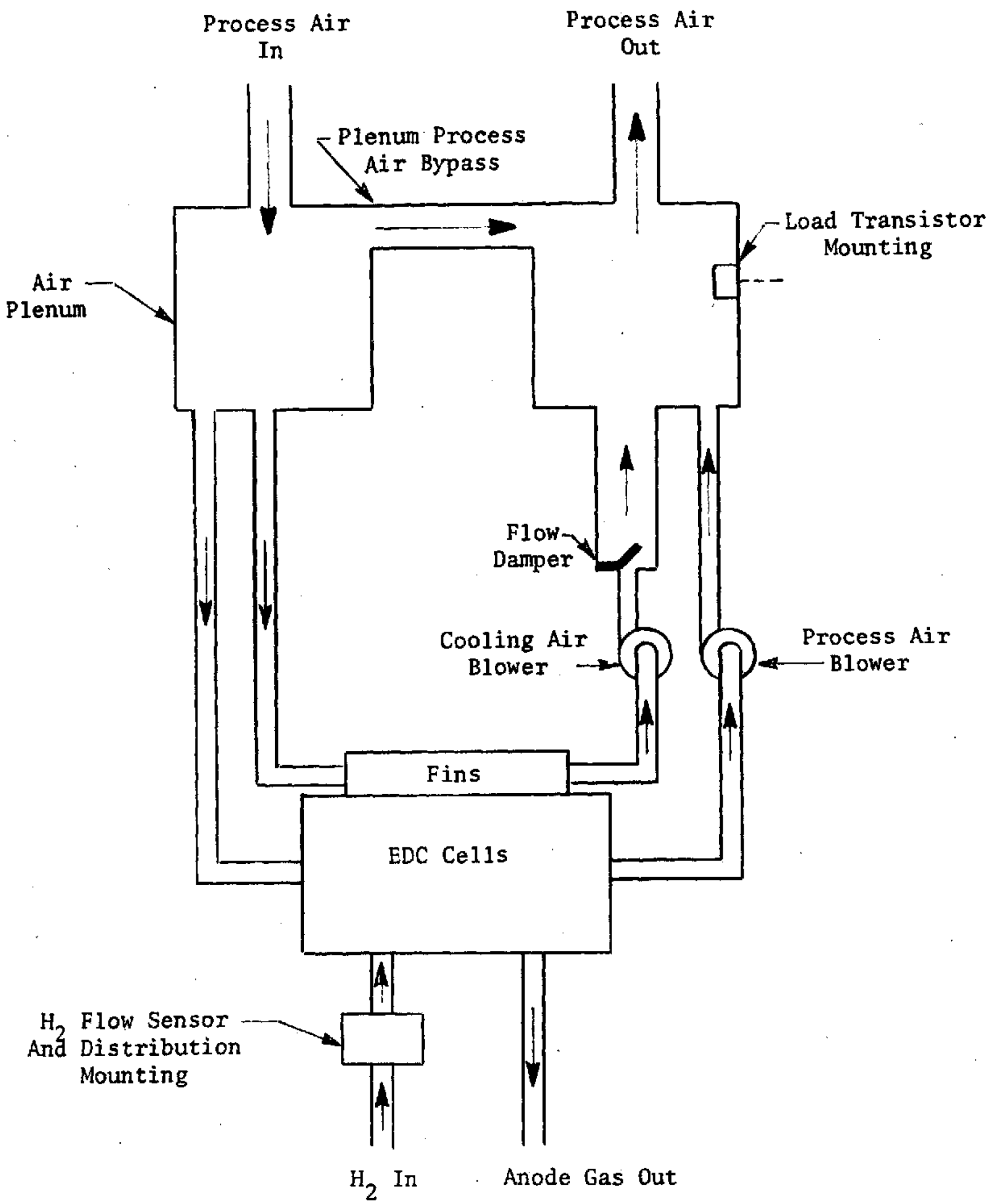

FIGURE 2 SIMPLIFIED CS-6 FUNCTIONAL BLOCK DIAGRAM

Each loop has its own process air blower, cooling air blower, H_2 flow sensor and distribution mounting, and three EDC modules. For math modeling purposes, both process loops have the same performance characteristics. The simplification of the subsystem hardware shown in Figure 2 reduces the number of computer program outputs (and computer running time) required to describe CS-6 performance without sacrificing model accuracy.

Process air is drawn from the inlet portion of the plenum through the cathode compartments of the electrochemical cells by the process air blowers. Carbon dioxide is removed from the flowing air stream as it passes over the cathode of the EDC cells. The CO_2-depleted air stream is then returned to the outlet portion of the plenum. Likewise, cooling air is drawn by the cooling air blowers from the inlet portion of the plenum over the external fin portion of the electrochemical cells. The cooling air, at a higher temperature, is then returned to the outlet portion of the plenum. Excess process air entering the plenum bypasses the subsystem through the plenum air bypass.

Process H_2 used by the electrochemical modules is manifolded to each module through two identical H_2 sensor and flow distribution mounting blocks. Each flow distribution block equally manifolds H_2 flow to each of the three 16-cell modules it serves. The H_2 flows in series through the 16 cells of each module.

Hardware Description

The CS-6 subsystem components were divided into Line Replaceable Units (LRUs). The list of the major subsystem LRUs is presented in Table 2. Front and rear photographs of the CS-6 showing the LRUs are presented in Figures 3 and 4, respectively. Each of the LRUs were analyzed for power required, heat generation, effect on gas stream pressure, temperature and composition, and actual component weight for use in the total subsystem equivalent weight determination. Those components that did not require power[a], generate heat, or affect gas stream parameters during steady-state operation were not modeled. The LRUs not modeled were the process air sensors, the electric shutoff valves, the backpressure regulator, the pressure sensors, the combustible gas sensors, and the manual shutoff valve. The electrical, motor-driven shutoff valves are not actuated during normal operation and hence require no power and generate no heat. Their actuation only occurs during mode transitions (such as normal to shutdown); however, even then the energy requirement is less than 57.5 J (0.016 watt-hours). All other components were characterized for use in the computer simulation model. A brief description of those LRUs that were modeled follows.

Electrochemical Modules

The CS-6 contains six electrochemical modules. Each of the electrochemical modules contains 16 cells. The electrochemical modules perform the actual CO_2 removal process by removing CO_2 from the cathode air stream and concentrating it

(a) All sensor power required is accounted for in the controllers.

TABLE 2 CS-6 LINE REPLACEABLE UNITS

	SSP Item No.	Qty. Req'd
Module, Electrochemical	890	6
Blower, Process Air	543	2
Blower, Cooling Air	345	2
Sensor, Process Air	875	4
Valve, Shutoff, Electric	305	3
Valve, Shutoff, Electric	306	6
Mounting, H_2 Flow Sensor & Distribution	882	2
Valve, Regulator, Backpressure	310	1
Sensor, Pressure	877	3
Sensor, Combustible Gas	178	4
Controller, Primary	871	1
Controller, Emergency	872	1
Unit, Data Acquisition	970	1
Mounting, Load Transistor	876	1
Valve, Shutoff, Manual	507	1

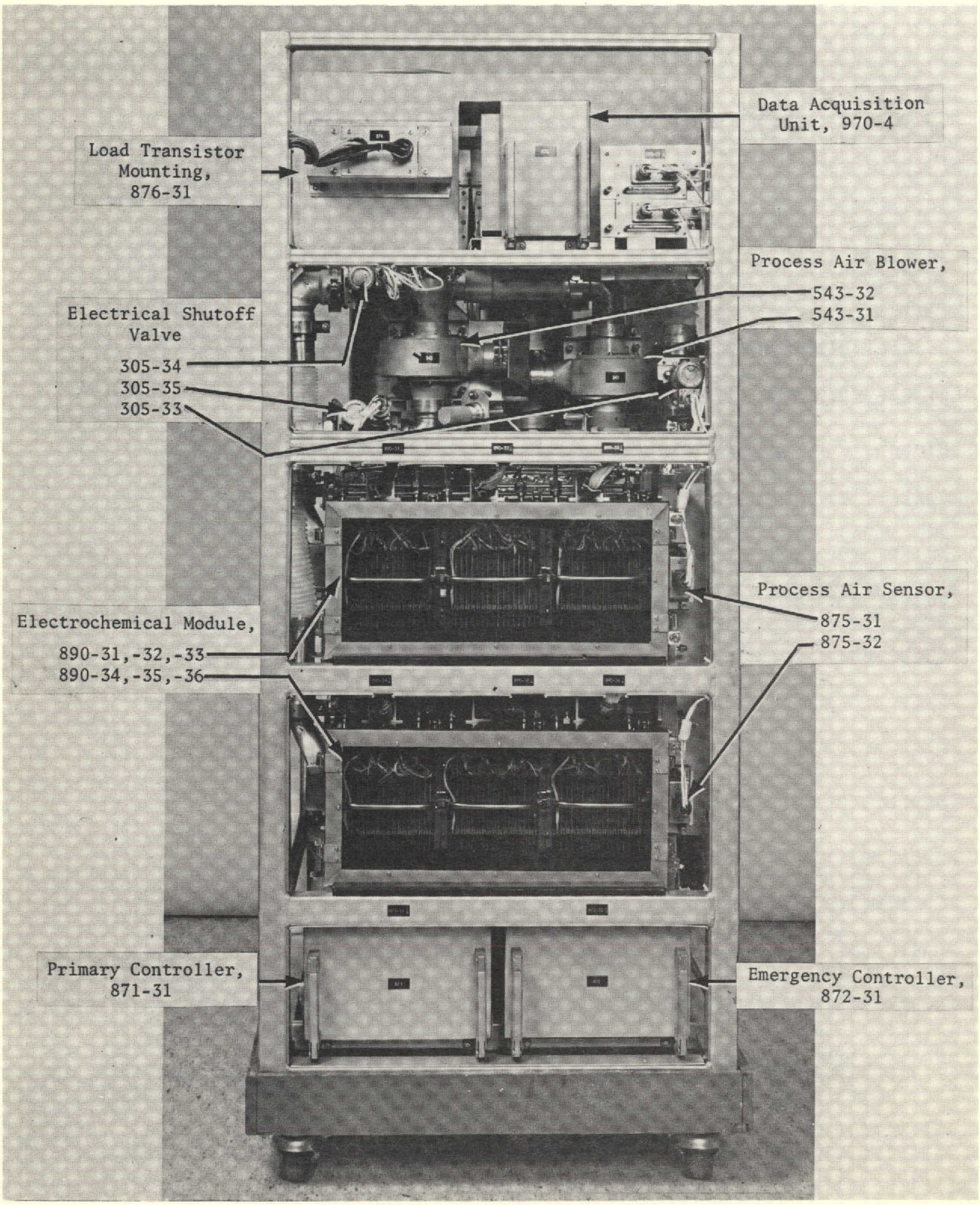

FIGURE 3 CS-6 SUBSYSTEM (FRONT)

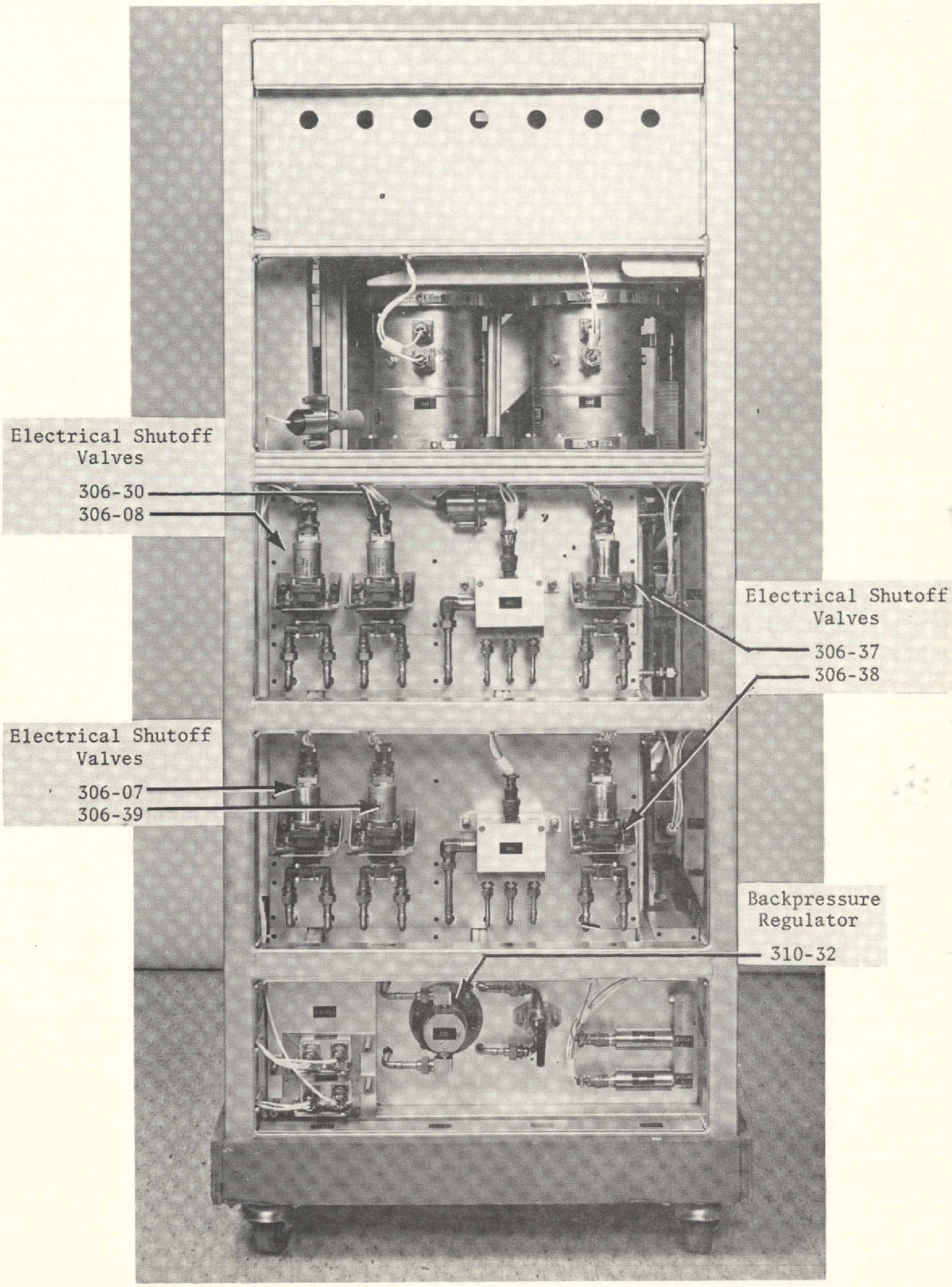

FIGURE 4 CS-6 SUBSYSTEM (BACK)

into the process H_2 stream. Moist air containing CO_2 is fed into the cathode where the electrochemical reaction of oxygen (O_2) in the air, water, and electrons form hydroxyl ions (OH^-). The CO_2 from the air then reacts with OH^- forming carbonate ions. The output from the cathode compartment is moist air at a reduced pCO_2. At the anode side, H_2 is fed into the cell and electrochemically reacts with OH^- to form water and electrons. The decrease in the OH^- concentration in the electrolyte at the anode produces an equilibrium shift in the electrolyte which causes CO_2 to be released. The output from the anode compartment is CO_2 mixed with unreacted H_2. The overall reaction is exothermic and is accompanied by the formation of electrical energy. The CO_2 removal process is primarily a function of the inlet air pCO_2, air flow rate, cell current, and cell moisture balance. Cell voltage and power production is primarily a function of cell current density and temperature.

Process Air Blowers

The CS-6 contains two centrifugal blowers to draw process air from the plenum through the cathode compartment of the electrochemical cells. One blower is used for each process loop. The process air flows in parallel through the 48 cells of each group of three modules. The blowers are located downstream of the electrochemical modules such that heat generated by the blowers will not have an adverse effect on the moisture balance within the electrochemical cells. The blower power used to control the cathode air flow rate is dissipated as heat into the cathode air stream exhausting the blower.

Cooling Air Blowers

The CS-6 contains two vane axial blowers to draw process air from the plenum over the fins of the electrochemical modules. Each blower draws the air in parallel over the fins of the 48 cells of a group of three modules. All heat dissipated as inefficiencies within the electrochemical module that is not removed by the cathode process air stream and process H_2 streams is removed by the cooling air stream. One cooling air blower is used for each process loop. The cooling air blowers are located downstream of the electrochemical modules. The amount of cooling air required is determined by the temperature differential between the dew point of the incoming process air and the dry bulb temperature of the exiting process air stream from the module. The cooling air blower speed is continuously modulated to vary the cooling air flow rate over the cell cooling fins as required. All power used by the cooling air blowers is dissipated as heat into the cooling air exiting the blowers.

Hydrogen Flow Sensor and Distribution Mounting

The CS-6 contains two H_2 flow sensor and distribution mountings designed to provide equal H_2 flow to each of the six CS-6 submodules. Each flow distribution block is located upstream of the three electrochemical modules it serves. The distribution block consists of three calibrated orifices and three flow sensors. Power required by the flow sensors is accounted for in the controllers and there is no heat generation. The blocks do affect H_2 stream pressure drop.

Primary Controller

The primary controller controls module current, process (cathode) air flow rate, and the process air inlet dew point to module temperature differential. Two control modes can be selected, Mode A and Mode B. In Control Mode A, current and process air flow rate are controlled at a constant level throughout CS-6 operation. In Control Mode B, both parameters are a function of an external 0 to 5 volt DC signal which is assumed to originate from a pCO_2 sensor. The module temperature control is independent of Control Mode A or B and basically is a control of the cooling air blower speed to maintain the process air inlet dew point to module temperature differential constant. The primary controller also sequentially actuates subsystem components to place them in the proper configuration as dictated by an operating mode command or when an out-of-tolerance condition is sensed by the primary controller. Primary controller-initiated shutdowns are those that are time critical and require immediate action. There are four primary controller initiated shutdowns: (1) high H_2 pressure (48 kN/m^2 (7.0 psig)), (2) low H_2 pressure (<17 kN/m^2 (2.5 psig)), (3) high H_2-in-air mixture (>1.5%) in the front of the subsystem, and (4) high H_2-in-air mixture (>1.5%) in the back of the subsystem.

Power required to run the controllers, not including the electrochemical power generated by the electrochemical reactions, is dissipated as heat to the surrounding environment and not to any process stream.

Emergency Controller

The emergency controller consists of a shutdown sequencer to provide for proper component sequencing during an emergency controller-initiated subsystem shutdown. Any out-of-tolerance condition for any one of eight subsystem parameters can initiate this shutdown sequence. Those conditions which can cause a shutdown are:

1. High or low module temperature to inlet air dew point temperature differential (12.2K (22F)) above the inlet dew point air temperature or less than 8.9K (16F) above the inlet dew point temperature.

2. High power transistor temperature in the load transistor mounting heat sink assembly (in excess of 366K (200F)).

3. Greater than 2% H_2-in-air mixture sensed by a combustible gas sensor located in the front of the subsystem.

4. Greater than 2% H_2-in-air mixture sensed by a combustible gas sensor located in the rear of the subsystem.

5. High anode gas exhaust pressure in excess of 52 kN/m^2 (7.5 psig).

6. Loss of primary controller power.

7. A H_2 exhaust pressure less than 14 kN/m^2 (2.0 psig).

8. Low cell voltage in any one of the 96 cells (less than -0.25V).

Power utilized by the emergency controller is dissipated as heat given off to the surrounding cabin environment.

Load Transistor Mounting

The load transistor mounting is located in the outlet portion of the process air plenum to dissipate the power generated by the electrochemical cell reactions as heat and reject it to the process air stream leaving the plenum.

CS-6 MATH MODEL TEST PROGRAM

Experimentation specifically aimed at supporting the development of the CS-6 computer simulation model was required to establish the performance characteristics of the CS-6 and its individual LRUs. Seven tests were conducted. Six were directly used to characterize the performance of LRUs while the seventh established subsystem performance and intercomponent interface parameters for eventual math model computer program verification. The six LRUs characterized were: (1) the electrochemical modules (to compare predictability of the module math model previously developed), (2) the process air blowers, (3) the cooling air blowers, (4) the H_2 flow sensor and distribution mounting, (5) the primary controller, and (6) the emergency controller. The remaining LRUs consisting of valves and sensors were not characterized since valve power and heat loads are negligible and sensor power and heat load are included under either the primary or emergency controller.

Electrochemical Modules

A series of three experiments were conducted to verify the predictibility of the electrochemical modules' performance within the CS-6 to determine if any upgrading of the previously established EDC cell math model was required. The electrochemical modules were characterized as a function of inlet pCO_2, current density, and air flow rate over nominal operating ranges.

Process Air Inlet pCO_2

Module performance, specifically CO_2 removal efficiency, was experimentally characterized for a process air inlet pCO_2 range of 67 to 800 N/m^2 (0.5 to 6.0 mm Hg). The results of the pCO_2 test and the math model prediction curve for the test parameters are presented in Figure 5. The correlation between math model prediction and experimental data was excellent, thereby verifying the predictability of the electrochemical math model as a function of process air inlet pCO_2.

Current Density

The effect of current density on electrochemical module performance was characterized for 10.8 to 37.7 mA/cm^2 (10 to 35 ASF). The results of the experiment and the math model prediction curve for the test parameters are presented in Figure 6.

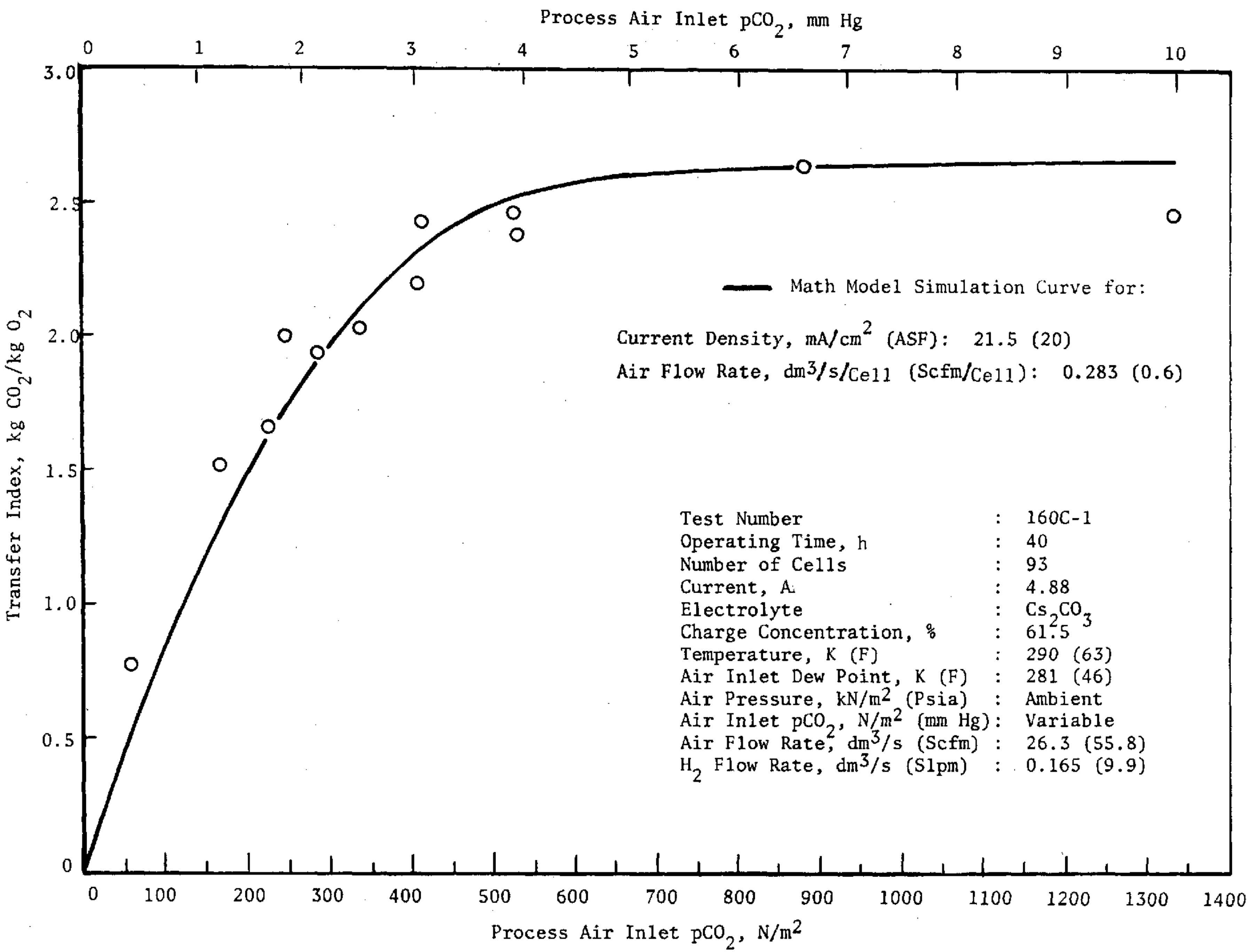

FIGURE 5 COMPARISON OF CS-6 PERFORMANCE DATA AND MATH MODEL SIMULATION CURVE FOR TRANSFER INDEX VERSUS INLET pCO_2

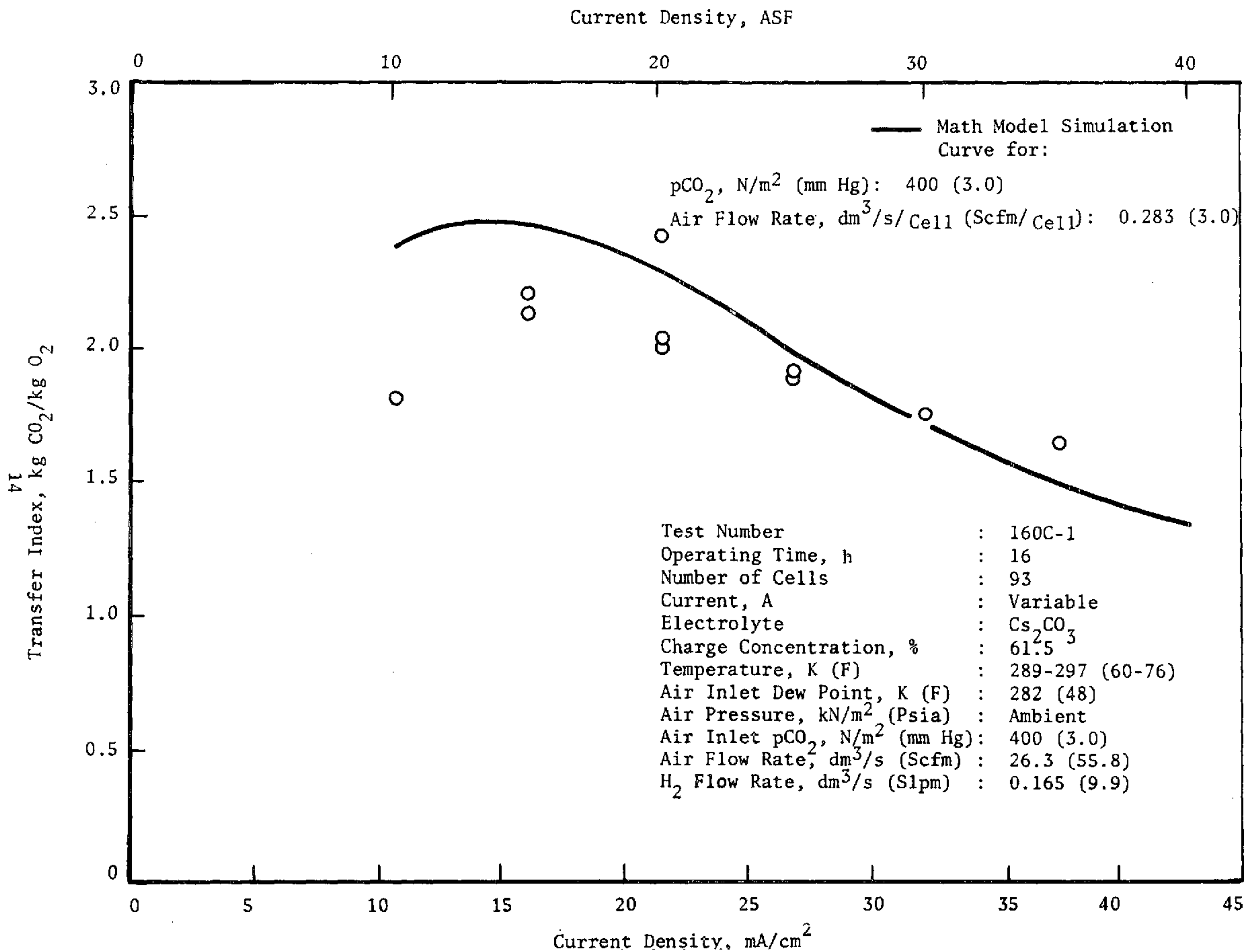

FIGURE 6 COMPARISON OF CS-6 PERFORMANCE DATA AND MATH MODEL SIMULATION CURVES FOR TRANSFER INDEX VERSUS CURRENT DENSITY

The test was conducted at CS-6 baseline interface conditions. At steady-state, moisture-in-balance conditions, the predictions of the math model as previously developed for CO_2 removal efficiencies agreed well with the performance data observed for the CS-6. At the lower current densities, the EDC cell math model predicted out-of-tolerance moisture conditions (wet) due to insufficient module heat generation (module subcooling). Subsystem operation at the lower current densities yielded lower than predicted transfer efficiencies characteristic of operation at wet conditions[5]. The data indicated excessively moist conditions, as correctly predicted by the math model. At the higher current densities, the math model predicted that the cell moisture conditions were removing water from the electrolyte causing the modules to dry out. Subsystem operation at the higher current densities yielded higher than predicted CO_2 removal efficiencies characteristic of operation at dry conditions[5]. The data indicated very dry moisture conditions within the modules, as correctly predicted by the math model. The deviations from in-moisture-balance operation were caused by the variation in cell current density which changes the amount of water and waste heat generated while maintaining the air flow rate and process air inlet moisture conditions constant at SSP baseline conditions without adjustment in module temperature level.

The previously established EDC cell math model predicts CO_2 removal efficiencies based on the assumption that the cells are operating at steady-state conditions and that moisture balance is maintained within a specific, optimum range. Steady-state operation, however, can also be achieved at less than optimum moisture conditions within the electrochemical modules. Since this latter condition is a possible operating mode for the CS-6, a moisture balance correction to allow prediction of CO_2 removal efficiencies as a function of the cell moisture conditions, as indicated by the data, was subsequently incorporated prior to completing the CS-6 subsystem math model.

Cathode Air Flow Rate

The effect of varying cathode air flow rates was characterized for the range of 14.2 to 28.3 dm^3/s (30 to 60 scfm). The results of the experiment and the EDC cell math model prediction curve for the test parameters are presented in Figure 7.

Air flow rate has a large effect on the heat and water removal rates and the moisture balance conditions within the electrochemical cells. The data used in the CO_2 removal efficiency correlation of the EDC cell math model was, as stated above, based on cells operating in an optimum moisture balance range and did not take into account the large changes in cell moisture conditions caused by varying the air flow rate, as experienced in the actual subsystem operation. The CO_2 removal efficiency correlation of the initial EDC cell math model was, therefore, not adequate to predict CO_2 removal efficiency as a function of air flow rate. Subsequently, additional data gathered on the CS-6 after the completion of the original EDC cell math model was used to upgrade the air flow correlation for electrochemical modules. This upgraded version was included in the CS-6 Base Program.

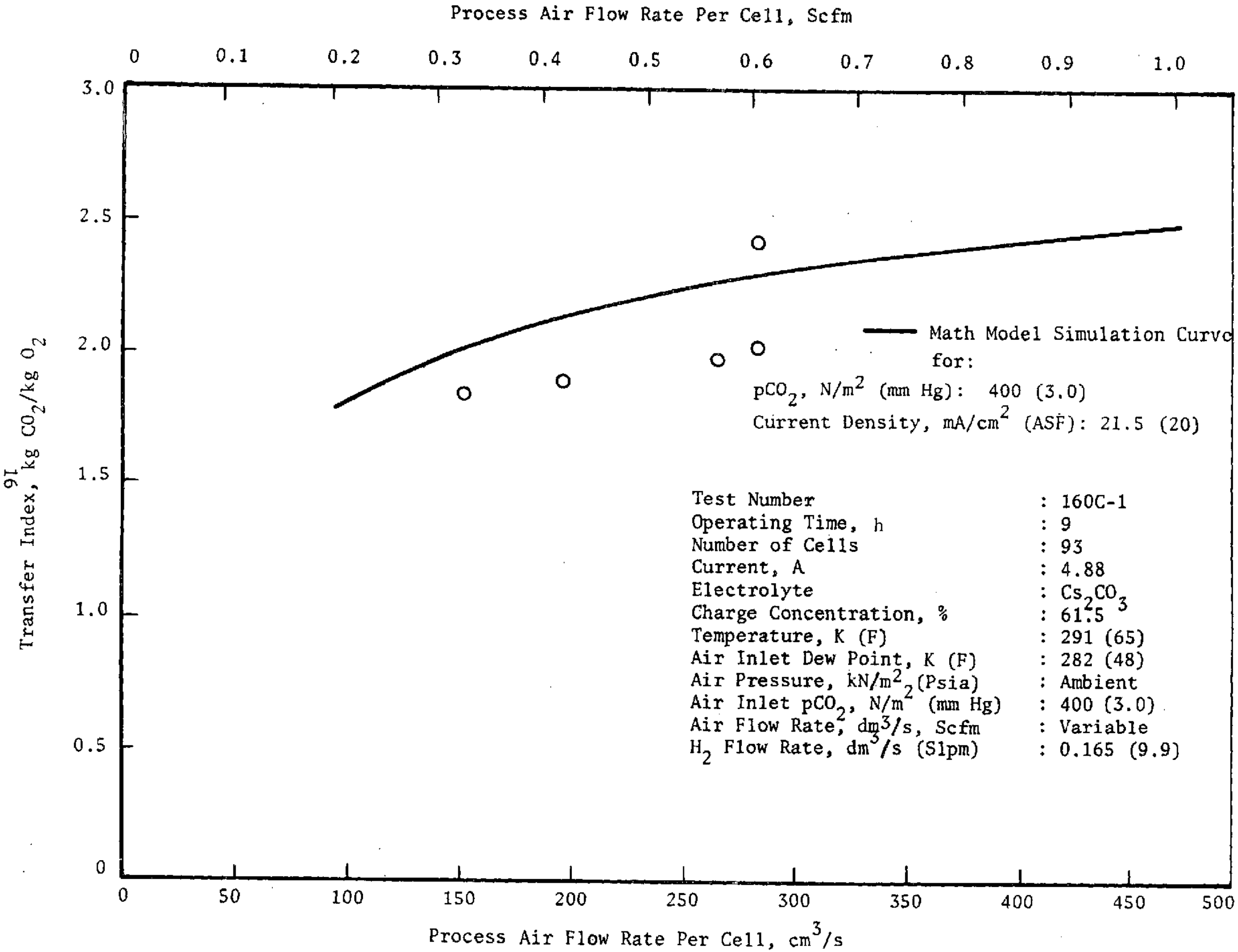

FIGURE 7 COMPARISON OF CS-6 PERFORMANCE DATA AND MATH MODEL SIMULATION CURVES FOR TRANSFER INDEX VERSUS AIR FLOW RATE

Process Air Blowers

The two CS-6 process air blowers were characterized to obtain air stream pressure drops and blower power and heat load as a function of process (cathode) air flow rate. The major pressure drop producing components in this air stream are the EDC modules. The results of the module pressure drop versus flow rate experiment are shown in Figure 8. System pressure drop as a function of air flow rate is given in Figure 9. Blower power for the process air blower of Section 1 and Section 2 as a function of air flow rate, at a corresponding system pressure drop, is given in Figures 10 and 11, respectively.

The modules and system pressure drop versus air flow rate curves relate typical pressure drop data as a function of air flow rate. The blower power curve, however, contains a spike at 14.2 to 16.5 cm^3/s (30 to 35 scfm), resulting from the combination of blower motor characteristics and blower speed control circuitry. The spike was verified during all forms of operation and implies that only a small change in air flow rate at flow rates greater than 14.2 dm^3/s (30 scfm) can cause large variations in the blower power requirement.

Cooling Air Blowers

The two CS-6 cooling air blowers were experimentally characterized to establish blower power, heat load, and cooling air passage pressure drop. The results of the cooling air pressure drop versus air flow rate test at two levels of plenum inlet pressure levels are presented in Figure 12. The pressure drop associated with ducting to and from the electrochemical modules did not significantly contribute to the cooling air pressure drop in comparison to the module cooling air pressure drop. The cooling air blower power versus air flow rate curves are shown in Figure 13.

Figure 13 shows that for a plenum inlet air pressure of 286 to 336 N/m^2 (1.15-1.35 in water), a certain amount of cooling air (approximately 10 dm^3/s (21 cfm) flows through the cooling air passages with the cooling blowers off, i.e., blower power equal to zero. The amount of air that bypasses the plenum and flows over the cooling fins of the modules, when the cooling air blowers are off, is determined by the overall system process air flow rate entering the plenum. The higher the total system process air flow the higher the plenum pressure differential and the higher the leakage air flow through the cooling air passages. Dampers were installed in the cooling air passages to prevent this bypass flow from occurring during times when cooling is not required. The dampers, however, were not totally leak-tight and some air flow constantly bypassed through the cooling air passages during cooling blower off operation. This contributed to module subcooling during low current density and high process (cathode) air flow rates.

Primary Controller

The CS-6 primary controller was characterized to determine the heat load and the power required during steady-state CS-6 operation. All blower power, which only passes through the controller, is handled separately and is not included in this

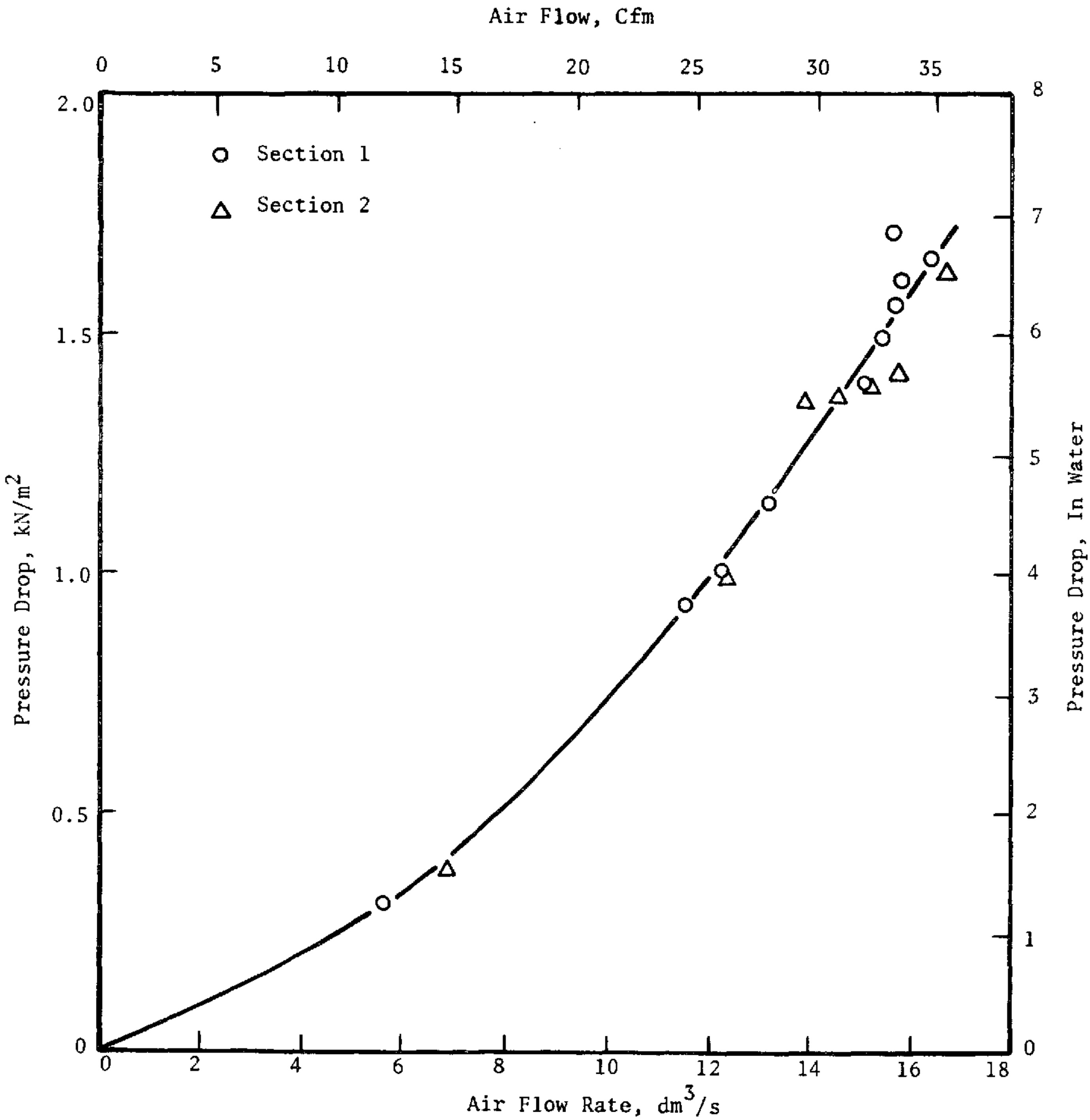

FIGURE 8 EDC MODULE PROCESS AIR PRESSURE DROP VERSUS AIR FLOW RATE

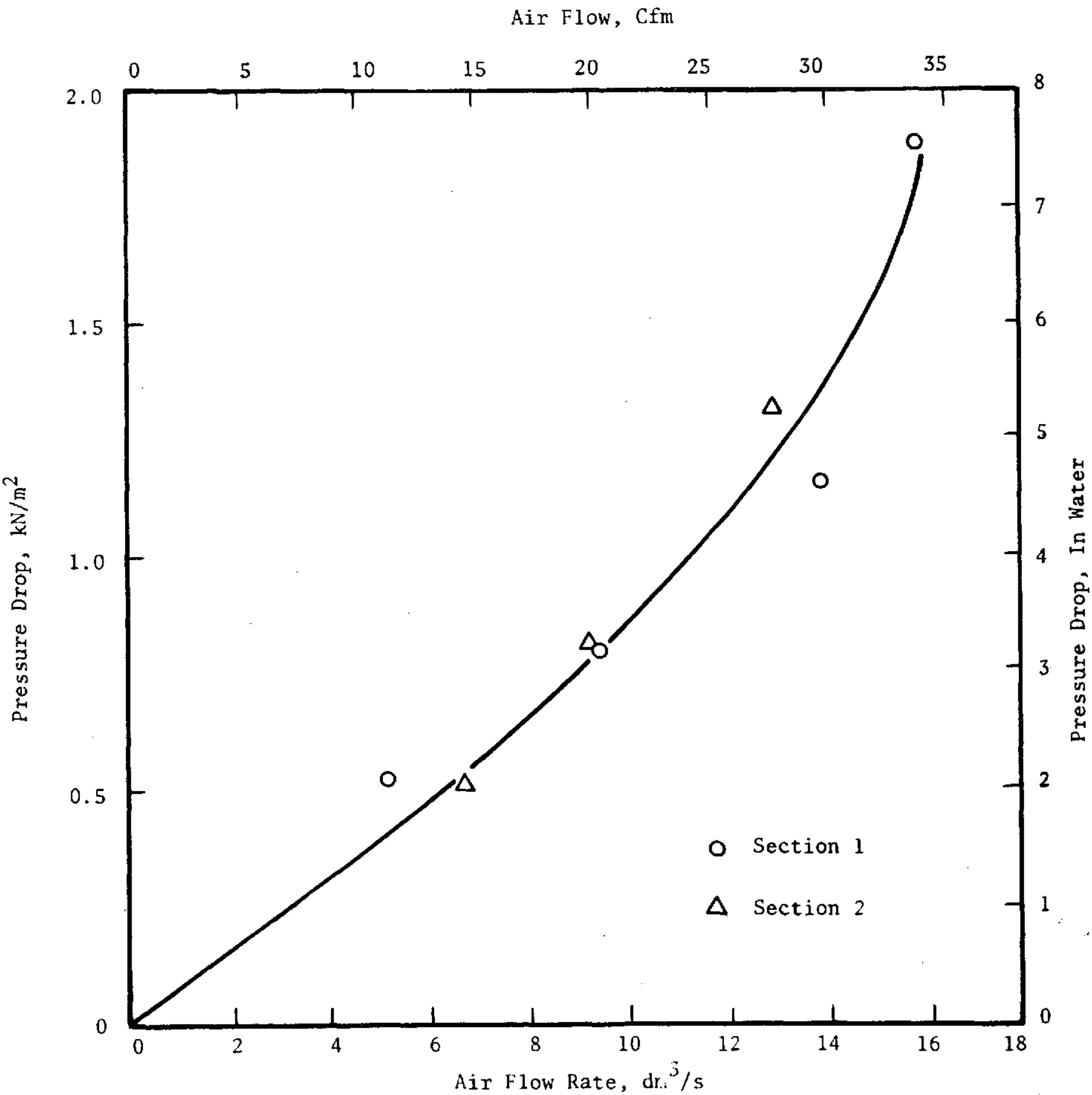

FIGURE 9 SYSTEM PROCESS AIR PRESSURE DROP VERSUS AIR FLOW RATE

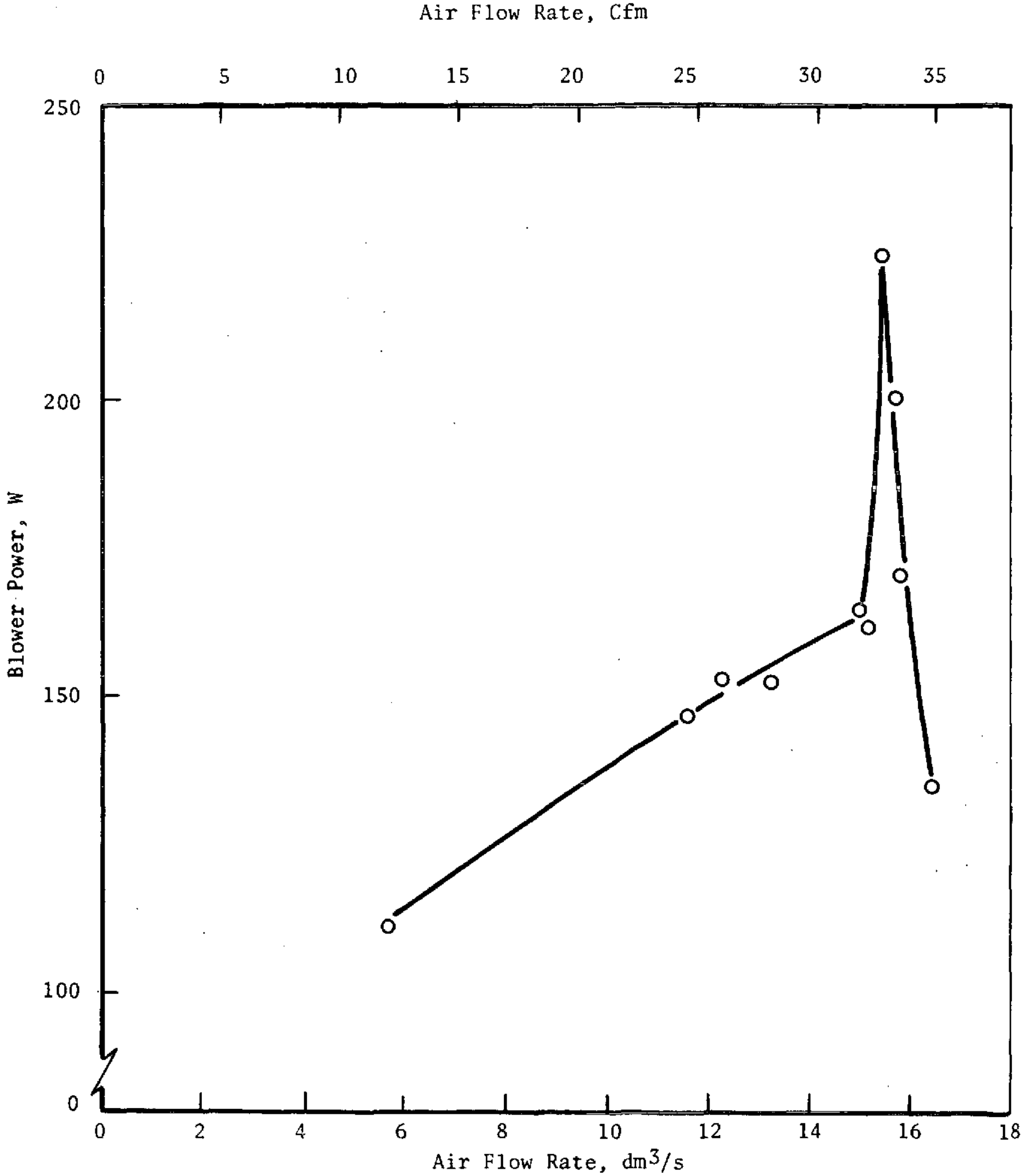

FIGURE 10 PROCESS AIR BLOWER POWER VERSUS AIR FLOW RATE (SECTION 1)

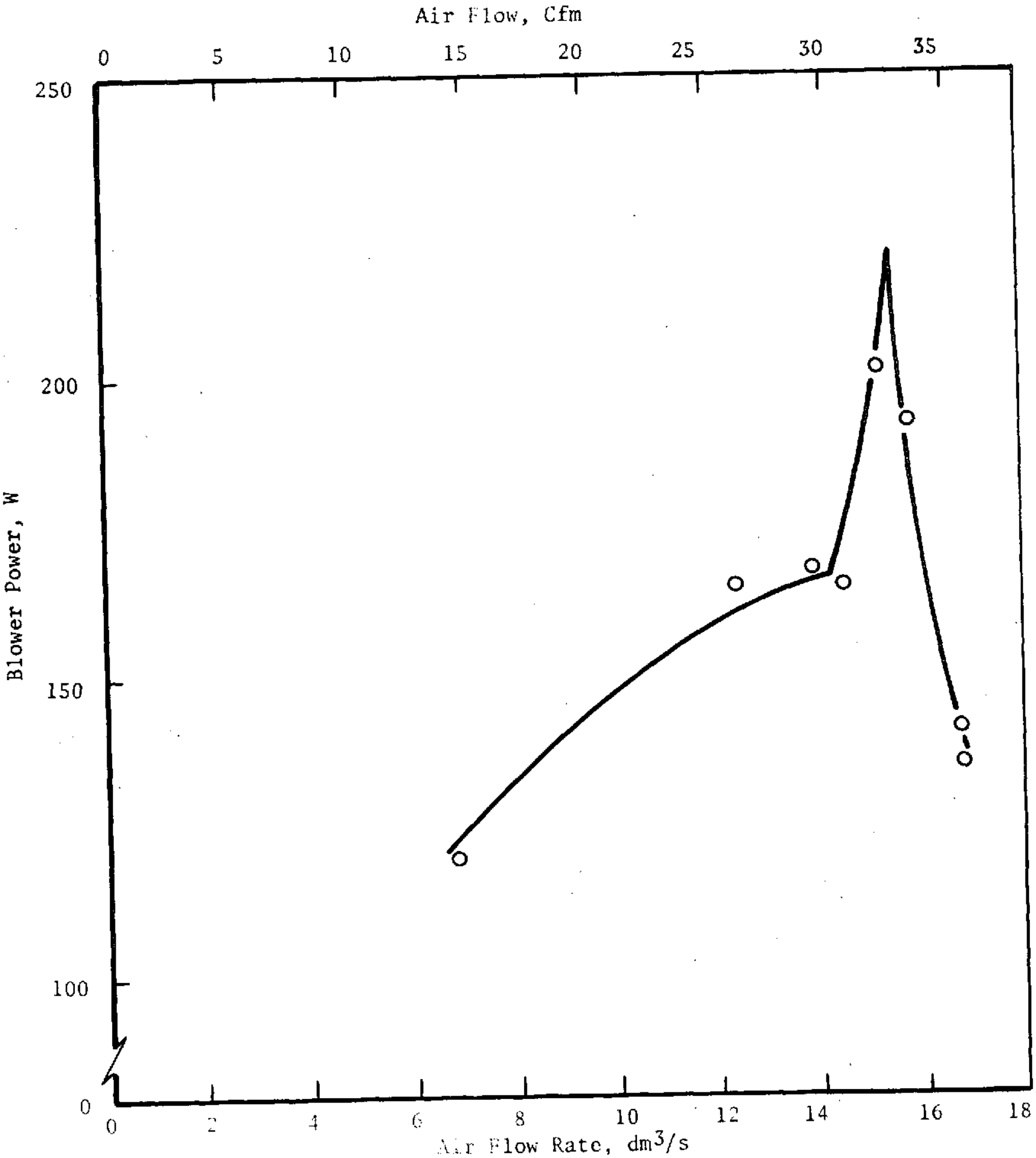

FIGURE 11 PROCESS AIR BLOWER POWER VERSUS AIR FLOW RATE (SECTION 2)

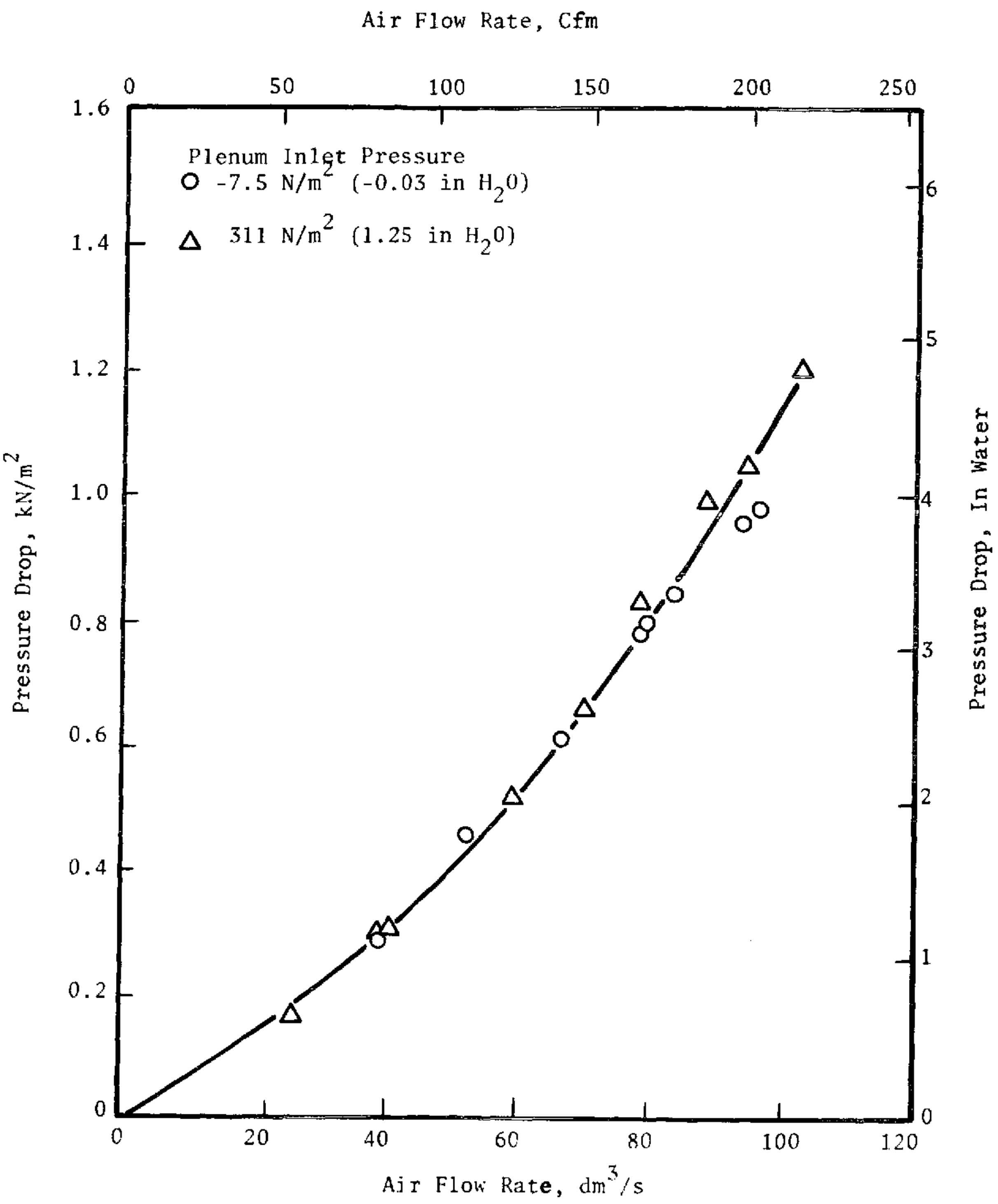

FIGURE 12 COOLING AIR PRESSURE DROP VERSUS AIR FLOW RATE

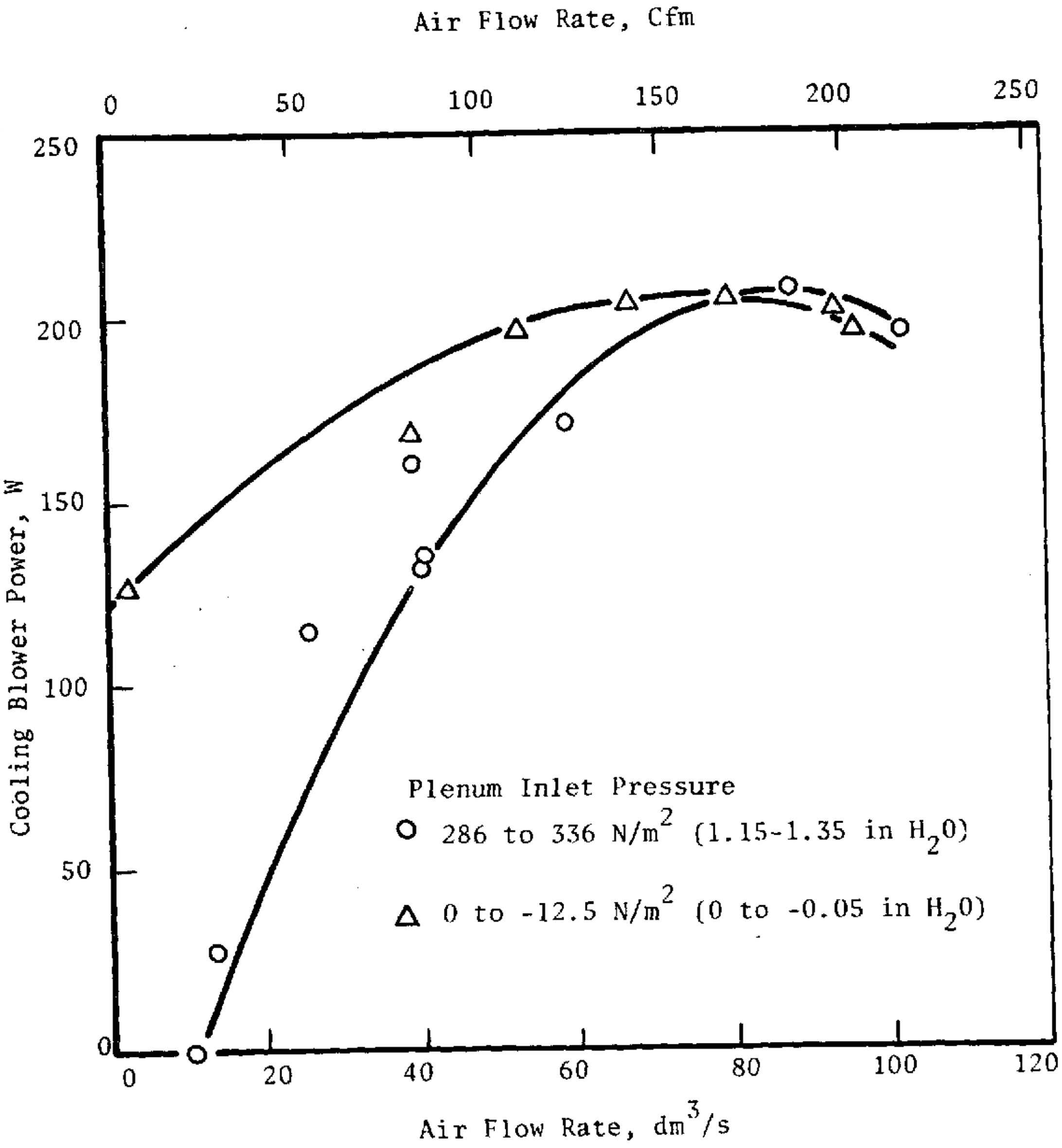

FIGURE 13 COOLING AIR BLOWER POWER VERSUS AIR FLOW RATE

requirement. The amount of power attributed to the primary controller to control the operation of the CS-6 subsystem at steady-state conditions as measured by a wattmeter on the power input was 85 watts. This power requirement is constant and independent of subsystem parameter variations (i.e., current density, cooling blower speed, or process air blower speed).

Emergency Controller

The CS-6 emergency controller was characterized to obtain the heat load and the power required during steady-state operation. The steady-state emergency controller power, as measured by a wattmeter, was 45 watts during normal CS-6 operation. This power requirement is constant and independent of subsystem parameter variations.

CS-6 Subsystem

The CS-6 subsystem was characterized as a function of process air inlet pCO_2, current density, and process air flow rate to determine intercomponent interface conditions between LRUs within the CS-6. The objective of the testing was to verify CS-6 math model prediction using these various intercomponent temperatures, pressures, etc. The testing consisted of running the CS-6 at steady-state conditions and monitoring pressures and temperatures throughout the system as a function of changes in inlet pCO_2, cell current density, and process air flow rate. The location of the sampling taps are shown in Figure 14. The results of the tests are presented in Table 3 and were used to verify math model prediction. The subsystem was tested using existing ground support test equipment which was not capable of supplying the total process air requirement to the plenum inlet. Only cooling air was supplied to the plenum. Process air was supplied to the electrochemical modules by a separate Air Supply Unit (ASU) at the required pCO_2, dew point, and dry bulb temperature. The cooling air stream was at ambient pCO_2 levels, but the temperature and dew point were maintained close to that of the process air from the ASU. Exact temperature and dew point correlation, however, was not obtained. Table 3 represents the data as if the CS-6 had been run in its designed configuration (i.e., all process air entering the plenum). Slight discrepancies in stream temperatures and dew points are present, but they had no affect on the modeling effort.

Hydrogen Flow Sensor and Distribution Mounting

The two H_2 flow sensor and distribution mounting blocks were characterized to obtain the nitrogen (N_2) and H_2 pressure drops as a function of flow rate through the distribution mounting. The results of the N_2 and H_2 pressure drop experiments are given in Figure 15. The H_2 pressure drop through the EDC modules was also characterized and is presented in Figure 16.

CS-6 BASE PROGRAM

The CS-6 Base Program is the computer program that was written to simulate the steady-state performance of the CS-6 as a function of variations in inlet stream composition temperatures and flow rates, outlet stream pressures, and the CS-6

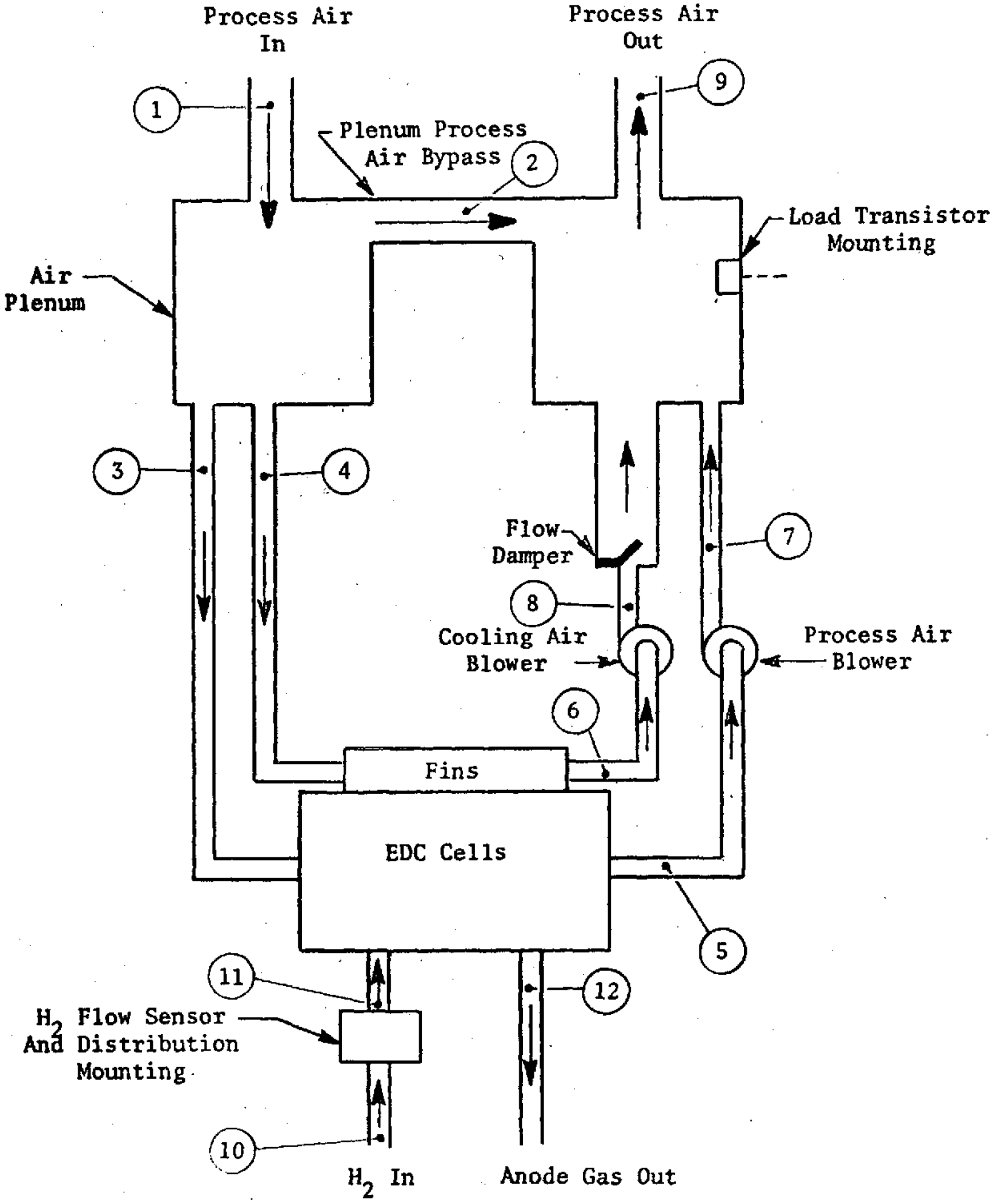

FIGURE 14 LOCATION OF GAS SAMPLING PORTS

TABLE 3 CS-6 INTERCOMPONENT INTERFACE PARAMETERS FOR BASELINE OPERATING CONDITIONS[a]

		1	2	3	4	5	6	7	8	9	10	11	12
Flow Rate,	dm^3/s	210	165	25	19	25	19	25	19	210	0.162	0.162	0.154
	Scfm	444	350	54	40	54	40	54	40	444	-	-	-
	Slpm	-	-	-	-	-	-	-	-	-	9.7	9.7	9.25
Pressure,[b]	kN/m^2	0.242	0.075	-0.580	X[c]	1.910	0.030	0.062	X	0.060	51.3	34.6	X
	In H_2O	0.97	0.30	-2.33	X	-7.67	0.12	0.25	X	0.24	-	-	-
	Psig	-	-	-	-	-	-	-	-	-	7.4	5.0	X
Temperature,	K	284	284	286	284	291	290	299	X	284	297	297	291
	F	51.5	51.5	55.8	51.5	64.8	63.0	78.5	X	51.8	76.0	76.0	65.0
Dew Point,	K	277	277	282	277	284	277	284	277	279	296	296	286
	F	40.0	40.0	48.0	40.0	51.2	40.0	51.2	40.0	43.2	74.0	74.0	56.0

(a) Cell current = 4.88A.
(b) Above ambient.
(c) X indicates data not taken.

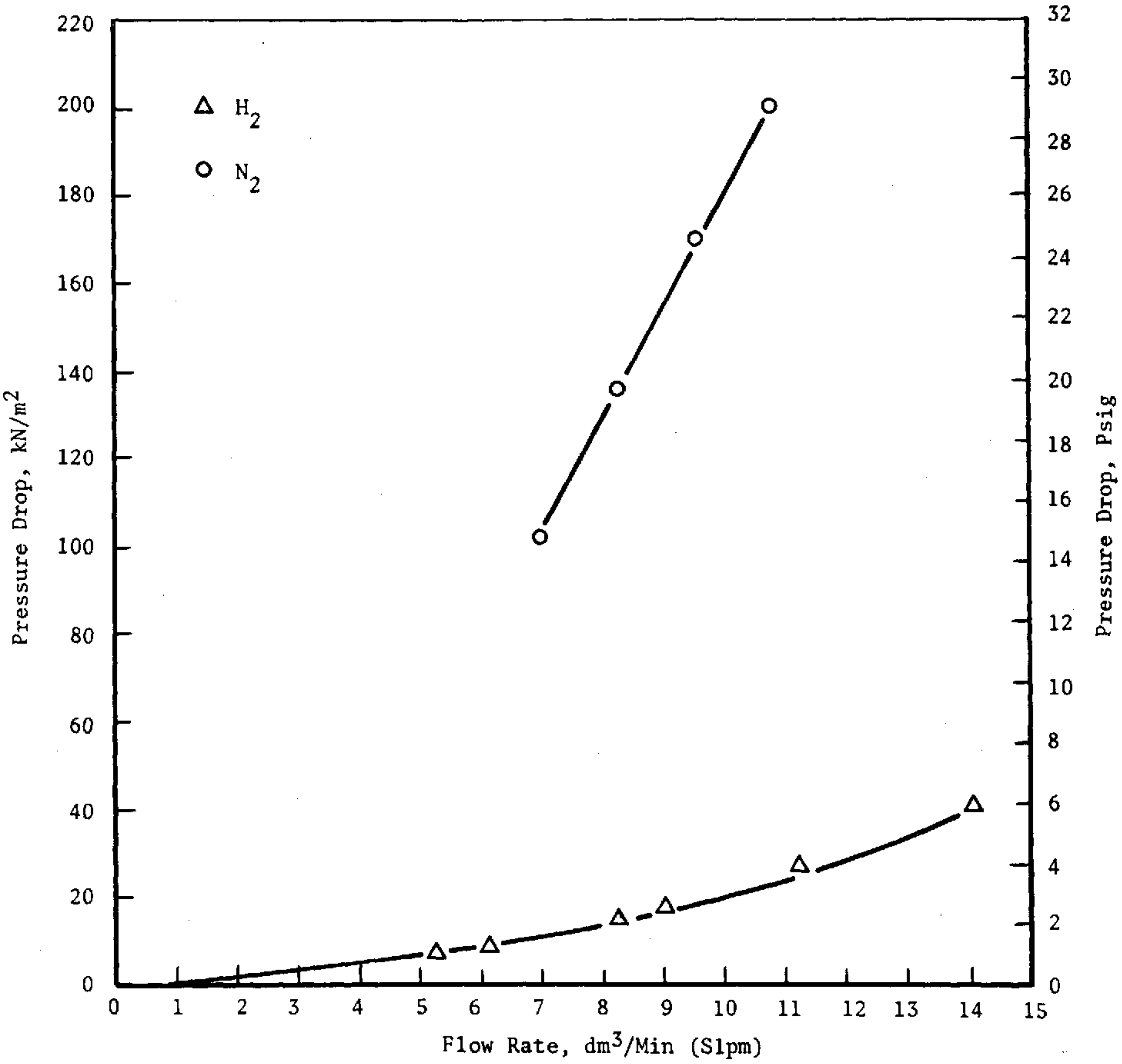

FIGURE 15 H_2 DISTRIBUTION BLOCK PRESSURE DROP FOR PROCESS H_2 AND N_2 PURGE

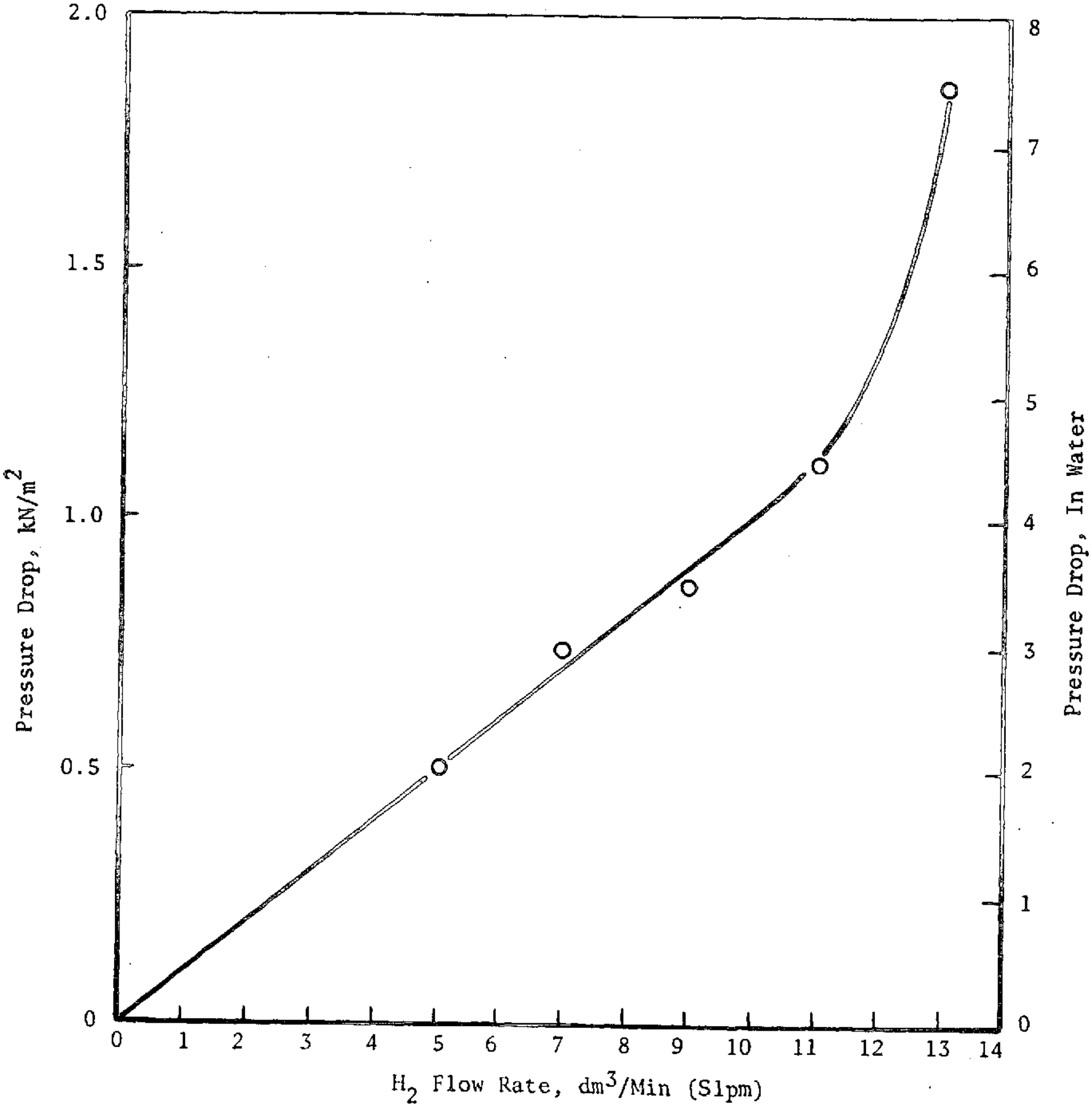

FIGURE 16 H_2 PRESSURE DROP ACROSS MODULES control parameters. The CS-6 input variable ranges are given in Table 4. All inputs to the computer program are entered in the engineering units shown in Table 4. Table 5 is a complete list of the program input and output variables and their units. The program also provides various checks to insure that input data is within the model's range of predictability and to identify out-of-tolerance operating conditions.

The program contains previously developed correlations describing the performance of the EDC cells.[1] Additional correlations were developed describing CS-6 subsystem LRUs and process streams. The Base Program combines these correlations with steady-state mass and energy balances, and the program checks to simulate steady-state CS-6 performance. The original EDC math model computer program was not used directly as a subroutine in the Base Program since the assumption of cooling air being delivered at the required rate, optimum moisture balance conditions, and exact control of module temperature were not applicable because of the characteristics of the subsystem hardware. A certain amount of program rearranging was also desired to decrease computer running time by calculating those items that require an iterative solution prior to the gross calculation of stream variables.

Model Analyses

The math model which resulted in the CS-6 Base Program was developed by first defining the inlet and outlet stream characteristics and parameters for the CS-6 at the subsystem level. An initial computer program was written to describe the subsystem interfaces by expanding the math model developed for the EDC cells. The analyses that were used to derive the mathematical expressions describing the CS-6 intercomponent interface parameters were developed and incorporated into the initial program as required to calculate the remaining program outputs.

To clarify variable notation, numerical identifiers were given to the process streams and equation variables. The stream identification numbers are presented in Figure 17.

Process Air Correlations

The inlet process air stream to the CS-6 is divided into three streams: the cooling air stream, the process (cathode) air stream, and the air plenum bypass stream. Mathematical expressions were required and developed to describe the stream flow characteristics and blower power requirements.

Cooling Air Pressure Drop. The pressure drop associated with flow through the cooling air passages is the same as the pressure drop measured across the cooling air fins of the electrochemical modules since the pressure drop associated with the ducting is negligible. The correlation describing the cooling air passage pressure drop was derived by a least squares curve fit of pressure drop data as a function of air flow rate to a general quadratic equation. The equation was forced to pass through the origin so that there would be zero pressure

TABLE 4 CS-6 BASE PROGRAM INPUT VARIABLE RANGES

Cabin Atmosphere	
Total Pressure, PØPSA	13.7-15.7 Psia
pCO_2, PCØ	0.5-10 mm Hg
pO_2, POØPSA	2-4 Psia
Process Air Outlet	
Total Pressure, P8PSA	13.7-15.7 Psia
Process Air Inlet	
Temperature, T7	44-80F
Flow Rate, V7	0-600 Scfm[(a)]
Dew Point Temperature, DW7	41-70F
Anode H_2/CO_2 Outlet	
Total Pressure, P4PSA	14.8-21.2 Psia
System H_2 Inlet	
Temperature, T9	65-75F
Flow Rate, V9SL	0-18 Scfm[(a)]
Dew Point Temperature, DW9	10-75F
Modules	
Number of Cells in Current, N	90-96
Current, I	2.44-9.76 A
DELT1[(b)]	10-25F
Cathode Air Flow Rate, V1	19.2-76.8 Scfm (96 cells)
Penalty Weight Factors	
Power, PWPEN	0-2 Lb/Watt
Heat Rejection to Ambient, HTPEN	0-2 Lb/Btu/Hr
Water Vapor Rejection to Ambient, H2OPEN	0-500 Lb/Lb H_2O/Hr
Oxygen Consumption, OXPEN	0-3000 Lb/Lb O_2/Hr
Program Control	
NFLAG[(c)]	0-1

(a) Reference conditions for standard flow units: 70F, 14.7 Psia
(b) DELT1 = (Module temperature - cathode air inlet dew point temperature)
(c) NFLAG = 0 Out of tolerance moisture conditions do not stop program.
1 Out of tolerance moisture conditions do stop program.

TABLE 5 CS-6 BASE PROGRAM INPUT AND OUTPUT VARIABLES

Input Variables	
Cabin Atmosphere	Total Pressure, Psia pCO_2, mm Hg pO_2, Psia
Process Air Outlet	Total Pressure, Psia
Process Air Inlet	Temperature, F Flow Rate, Scfm Dew Point Temperature, F
Anode H_2/CO_2 Outlet	Total Pressure, Psia
Anode H_2 Inlet	Temperature, F Flow Rate, Slpm Dew Point Temperature, F
Modules	Number of Cells in Circuit Current, A DELT1[a], F Cathode Air Flow Rate, Scfm
Penalty Weight Factors	Power Consumption, Lb/Watt Heat Rejection, Lb/Btu/Hr Water Vapor Rejection, Lb/Lb/Hr O_2 Consumption, Lb/Lb/Hr
Control	NFLAG 0 = ignore out-of-tolerance moisture conditions 1 = abort for out-of-tolerance moisture conditions
Output Variables	
Control	Preferred Value of DELT1[a], F
Module	Transfer Index, Lb CO_2/Lb O_2 Transfer Efficiency, % Cell Voltage, V Module Voltage, V CO_2 Removal Rate, Lb/Hr O_2 Consumption Rate, Lb/Hr H_2 Consumption Rate, Lb/Hr Water Production Rate, Lb/Hr Current Density, A/Ft^2 Heat Load of Modules, Btu/Hr Power Production of Modules, Watt

(a) DELT1 = Module Temperature - Inlet Cathode Air Dew Point Temperature

-continued-

Table 5 - continued

Cathode Air Inlet	Total Pressure, mm Hg pCO_2, mm Hg pH_2O, mm Hg CO_2 Flow Rate, Lb/Hr Water Flow Rate, Lb/Hr CO_2 Flow Rate, Scfm Water Flow Rate, Scfm O_2 Flow Rate, Scfm N_2 Flow Rate, Scfm Temperature, F Dew Point Temperature, F Relative Humidity, %
Cathode Air Outlet	Total Pressure, mm Hg Module Cathode Air Pressure Drop, mm Hg pCO_2, mm Hg pH_2O, mm Hg Total Flow Rate, Scfm CO_2 Flow Rate, Scfm Water Flow Rate, Scfm O_2 Flow Rate, Scfm N_2 Flow Rate, Scfm CO_2 Flow Rate, Lb/Hr Water Flow Rate, Lb/Hr Temperature, F Dew Point Temperature, F Relative Humidity, % Cathode Air Blower Outlet Total Pressure, mm Hg Cathode Air Blower Outlet Flow Rate, Scfm Cathode Air Blower Outlet Temperature, F
Process Air Inlet	Total Pressure, mm Hg pH_2O, mm Hg pN_2, mm Hg CO_2 Flow Rate, Scfm Water Flow Rate, Scfm O_2 Flow Rate, Scfm N_2 Flow Rate, Scfm Dew Point Temperature, F Relative Humidity, %
Process Air Outlet	Total Pressure, mm Hg pCO_2, mm Hg Plenum Bypass Flow Rate, Scfm Plenum Bypass Pressure Drop, mm Hg Total Flow Rate, Scfm Water Flow Rate, Scfm CO_2 Flow Rate, Scfm

Table 5 - continued

Process Air Outlet	O_2 Flow Rate, Scfm
	pH_2O, mm Hg
	Temperature, F
	Dew Point Temperature, F
	Relative Humidity, %
H_2 Inlet	Total Pressure, mm Hg
	Water Vapor Pressure, mm Hg
	Distribution Block Pressure Drop, mm Hg
	Module Inlet Total Pressure, mm Hg
	Module Inlet pH_2O, mm Hg
	Module Inlet pH_2, mm Hg
	Total Flow Rate, Scfm
	H_2 Flow Rate, Scfm
	Water Flow Rate, Scfm
	H_2 Flow Rate, Lb/Hr
	Minimum Required Flow Rate, Slpm
H_2 Outlet	Total Pressure, mm Hg
	Module Anode Gas Pressure Drop, mm Hg
	Water Vapor Pressure, mm Hg
	Flow Rate, Scfm
	CO_2 Flow Rate, Scfm
	H_2 Flow Rate, Scfm
	Water Flow Rate, Scfm
	Flow Rate, Slpm
	CO_2 Flow Rate, Slpm
	H_2 Flow Rate, Slpm
	Total Flow Rate, Lb/Hr
	CO_2 Flow Rate, Lb/Hr
	H_2 Flow Rate, Lb/Hr
	Water Flow Rate, Lb/Hr
	Dew Point Temperature, F
	CO_2-H_2 Weight Ratio, Lb CO_2/Lb H_2
	H_2-CO_2 Volume Ratio, Slpm H_2/Slpm CO_2
Heat Balance, Modules	Modules Heat Load, Btu/Hr
	Cathode Air Heat Pickup, Btu/Hr
	Anode Gas Heat Pickup, Btu/Hr
	Cooling Air Heat Pickup, Btu/Hr
Cooling Air	Inlet Pressure, mm Hg
	Coolant Channel Pressure Drop, mm Hg
	Outlet Pressure, mm Hg
	Flow Rate, Scfm
	Inlet Temperature, F
	Outlet Temperature, F

Table 5 - continued

Cooling Air	Heat Transfer Coefficient, $Btu/Hr/Ft^2/F$ Fin Efficiency, % Flow Rate Over Cells in Circuit, Scfm In Circuit Outlet Temperature, F Cooling Blower Outlet Pressure, mm Hg Cooling Blower Outlet Flow Rate, Scfm Cooling Blower Outlet Temperature, F Cooling Damper Pressure Drop, mm Hg Minimum Leakage Flow Rate, Scfm
Actual Volumetric Flow Rates	Modules Cathode Air Inlet, Cfm Modules Cathode Air Outlet, Cfm Modules H_2 Inlet, Cfm Modules H_2-CO_2 Outlet, Cfm Modules Cooling Air Inlet, Cfm Modules Cooling Air Outlet, Cfm Modules Cooling Air Outlet From Cells in Circuit, Cfm Process Air Inlet, Cfm Process Air Outlet, Cfm System H_2 Inlet, Cfm Process Air Plenum Bypass Outlet, Cfm Cathode Air Blowers Outlet, Cfm Cooling Blowers Outlet, Cfm Cooling Dampers Outlet, Cfm
Equivalent Weight	Cooling Blower Power, Watt Cathode Blower Power, Watt Primary Controller Power, Watt Emergency Controller Power, Watt Data Acquisition Unit Power, Watt Total System Power, Watt Total Heat Rejection, Btu/Hr Power Consumption Penalty Weight, Lb Heat Rejection Penalty Weight, Lb Water Vapor Rejection Penalty Weight, Lb O_2 Consumption Penalty Weight, Lb Hardware Weight, Lb Total Equivalent Weight, Lb

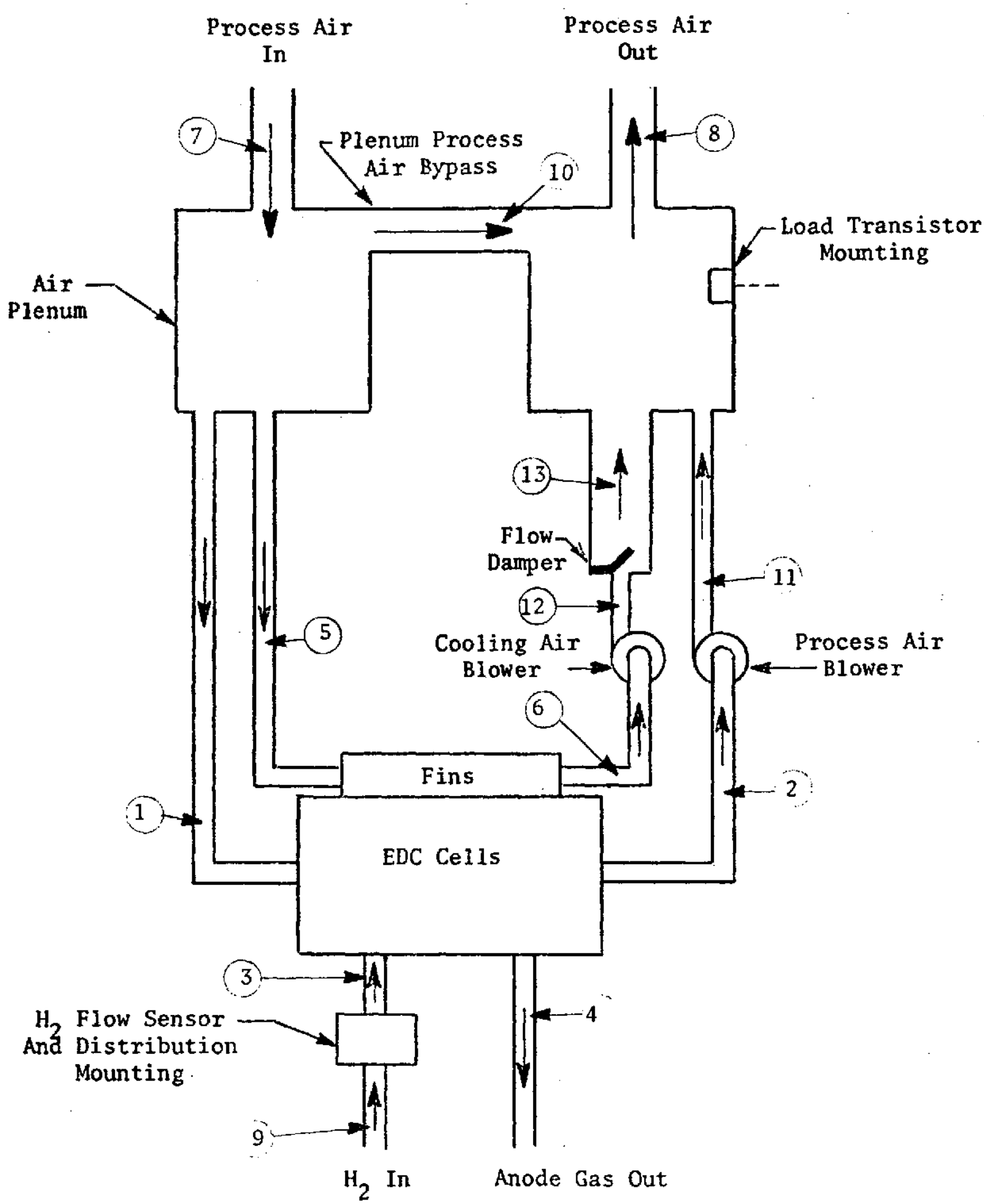

FIGURE 17 PROCESS STREAM IDENTIFICATION NUMBERS

drop at zero air flow rate. The correlation derived for the pressure drop as a function of cooling air flow rate was

$$\Delta P56 = 0.0101\ V5 + 1.303 \times 10^{-5}\ V5^{2}\text{(a)} \qquad (1)$$

where

$\Delta P56$ = the cooling air pressure drop, mm Hg

V5 = the cooling air flow rate, scfm

Plenum Bypass Pressure Drop. Air that is not drawn through the electrochemical modules or over the cooling fins bypasses the subsystem hardware through the air plenum bypass. A correlation describing the pressure drop as a function of the air plenum bypass flow rate was derived from experimental data. The experimental data was curve-fitted to a general equation describing the pressure drop as a function of the plenum bypass air flow rate squared. The mathematical expression obtained is

$$\Delta P78 = 2.25 \times 10^{-5}\ V10^{2} \qquad (2)$$

where

$\Delta P78$ = the air plenum bypass pressure drop, mm Hg

V10 = the air plenum bypass flow rate, scfm

The pressure drop was expressed as the square of the flow rate because of the high turbulent flow characteristics and the dominance of entrance and exit effects within the plenum bypass. The turbulence and entrance and exit effects both lead to a second power relationship[6,7].

Cooling Air Damper Leakage Pressure Drop. Pressure drop associated with the cooling air dampers occurs when the cooling air blowers are off and cooling air leaks around the dampers. The geometry of the closed dampers is such that a slot flow correlation was indicated. The correlation derived from experimental data is

$$\Delta P1213 = 8.6117 \times 10^{-4}\ V5^{2} \qquad (3)$$

where

$\Delta P1213$ = the cooling air damper pressure drop, mm Hg

V5 = the cooling air flow rate, scfm

The cooling air damper correlation presented only applies when the cooling air blowers are off. The dampers are weighted such that when the cooling air

(a) All variables used in the equation presented in the Model Analyses section use the common engineering units since the equations were derived for direct use in the computer program.

blowers start, the dampers open. The cooling damper leakage pressure drop is assumed to remain constant as the dampers open.

Flow Rate Through the Cooling Air Dampers. When the cooling air blowers are off, it is necessary to determine the cooling air flow rate caused by cooling air damper leakage. Air that is not drawn through the cathode compartments of the EDC cells must either flow through the cooling air dampers or the air plenum bypass during cooling air blower off operation. The air flow division is given by the equation

$$V7 = V10 + V5 + V1 \tag{4}$$

where

$V7$ = the inlet plenum air flow rate, scfm

$V1$ = the process (cathode) air flow rate, scfm

The pressure drop through the air plenum bypass and the cooling air dampers must be equal, and the air flow will therefore divide to obtain the equal pressure drops. The pressure drop equality is given by the equation

$$\Delta P78 = P56 + \Delta P1213 \tag{5}$$

The division of air flow rate between the air plenum bypass and the cooling air cavities can be calculated by solving equations (1-5) simultaneously for V5, given V1 and V7. The resulting equation is

$$V5 = \frac{-QB + [QB^2 - 4(QA)(QC)]^{\frac{1}{2}}}{2QA} \tag{6}$$

where

$$QA = -8.517 \times 10^{-4}$$

$$QB = (4.5 \times 10^{-5})(V7 - V1) + 0.0101$$

$$QC = -2.25 \times 10^{-5} (V7 - V1)^2$$

Substitution of V1, V7, and V5 into equations (2-5) yields V10, $\Delta P78$, $\Delta P56$, and $\Delta P1213$, respectively.

Process Air Inlet Pressure. The process air inlet pressure is calculated after the heat balance is done and all flow rates have been established through the three air passages. The inputs to the math model are the outlet pressure at the plenum as would be specified by the subsystem interfacing downstream of the CS-6. The process air inlet pressure then is equal to the outlet pressure plus the pressure drop across the plenum bypass, as given by the equation

$$P7 = P8 + \Delta P78 \tag{7}$$

where

P7 = the process air inlet pressure, mm Hg

P8 = the process air outlet pressure, mm Hg

EDC Module Pressure Drop. The expression for the process air drawn through the cathode compartment of the EDC cells was derived from experimental data. A general quadratic equation passing through the origin was least squares fit to the experimental data. The equation obtained is

$$\Delta P12 = 0.04877V1 + 0.001903V1^2 \tag{8}$$

where

$\Delta P12$ = the EDC module pressure drop, mm Hg

Process Air Blower Power. The expression for the process air blower power as a function of air flow rate was derived from the experimental data gathered on both blowers. Because of the spike in the power curve caused by the blower speed controller, the total power curve was modeled by three straight line segments. The equations derived were

$$PWRCTB = 2.8V1 + 153.8;\ \text{for } V1 \leq 62 \tag{9}$$

$$PWRCTB = 40V1 - 2150;\ \text{for } 62 < V1 \leq 65 \tag{10}$$

$$PWRCTB = -34V1 + 2660;\ \text{for } 65 < V \leq 70 \tag{11}$$

where

PWRCTB = the process (cathode) air blower power, W

Cooling Air Blower Power. The cooling air blower power is a function of the cooling air flow rate and the air plenum bypass pressure drop. As air plenum bypass pressure drop increases (higher bypass flow rates), cooling air blower power was observed to decrease for a given cooling requirement. This decrease is caused by the increased leakage flow rate through the cooling air dampers at the higher plenum bypass pressure drop. Cooling blower power as a function of air flow rate was measured experimentally for two air plenum pressure drops. The correlations obtained through curve fitting for the two power curves are given by the equations

$$PWH = 410 - 0.00396\ (V5 - 368)^2 \tag{12}$$

$$PWL = 410 - 0.00178\ (V5 - 306)^2 \tag{13}$$

where

PWH = the power at $\Delta P78$ of 1.25 in water, W

PWL = the power at $\Delta P78$ of 0.05 in water, W

An empirically derived interpolation parameter, TR, is used to calculate the cooling air blower power at different plenum bypass pressure drops. The interpolation equation obtained was

$$PWRCLB = (TR)(PWH) + (1-TR)(PWL) \tag{14}$$

where

PWRCLB = the cooling blower power, W

$$TR = \left(\frac{\Delta P78}{2.4297} + 0.0385\right)^{A} \tag{15}$$

$$A = 0.128 + 0.0546 \Delta P78 \tag{16}$$

Process Hydrogen Correlations

Correlations for the process H_2 stream were required to calculate the EDC module H_2 pressure drop as a function of H_2 flow rate, H_2 pressure drop across the H_2 flow and sensor distribution mounting, and to upgrade the anode gas outlet dew point correlation used in the EDC cell math model.

EDC Module Hydrogen Pressure Drop. The pressure drop through the anode compartment of the 16 series connected EDC cells as a function of H_2 flow rate was derived from experimental data. The two equations describing the anode compartment pressure drop are

$$\Delta P34 = 0.3822 \left(\frac{14.1}{P4}\right)^{0.8} V3; \text{ for } V3 < 22 \tag{17}$$

$$\Delta P34 = \left(\frac{14.1}{P4}\right)^{0.8} [8.3183 + 0.4187 (V3 - 21.5801)^{1.75}] \text{ for } V3 \geq 22 \tag{18}$$

where

$\Delta P34$ = the anode pressure drop, mm Hg

V3 = the H_2 flow rate, slpm

P4 = the anode gas outlet pressure, psia

Hydrogen Distribution Mounting Pressure Drop. The pressure drop associated with H_2 flow through the H_2 distribution mounting was derived from experimental data. The two equations obtained are

$$\Delta P93 = 10.64 \left(\frac{14.1}{P3}\right)^{0.8} V3; \text{ for } V3 \leq 6.2 \tag{19}$$

$$\Delta P93 = \left(\frac{14.1}{P3}\right)^{0.8} \left[35.14V3 - 195.25 + e^{(7.75-0.6537V3)}\right] \text{ ; for}$$

$$V3 > 6.2 \qquad (20)$$

where

$\Delta P93$ = the H_2 distribution mounting pressure drop, mm Hg

$P3$ = module H_2 inlet pressure, psia

Anode Gas Dew Point Correlation. The anode gas dew point can be estimated from the module temperature and the inlet and outlet cathode air dew points. The correlation derived from experimental data is given by the equation

$$DW4 = 0.77 \left(\frac{DW1 + DW2}{2}\right) + 0.23\ (T2) \qquad (21)$$

where

DW4 = anode gas outlet dew point, F

DW1 = cathode air inlet dew point, F

DW2 = cathode air outlet dew point, F

T2 = module temperature, F

The data that was used to derive the correlation is presented in Table 6.

EDC Module Correlations

The EDC cell and module math model previously developed required upgrading in three areas: the module temperature and heat balance, the effect of process (cathode) air flow rate on CO_2 removal efficiency, and the effect of cell moisture conditions on CO_2 removal efficiency.

Module Temperature Correlation. The process (cathode) air out temperature, defined as the module temperature, is controlled to a set level above the process air inlet dew point temperature. The module temperature is maintained by controlling the cooling air blower speed to give the desired process air outlet to inlet air dew point temperature differential. Four conditions exist which prevent the module temperature control from maintaining the temperature differential:

1. Insufficient blower capacity.
2. Excessive cooling air damper leakage.
3. Insufficient cooling air temperature.
4. Insufficient module heat generation.

TABLE 6 ANODE GAS OUTLET DEW POINT TEMPERATURE CORRELATION DATA[a]

Inlet Cathode Air Dew Point Temperature, K	280.9	281.4	280.3	281.4
Inlet Cathode Air Dew Point Temperature, F	46.0	47.0	45.0	47.0
Outlet Cathode Air Dew Point Temperature, K	284.2	284.0	283.8	284.3
Outlet Cathode Air Dew Point Temperature, F	52.0	51.6	50.0	52.2
Outlet Cathode Air Temperature, K	299.2	299.7	297.0	299.5
Outlet Cathode Air Temperature, F	79.0	79.8	75.0	79.5
Outlet Anode Gas Dew Point Temperature				
Observed, K	286.4	286.7	285.2	286.8
Observed, F	56.0	56.5	53.8	56.6
Calculated, K	286.4	286.6	285.2	286.7
Calculated, F	55.9	56.3	53.8	56.5

(a) CS-6 anode gas dew point data obtained during math model testing.

Should one of these four conditions occur, it is necessary to calculate what temperature the module will reach with the cooling air blowers in operating range (off to maximum capacity). The new module temperature is iteratively determined by solving the heat balance equations for cell voltage, heat generated, fin heat transfer coefficient, fin efficiency, heat removal by the gas streams, and the log mean temperature driving force for heat removal until the following two equations are satisfied:

$$\mathrm{DTREQ} = \mathrm{DTAVA} \tag{22}$$

$$\mathrm{HEATLOAD} = \Delta H_{air} + \Delta H_{H_2} + \Delta H_{cool} \tag{23}$$

where

DTREQ = the required log mean ΔT driving force

DTAVA = the available log mean ΔT driving force

HEATLOAD = the heat generated

ΔH_{air} = the heat removed by the process (cathode) air

ΔH_{H_2} = the heat removed by the anode gas

ΔH_{cool} = the heat removed by the cooling air

Air Flow Correlation. Experimental data indicated that the correlation originally developed to predict CO_2 removal as a function of process (cathode) air flow rate required upgrading. The air flow correlation was therefore upgraded based on CS-6 performance data[2]. The new correlation that was obtained is given by the equations

$$\mathrm{PA} = (pCO_2)\ (V1/0.44N)^{f(pCO_2)} \tag{24}$$

$$f(pCO_2) = [1 + 0.84\ (pCO_2)]e^{-0.84(pCO_2)} \tag{25}$$

where

PA = the normalized pCO_2 for air flow rate, mm Hg

N = the number of EDC cells

The normalized pCO_2, PA, is then used in place of the actual pCO_2 in the CO_2 removal efficiency correlations.

Moisture Balance-Carbon Dioxide Removal Efficiency Correlation. The original EDC cell math model assumed that moisture was maintained within a preferred operating range. The CO_2 removal efficiency correlation did not account for changes in CO_2 removal efficiency for moisture conditions outside the preferred range. Moisture conditions outside the preferred range occur since the module temperature to process air inlet dew point temperature differential (DELT1) control does not vary with changes in current and air flow rate. Hardware limitations in controlling DELT1 and improper setting of DELT1 also cause nonpreferred moisture balance conditions to occur. A correlation was therefore developed to account for changes in CO_2 removal efficiency as a function of moisture balance. The correlations derived from experimental data[5] are given by the equation

$$TI^1 = TI\ [1 + 0.03536(DELT1 - 18.33)] \tag{26}$$

where

TI^1 = the Transfer Index corrected for moisture balance

TI = the noncorrected Transfer Index

The data that was used to derive the correlation is presented in Figure 18.

Computer Program

The CS-6 Base Program consists of a main program and eight subroutines. The main program manages input and output, directs calculation of heat and mass balances, checks for cooling and cathode air blower operation within range, checks for sufficient H_2 flow, checks plenum bypass flow, checks cell moisture conditions within tolerance, completes all stream definitions, and calculates total subsystem equivalent weight. The subroutines are called by the main program and by each other to calculate water vapor pressure from dew point temperature (PHTO), to calculate the dew point temperature from water vapor pressure (DEWT), to calculate TI (TICOR), to find the root of a function (ROOT), to calculate module temperature offset (TDRIFT), to calculate required and actual module cooling air temperature drops dependent upon module temperature (ERT1), to calculate required and actual module-cooling air temperature drops dependent upon cooling air flow rate (ERT), and to check input variable ranges(T).

Program Description

A detailed description of the program is presented in the main program flow chart and the subroutine flow charts, Appendix A. The program can be represented by ten major divisions for simplicity.

1. Read in and playback input data.

2. Check input ranges.

3. Check for sufficient H_2 flow and cathode blowers within range.

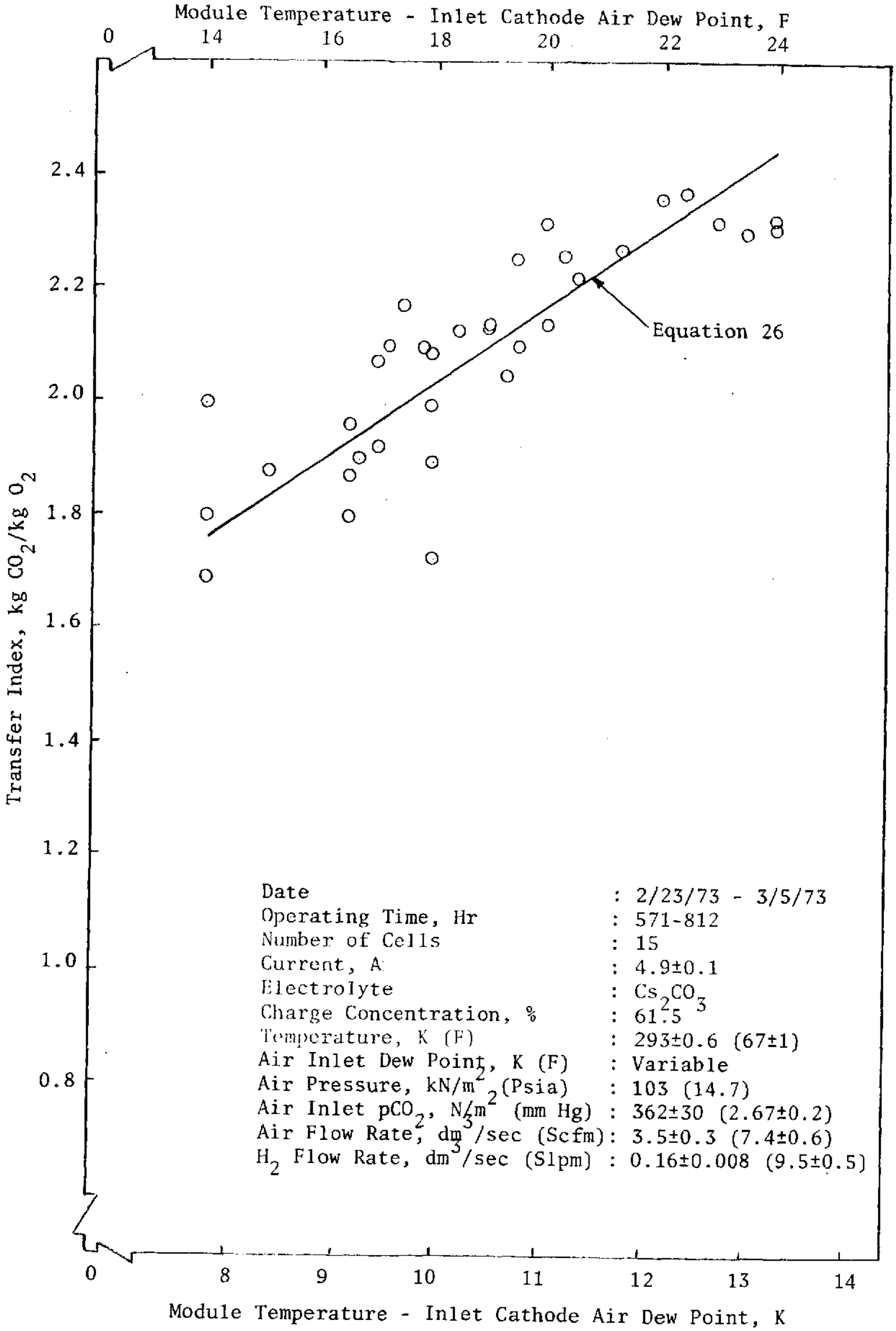

FIGURE 18 EFFECT OF MOISTURE CONDITIONS ON TRANSFER INDEX

4. Perform the heat balance including iterative solution governing module's heat load, cooling fin efficiency and heat transfer coefficient, cooling air flow rate, and module temperature.

5. Check the plenum bypass flow rate.

6. Calculate only stream parameters required for moisture balance checks.

7. Check module moisture conditions.

8. Complete all stream definitions.

9. Calculate subsystem equivalent weights.

10. Output results.

Also contained in Appendix A are the CS-6 Base Program Listing, the checks and messages performed by the program, and the nomenclature and units' definitions.

Program Assumptions

The following assumptions were made in developing the CS-6 Base Program:

1. Gas pressures are governed by the Ideal Gas Law and Dalton's Law.

2. Inlet H_2 flow rate greater than 1.3 times the stoichiometric amount does not affect TI.

3. Cabin air contains only N_2, O_2, CO_2, and water in signficant amounts.

4. Heat losses, leaks, and pressure drops in intercomponent lines are negligible.

5. The number of allowable cells in CS-6 is 90-96.

6. Pressure drops depend upon standard flow rates only, except in the H_2 sensor block and anode passages, where absolute pressure may differ significantly from atmospheric.

7. Transfer Index is proportional to a power of cathode air flow which approaches 1 as pCO_2 approaches 0, and diminishes to 0 as pCO_2 increases.

8. The dependence of TI upon moisture conditions is approximated by a linear function of the difference between module temperature and inlet cathode air dew point temperature.

9. Steady-state exists in the subsystem.

10. At least 5% of the inlet process air must pass through the plenum bypass to prevent backmixing of the outlet stream with the inlet stream.

11. The outlet H_2 dew point temperature is approximated by a weighted average of the module temperature, the inlet cathode air dew point, and the outlet cathode air dew point. Cathode air removes the remaining moisture produced.

12. Cooling air dampers remain closed when the cooling blowers are off.

13. When open, cooling dampers' pressure drop remains constant.

14. Heat loss of modules and blowers to the ambient air is negligible.

15. Primary controller, emergency controller, and data acquisition unit (DAU) reject waste heat only to the ambient.

16. Activation of valves is brief (less than one second) and adds no significant power penalty.

17. Cooling air blower power depends upon flow rate reaching a plateau and declining slightly at maximum flow. At lower flow rates, the power depends increasingly upon the plenum bypass pressure drop.

18. Cathode air blower power depends upon flow rate. The prediction range does not extend to very low flow rates, and the effect of differential pressure is neglected.

19. Cooling fin efficiency and heat transfer coefficient depend on cooling air flow rate only.

20. Differences between cells, modules, and sections are insignificant.

21. Inlet cooling air and inlet cathode air have the same temperature and pressure.

Program Features

The following features were incorporated into the CS-6 Base Program.

1. The program checks each set of input data to insure that each parameter is within its prediction range.

2. Cooling air flow rate is calculated for the set point module temperature. Under certain conditions, however, the subsystem hardware is unable to provide the required cooling air flow rate to control module temperature at the set point. These conditions are (1) insufficient blower capacity, (2) excessive cooling damper leakage, (3) insufficient cooling air temperature, and (4) insufficient module heat generation. For these conditions program logic calculates the temperature to which the modules would drift with the cooling blowers in range, and proceeds.

3. All significant pressure drops are calculated based on flow rates and, where appropriate, absolute pressure.

4. Inlet stream pressures are calculated based on outlet stream pressures and system pressure drops.

5. All significant component power consumptions and heat rejections are calculated. All intermediate streams are completely specified regarding temperature, pressure, composition, and flow rate.

6. Total subsystem equivalent weight is calculated from adjustable penalty factors for heat rejection, power consumption, O_2 consumption, and water rejection.

7. Input data may be entered directly from a terminal or from a previously prepared data file for convenience when a large number of problems are to be done during the same run.

Model Results

Sample problems were run using the CS-6 Base Program to verify the model's predictability for subsequent incorporation into the CS-6 Cabin pCO_2 Simulation Program. Output data from the program was checked against experimental data and the model upgraded throughout the development phase. Several sample outputs are presented in Appendix B. The results corresponded well to experimental data as expected since the major math model correlations (i.e., CO_2 removal efficiency, blower power, gas stream pressure drop, etc.) are empirically based.

CS-6 CABIN pCO_2 SIMULATION PROGRAM

The CS-6 Cabin pCO_2 Simulation Program is the computer program that was developed to simulate the steady-state spacecraft cabin pCO_2 profile resulting from the interaction of a repeating daily metabolic CO_2 generation profile and the CS-6 as the spacecraft CCS for a given cabin volume.

The program calculates and outputs cabin pCO_2, CO_2 removal rate and efficiency, cell voltage, subsystem power requirements, subsystem equivalent weight, and other subsystem parameters as a function of time for a given CO_2 generation profile. A list of the input variable ranges and their units are presented in Table 7. The complete list of input and output variables and their units are presented in Table 8.

Model Analysis

The specific functions performed by the pCO_2 simulation program are to define Mode B (if required) from the input parameters and perform the integration over each time interval to calculate the change in cabin pCO_2 (for both Mode A and Mode B).

Mode B Definition

A typical Mode B control scheme is presented in Figure 19. Current and air flow vary linearly with cabin pCO_2. Two sets of input data are used to define Mode B; the minimum and maximum pCO_2 levels and their corresponding current and air

TABLE 7 CS-6 CABIN pCO_2 SIMULATION PROGRAM
INPUT VARIABLE RANGES

Cabin Atmosphere	
Total Pressure, PØPSA	13.7-15.7 Psia
pCO_2, PCØ	0.0001-10 mm Hg
pO_2, POØPSA	2-4 Psia
Temperature, TØ	44-80F
Volume, VOLUME	10^2-10^5 Ft^3
Process Air Outlet	
Total Pressure, P8PSA	13.7-15.7 Psia
Process Air Inlet	
Temperature, T7	44-80F
Flow Rate, V7	0-600 Scfm[(a)]
Dew Point Temperature, DW7	41-70F
Anode H_2/CO_2 Outlet	
Total Pressure, P4PSA	14.8-21.2 Psia
System H_2 Inlet	
Temperature, T9	65-75F
Flow Rate, V9SL	0-18 Scfm[(a)]
Dew Point Temperature, DW9	10-75F
Modules	
Number in Circuit, N	90-96
Current, I	2.44-9.76 A
DELT1[(b)]	10-25F
Cathode Air Flow Rate, V1	5.0-76.8 Scfm (96 cells)
Penalty Weight Factors	
Power, PWPEN	0-2 Lb/Watt
Heat Rejection to Ambient, HTPEN	0-2 Lb/Btu/Hr
Water Vapor Rejection to Ambient, H2OPEN	0-500 Lb/Lb H_2O/Hr
Oxygen Consumption, OXPEN	0-3000 Lb/Lb O_2/Hr
Program Control	
KMODE[(c)]	0-1
NFLAG[(d)]	0-1
Minimum Current, BK(1)	2.44-9.76 A

(a) Reference conditions for standard flow units: 70F, 14.7 Psia
(b) DELT1 = Module temperature - cathode air inlet dew point temperature
(c) KMODE = 0 Mode A
1 Mode B
(d) NFLAG = 0 Out of tolerance moisture conditions do not stop program.
1 Out of tolerance moisture conditions do stop program.

-continued-

Table 7 - continued

pCO_2 for Minimum Current, BK(2)	0.0001-10 mm Hg
pCO_2 for Maximum Current, BK(3)	0.0001-10 mm Hg
Maximum Current, BK(4)	2.44-9.76 A
Minimum Cathode Air Flow Rate, BK(5)	5.0-76.8 Scfm
pCO_2 at Minimum Cathode Air Flow Rate, BK(6)	0.0001-10 mm Hg
pCO_2 at Maximum Cathode Air Flow Rate, BK(7)	0.0001-10 mm Hg
Maximum Cathode Air Flow Rate, BK(8)	5.0-76.8
Number of Days to be Simulated, DAYS	0-10 Days
Integration Time Increment, DT	1-15 Minutes[a]
Output Table Time Increment, DPRINT	1-100 Minutes[b]

(a) DT must be chosen so that the length of each time step in the CO_2 generation rate table is a whole multiple of DT.
(b) DPRINT must be a whole multiple of DT.

TABLE 8 CS-6 CABIN pCO_2 SIMULATION PROGRAM INPUT AND OUTPUT VARIABLES

Input Variables	
Cabin Atmosphere	Total Pressure, Psia pCO_2, mm Hg pO_2, Psia Temperature, F Volume, Ft^3
Process Air Outlet	Total Pressure, Psia
Process Air Inlet	Temperature, F Flow Rate, Scfm Dew Point Temperature, F
Anode H_2/CO_2 Outlet	Total Pressure, Psia
Anode H_2 Inlet	Temperature, F Flow Rate, Slpm Dew Point Temperature, F
Modules	Number of Cells in Circuit Current, A DELT1, F Cathode Air Flow Rate, Scfm
Penalty Weight Factors	Power Consumption, Lb/Watt Heat Rejection, Lb/Btu/Hr Water Vapor Rejection, Lb/Lb/Hr O_2 Consumption, Lb/Lb/Hr
Control	KMODE 0 = Mode A, 1 = Mode B NFLAG 0 = ignore out-of-tolerance moisture conditions 1 = abort for out-of-tolerance moisture conditions
Mode B	Minimum Current, A pCO_2 for Minimum Current, mm Hg pCO_2 for Maximum Current, mm Hg Maximum Current, A Minimum Cathode Airflow, Scfm pCO_2 for Minimum Airflow, mm Hg pCO_2 for Maximum Airflow, mm Hg Maximum Cathode Airflow, Scfm Maximum Number of Days to be Integrated, Day Integration Increment, Min Printing Increment, Min
Output Variables	
Control	Preferred Value of DELT1[(a)], F

-continued-

(a) DELT1 = Module Temperature - Inlet Cathode Air Dew Point Temperature

Table 8 - continued

Module	Transfer Index, Lb CO_2/Lb O_2
	Transfer Efficiency, %
	Cell Voltage, V
	Module Voltage, V
	CO_2 Removal Rate, Lb/Hr
	O_2 Consumption Rate, Lb/Hr
	H_2 Consumption Rate, Lb/Hr
	Water Production Rate, Lb/Hr
	Current Density, A/Ft^2
	Heat Load Modules, Btu/Hr
	Power Production of Modules, Watt
Cathode Air Inlet	Total Pressure, mm Hg
	pCO_2, mm Hg
	pH_2O, mm Hg
	CO_2 Flow Rate, Lb/Hr
	Water Flow Rate, Lb/Hr
	CO_2 Flow Rate, Scfm
	Water Flow Rate, Scfm
	O_2 Flow Rate, Scfm
	N_2 Flow Rate, Scfm
	Temperature, F
	Dew Point Temperature, F
	Relative Humidity, %
Cathode Air Outlet	Total Pressure, mm Hg
	Module Cathode Air Pressure Drop, mm Hg
	pCO_2, mm Hg
	pH_2O, mm Hg
	Total Flow Rate, Scfm
	CO_2 Flow Rate, Scfm
	Water Flow Rate, Scfm
	O_2 Flow Rate, Scfm
	N_2 Flow Rate, Scfm
	CO_2 Flow Rate, Lb/Hr
	Water Flow Rate, Lb/Hr
	Temperature, F
	Dew Point Temperature, F
	Relative Humidity, %
	Cathode Air Blower Outlet Total Pressure, mm Hg
	Cathode Air Blower Outlet Flow Rate, Scfm
	Cathode Air Blower Outlet Temperature, F
Process Air Inlet	Total Pressure, mm Hg
	pH_2O, mm Hg
	pN_2, mm Hg
	CO_2 Flow Rate, Scfm
	Water Flow Rate, Scfm

Table 8 - continued

	O_2 Flow Rate, Scfm
	N_2 Flow Rate, Scfm
	Dew Point Temperature, F
	Relative Humidity, %
Process Air Outlet	Total Pressure, mm Hg
	pCO_2, mm Hg
	Plenum Bypass Flow Rate, Scfm
	Plenum Bypass Pressure Drop, mm Hg
	Total Flow Rate, Scfm
	Water Flow Rate, Scfm
	CO_2 Flow Rate, Scfm
	O_2 Flow Rate, Scfm
	pH_2O, mm Hg
	Temperature, F
	Dew Point Temperature, F
	Relative Humidity, %
H_2 Inlet	Total Pressure, mm Hg
	Water Vapor Pressure, mm Hg
	Distribution Block Pressure and Drop, mm Hg
	Module Inlet Total Pressure, mm Hg
	Module Inlet pH_2O, mm Hg
	Module Inlet pH_2, mm Hg
	Total Flow Rate, Scfm
	H_2 Flow Rate, Scfm
	Water Flow Rate, Scfm
	H_2 Flow Rate, Lb/Hr
	Minimum Required Flow Rate, Slpm
H_2 Outlet	Total Pressure, mm Hg
	Module Anode Gas Pressure Drop, mm Hg
	Water Vapor Pressure, mm Hg
	Flow Rate, Scfm
	CO_2 Flow Rate, Scfm
	H_2 Flow Rate, Scfm
	Water Flow Rate, Scfm
	Flow Rate, Slpm
	CO_2 Flow Rate, Slpm
	H_2 Flow Rate, Slpm
	Total Flow Rate, Lb/Hr
	CO_2 Flow Rate, Lb/Hr
	H_2 Flow Rate, Lb/Hr
	Water Flow Rate, Lb/Hr
	Dew Point Temperature, F
	CO_2-H_2 Weight, Lb CO_2/Lb H_2
	H_2-CO_2 Volume Ratio, Slpm H_2/Slpm CO_2

Table 8 - continued

Heat Balance, Modules	Modules Heat Load, Btu/Hr Cathode Air Heat Pickup, Btu/Hr Anode Gas Heat Pickup, Btu/Hr Cooling Air Heat Pickup, Btu/Hr
Cooling Air	Inlet Pressure, mm Hg Coolant Channel Pressure Drop, mm Hg Outlet Pressure, mm Hg Flow Rate, Scfm Inlet Temperature, F Outlet Temperature, F Heat Transfer Coefficient, $Btu/Hr/Ft^2/F$ Fin Efficiency, % Flow Rate Over Cells in Circuit, Scfm In Circuit Outlet Temperature, F Cooling Blower Outlet Pressure, mm Hg Cooling Blower Outlet Flow Rate, Scfm Cooling Blower Outlet Temperature, F Cooling Damper Pressure Drop, mm Hg Minimum Leakage Flow Rate, Scfm
Actual Volumetric Flow Rates	Modules Cathode Air Inlet, Cfm Modules Cathode Air Outlet, Cfm Modules H_2 Inlet, Cfm Modules H_2-CO_2 Outlet, Cfm Modules Cooling Air Inlet, Cfm Modules Cooling Air Outlet, Cfm Modules Cooling Air Outlet From Cells in Circuit, Cfm Process Air Inlet, Cfm Process Air Outlet, Cfm System H_2 Inlet, Cfm Process Air Plenum Bypass Outlet, Cfm Cathode Air Blowers Outlet, Cfm Cooling Blowers Outlet, Cfm Cooling Dampers Outlet, Cfm
Equivalent Weight	Cooling Blower Power, Watt Cathode Blower Power, Watt Primary Controller Power, Watt Emergency Controller Power, Watt Data Acquisition Unit Power, Watt Total System Power, Watt Total Heat Rejection, Btu/Hr Power Consumption Penalty Weight, Lb Heat Rejection Penalty Weight, Lb Water Vapor Rejection Penalty Weight, Lb O_2 Consumption Penalty Weight, Lb Hardware Weight, Lb Total Equivalent Weight, Lb

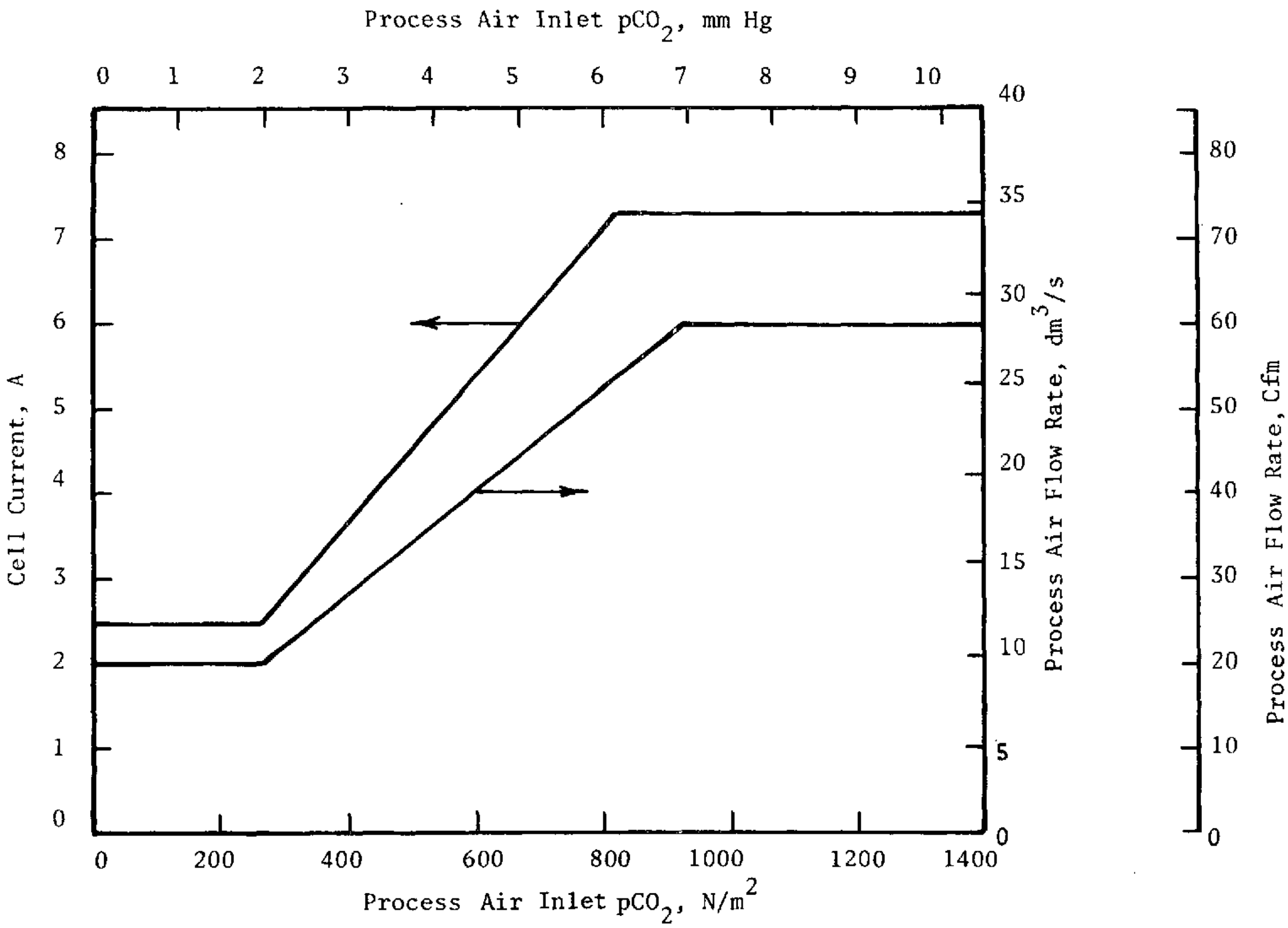

FIGURE 19 CONTROL MODE B (TYPICAL)

flow rates. The program takes the two sets of inputs, determines the slope and intercept for each set of inputs, and defines the equations for current and air flow as a function of pCO_2. These equations are then used in the pCO_2 integration when control Mode B is requested.

Cabin pCO_2 Integration

To obtain the cabin pCO_2 as a function of time, the main program performs a mass balance on CO_2 in the cabin for each of the integration intervals. Each mass balance yields the pCO_2 value at the end of the interval. The pCO_2 at the end of the interval depends upon the average net CO_2 removal rate during the interval, but the average removal rate depends upon the pCO_2 at the end of the interval. Neither value is known initially, therefore an iterative solution is necessary.

The equations which must be satisfied in the mass balance are:

$$P(t) = P(t-\Delta t) + \tfrac{1}{2}\left(\frac{dp}{dt}\bigg|_{t} + \frac{dp}{dt}\bigg|_{t-\Delta t}\right) \Delta t \qquad (27)$$

$$\frac{dp}{dt}\bigg|_{t} = k \quad [G(t) - R(P(t))] \qquad (28)$$

where

P = cabin pCO_2

t = time

Δt = integration increment

k = proportionality constant between net removal rate of CO_2 and cabin pCO_2

G = CO_2 generation rate, a function of time only, calculated by the main program

R = CO_2 removal rate, a function of cabin pCO_2 only, calculated by the CS-6 BASE subroutine

The use of the arithmetic average derivative in Equation 27 is the same approximation used in Simpson's Rule Integration. The error vanishes when the function P(t) is parabolic over the interval.

All variables are known for time $t-\Delta t$ when the integration begins. An approximation for P(t) is substituted into Equation 28 and solved using the CS-6 BASE subroutine. The result is substituted into Equation 27 to recalculate P(t). The correct P(t) is found when the approximate and the recalculated values of P(t) agree. For the first approximation labeled "1" in Figure 20, it is assumed that P(t) equals $P(t - \Delta t)$.

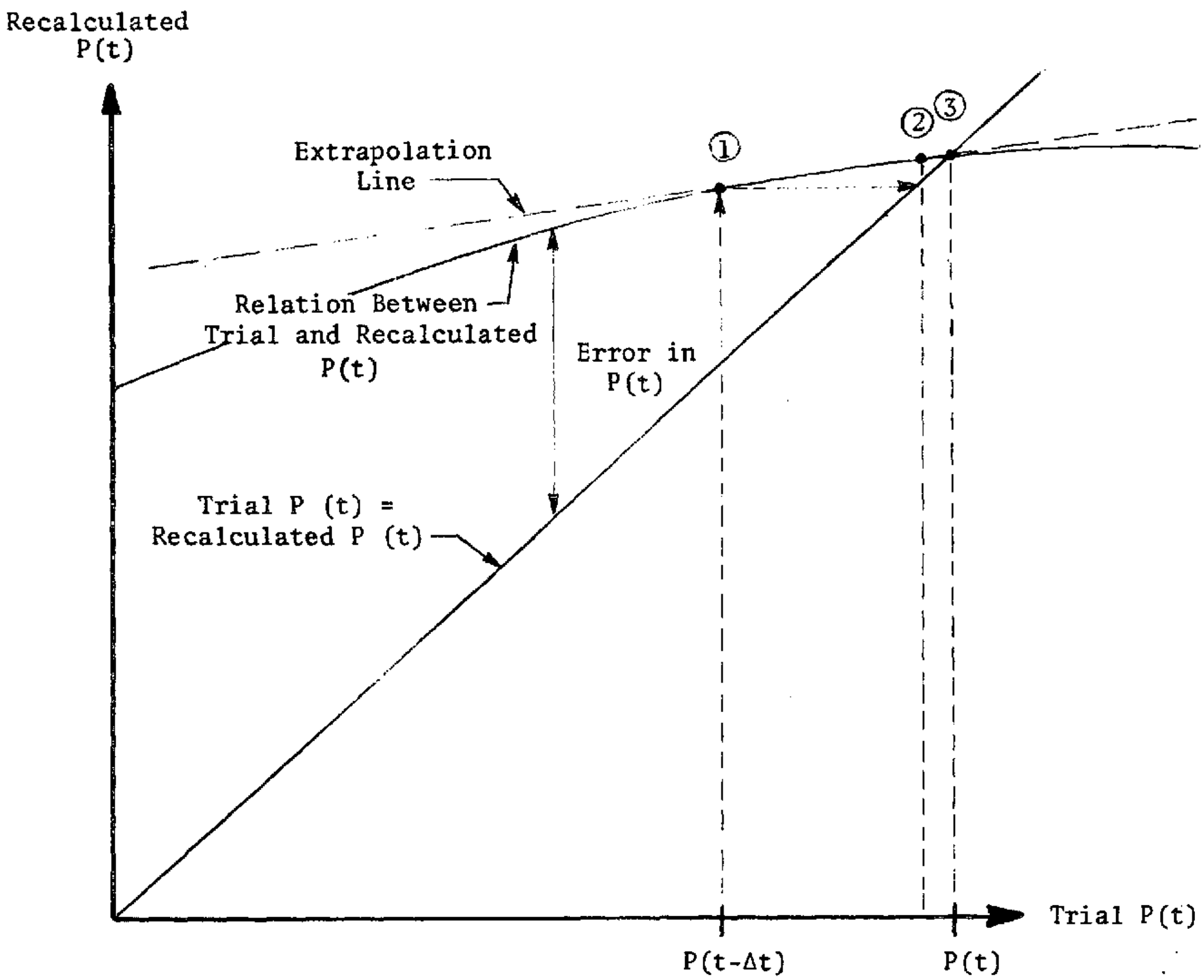

FIGURE 20 GRAPHIC REPRESENTATION OF CONVERGENCE SCHEME

The first trial value is substituted into Equations 27 and 28, giving a recalculated value. This value is then used as the second trial value of P(t), labeled "2" in Figure 20. The relation between trial and recalculated P(t) is close to linear when the time increments are 15 minutes or less. The final P value, labeled "3" in Figure 20, is at the intersection of the secant through points 1 and 2, and the 45 degree line.

The BASE subroutine is called for the second and third values of P only. It is not necessary for the first trial, which assumes constant pCO_2, since the CO_2 removal rate would then also be constant. Each integration increment requires only two subroutine calls with the convergence scheme used, compared to ten or more with schemes such as interval halving.

Computer Program

The CS-6 Cabin pCO_2 Simulation Program consists of the main program and a number of subroutines. The main program manages input and output and performs integration of net CO_2 removal to calculate the cabin pCO_2 profile. The BASE subroutine (the CS-6 Base Program adapted with minor modifications) provides all the CS-6 parameters to the main program, including CO_2 removal rate. Subroutines are utilized primarily by the BASE subroutine to relate water vapor pressure and dew point temperature, to calculate the CO_2 Transfer Index (TI), to find the root of a function, to calculate temperatures and flow rates, to satisfy subsystem heat balance, to check input parameters against their allowable ranges, and to calculate current and cathode air flow rate for Mode B CS-6 operation.

Program Description

A detailed description of the CS-6 Cabin pCO_2 Simulation Program is presented in the main program flow chart and the subroutine flow charts, Appendix C. The program can be divided into 14 major subdivisions for simplicity.

1. Determine input/output devices.
2. Read and write problem identifier.
3. Read in and print out (if desired) CO_2 generation table.
4. Read inputs for CS-6 BASE subroutine, Mode B parameters, integration and print out parameters.
5. Determine whether table describing CS-6 at time zero is to be printed, and input subscripts for selected variables to be printed as they vary with time.
6. Calculate Mode B parameters.
7. Print out input data.
8. Check inputs and print names of any that are outside the prediction ranges.

9. Print description at time zero if desired.

10. Print headings for table.

11. Call BASE to perform pCO_2 integration over one or more intervals until printing interval is reached.

12. Print a line in the table.

13. Continue from Step 11 unless it is the end of the day.

14. Continue from Step 2 if steady-state has been reached or if the maximum number of days has been integrated, otherwise continue from Step 10 to integrate pCO_2 for an additional day.

Appendix C also contains the program listing, program checks and messages, nomenclature and units, and the key to select output variables.

Program Assumptions

The following assumptions were made in the development of the CS-6 Cabin pCO_2 Simulation Program.

1. The CO_2 generation profile is a step function of time only.

2. Each step in the CO_2 generation profile is an integer number of minutes.

3. Module set point temperature, an input, does not change during the day. It is not a function of current density or air flow in either Mode A or B.

4. Cabin air is uniform in composition at any time.

5. The Ideal Gas Law applies to the cabin air.

6. The cabin air contains O_2, N_2, CO_2, and water vapor only.

7. Cabin pH_2O, pO_2, and total pressure are constant; pN_2 and pCO_2 vary.

8. The pCO_2 integration time increment, an integer number of minutes, is chosen so that each CO_2 generation step contains an integer number of increments.

9. In Mode B operation, current density and cathode air flow are linear functions of cabin pCO_2 but are bounded by minimum and maximum values.

10. The graph of cabin pCO_2 versus time can be represented by a series of parabolic segments.

Program Features

The following features were incorporated into the CS-6 Cabin pCO_2 Simulation Program:

1. The input items are checked by the program to insure that all are within the prediction ranges.

2. Input may be entered directly from a terminal to take full advantage of operator-program interaction, or from a previously prepared data file for convenience when a large number of runs are to be done at once.

3. Output may be printed directly at the terminal or written in one or more data files for convenience when a large amount of data is involved.

4. A program option allows a table containing all subsystem parameters, both constant and time dependent, to be either printed or omitted at time zero of the simulation.

5. Any number of the subsystem parameters may be selected for printing as they vary at simulated time intervals.

6. The pCO_2 integration performed by the main program combines maximum usage of past values of pCO_2 with an interpolation algorithm so that the BASE subroutine is required only twice during each simulated time interval. The first time, only enough of the BASE subroutine is executed to yield a trial CO_2 removal rate and check for achievement of steady-state in the CS-6. The second call of the BASE subroutine is extended only enough to calculate the final CO_2 removal rate, the other selected subsystem parameters, and to verify steady-state in the CS-6. These techniques have caused the calculation portion of the program to consume less computing time than the printing of results. Integration accuracy is four significant figures, minimum.

Model Results

The CS-6 Cabin pCO_2 Simulation Program was used to predict the cabin pCO_2 profile and selected CS-6 performance parameters for control Modes A and B. The CO_2 generation profile used for the runs is presented in Figure 21. Sample outputs for the pCO_2 Simulation Program are presented in Appendix D.

Sample cases for control Mode A were run to obtain the steady-state pCO_2 profile that would result, given initial cabin pCO_2 levels of 0 and 1333 N/m^2 (0 and 10 mm Hg). The results of three typical runs are presented in Figures 22, 23, and 24 for 4.88A, Mode A (1), 3.66A, Mode A (2), and 7.32A, Mode A (3), respectively. The remaining input parameters are presented in Table 9. Similar sample cases for control Mode B were run for initial pCO_2 levels of 0 and 1333 N/m^2 (0 and 10 mm Hg). The pCO_2 profiles for four typical sets of Mode B parameters (Table 10) are presented in Figures 25 through 28. The remaining Mode B inputs are presented in Table 11.

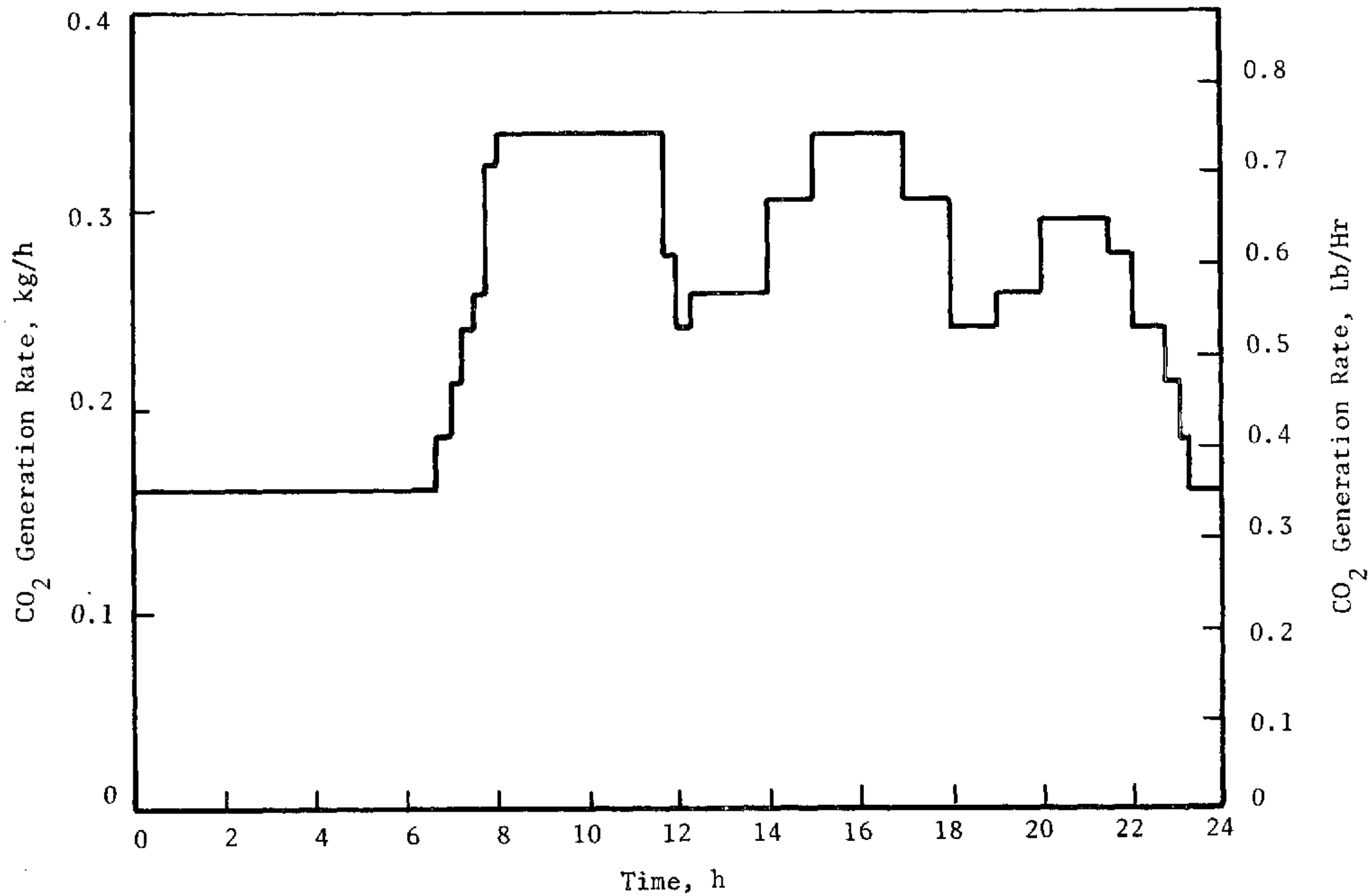

FIGURE 21 CABIN CO_2 GENERATION RATE PROFILE

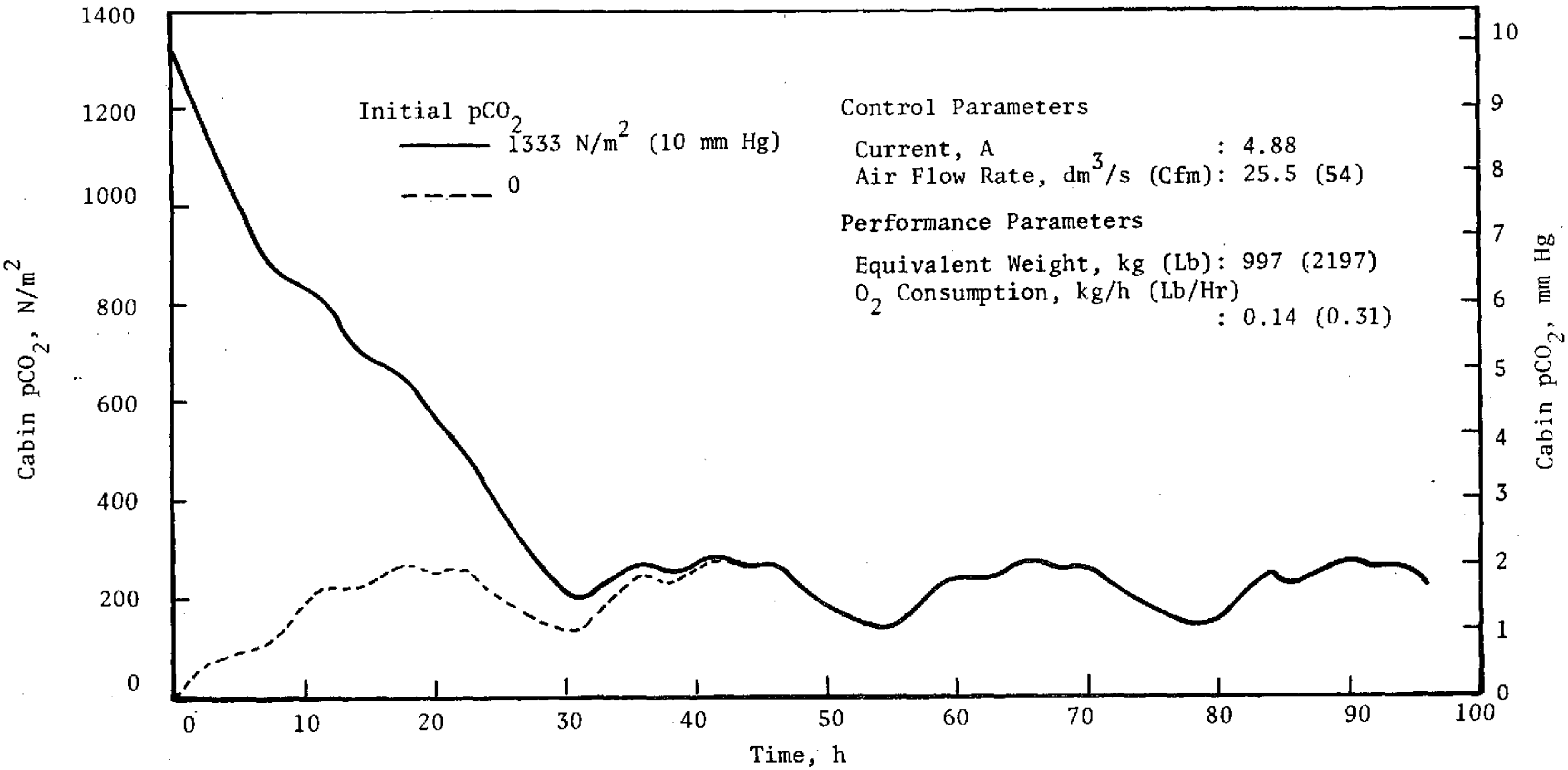

FIGURE 22 CABIN pCO_2 SIMULATION PROFILE FOR CONTROL MODE A(1)

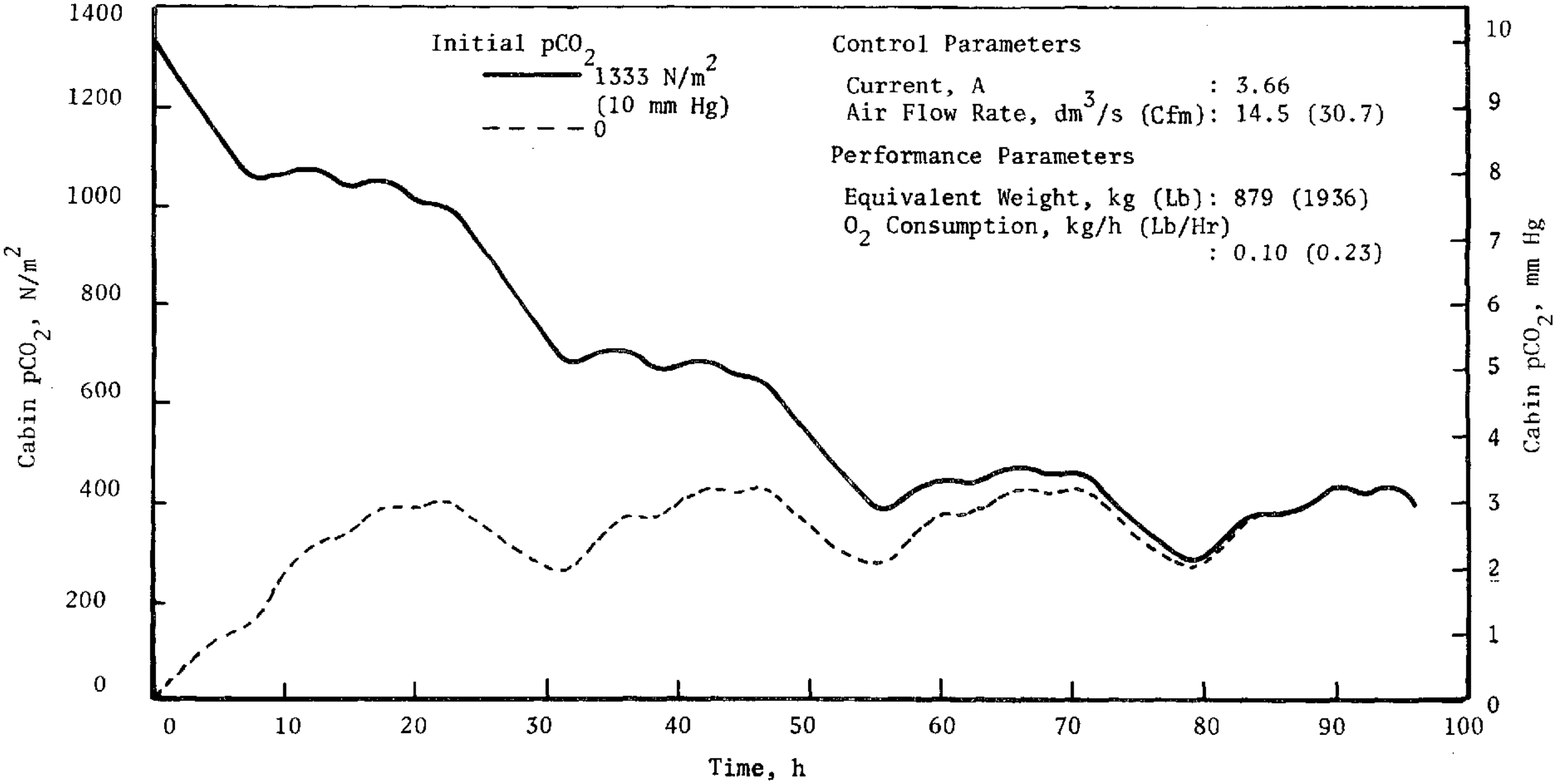

FIGURE 23 CABIN pCO_2 SIMULATION PROFILE FOR CONTROL MODE A(2)

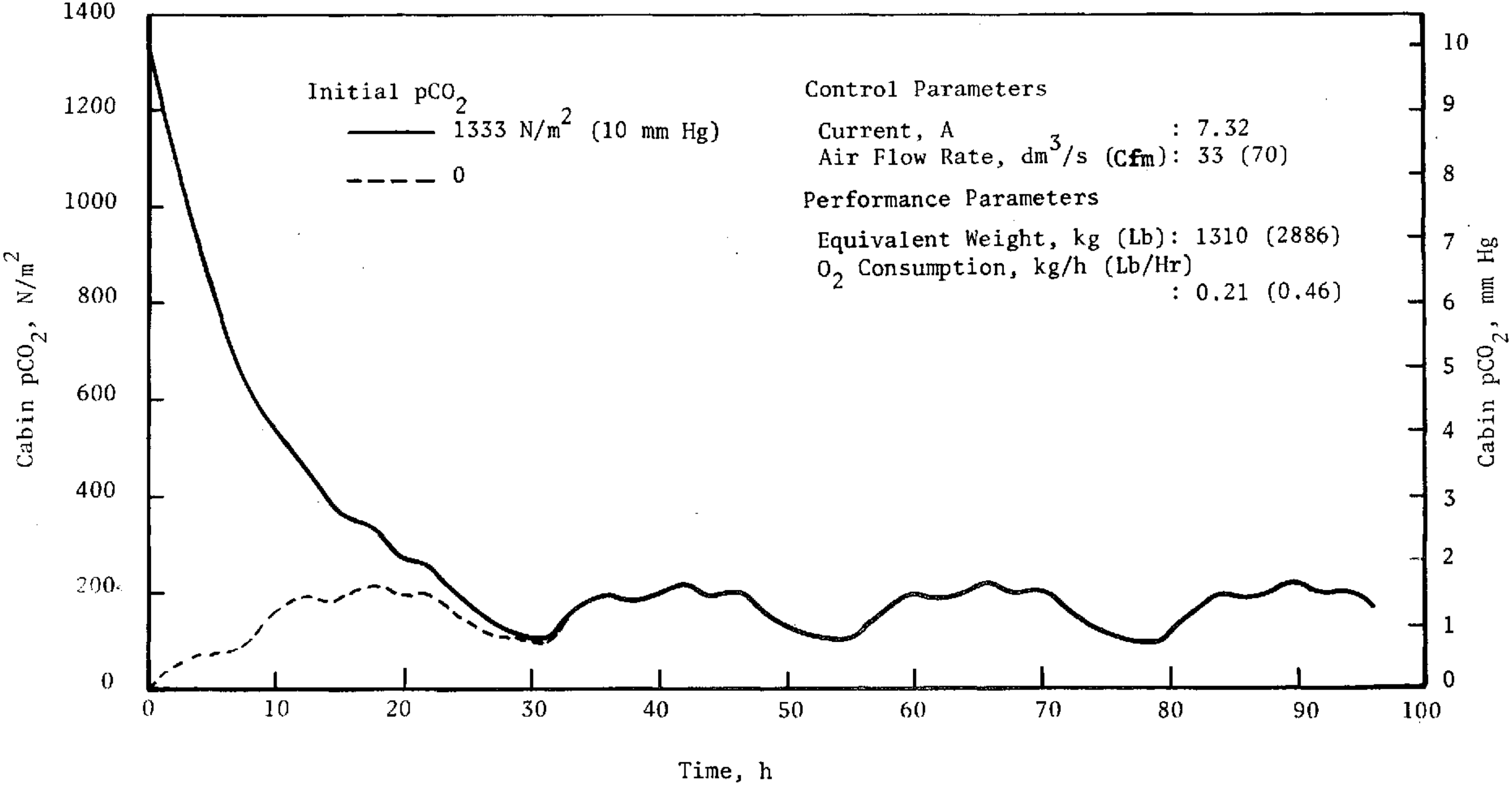

FIGURE 24 CABIN pCO_2 SIMULATION PROFILE FOR CONTROL MODE A(3)

TABLE 9 INPUT VARIABLES FOR SAMPLE MODE A PROBLEMS

Cabin Atmosphere	
Total Pressure, PØPSA	14.7 Psia
pCO_2, PCØ	0.001, 10 mm Hg
pO_2, POØPSA	3.1 Psia
Temperature, TØ	70F
Volume, VOLUME	8000 Ft^3
Process Air Outlet	
Total Pressure, P8PSA	14.75 Psia
Process Air Inlet	
Temperature, T7	55F
Flow Rate, V7	500 Scfm[(a)]
Dew Point Temperature, DW7	50F
Anode H_2/CO_2 Outlet	
Total Pressure, P4PSA	20 Psia
System H_2 Inlet	
Temperature, T9	72F
Flow Rate, V9SL	10 Scfm[(a)]
Dew Point Temperature, DW9	69F
Modules	
Number in Circuit, N	96
Current, I	4.00, 3.66, 7.32 A
DELT1[(b)]	22F
Cathode Air Flow Rate, V1	54, 30.7, 70 Scfm (96 cells)
Penalty Weight Factors	
Power, PWPEN	0.591 Lb/Watt
Heat Rejection to Ambient, HTPEN	0.128 Lb/Btu/Hr
Water Vapor Rejection to Ambient, H2OPEN	134 Lb/Lb H_2O/Hr
Oxygen Consumption, OXPEN	1536 Lb/Lb O_2/Hr
Program Control	
KMODE[(c)]	0
NFLAG[(d)]	1
Number of Days to be Simulated, DAYS	4 Days
Integration Time Increment, DT	15 Min[(e)]
Output Table Time Increment, DPRINT	60 Min[(f)]

(a) Reference conditions for standard flow units: 70F, 14.7 Psia
(b) DELT1 = Module temperature - cathode air inlet dew point temperature
(c) KMODE = 0 - Mode A; 1 - Mode B
(d) NFLAG = 0 - Out-of-tolerance moisture conditions do not stop program
1 - Out-of-tolerance moisture conditions do stop program
(e) DT must be chosen so that the length of each time step in the CO_2 generation rate table is a whole multiple of DT
(f) DPRINT must be a whole multiple of DT

TABLE 10 CONTROL MODE B PARAMETERS

Control Parameter	B(1)	B(2)	B(3)	B(4)
Minimum Current, BK(1), A	2.586	2.586	2.586	2.586
pCO_2 for Minimum Current, BK(2), mm Hg	2.5	1.0	1.0	2.5
pCO_2 for Maximum Current, BK(3), mm Hg	2.8	2.8	10.0	10.0
Maximum Current, BK(4), A	6.6	6.6	6.6	6.6
Minimum Cathode Air Flow Rate, BK(5), Scfm	20	20	20	20
pCO_2 at Minimum Cathode Air Flow Rate, BK(6), mm Hg	2.5	1.0	1.0	2.5
pCO_2 at Maximum Cathode Air Flow Rate, BK(7), mm Hg	2.8	2.8	10.0	10.0
Maximum Cathode Air Flow Rate, BK(8), Scfm	60	60	60	60

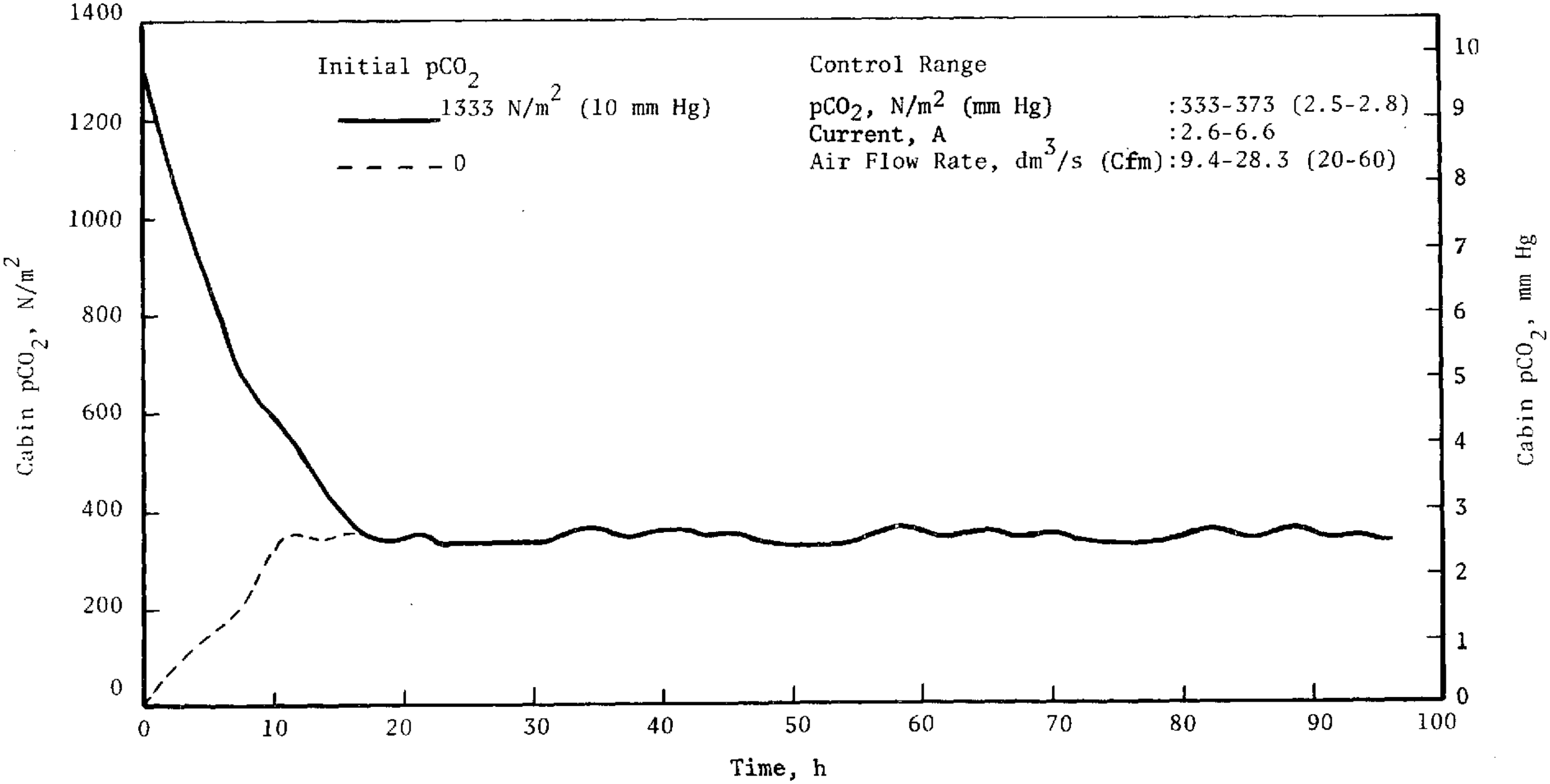

FIGURE 25 CABIN pCO_2 SIMULATION PROFILE FOR CONTROL MODE B(1)

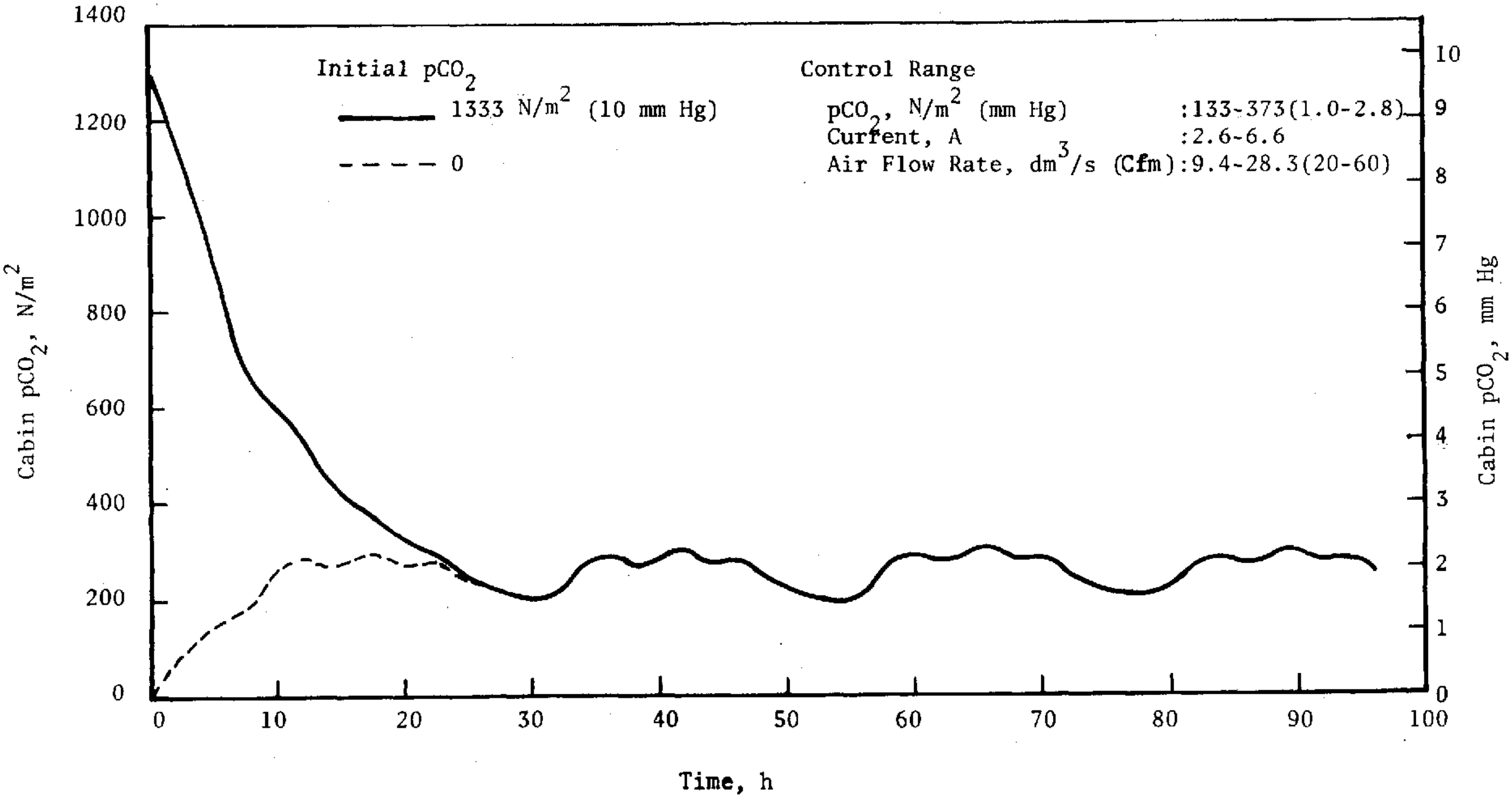

FIGURE 26 CABIN pCO_2 SIMULATION PROFILE FOR CONTROL MODE B(2)

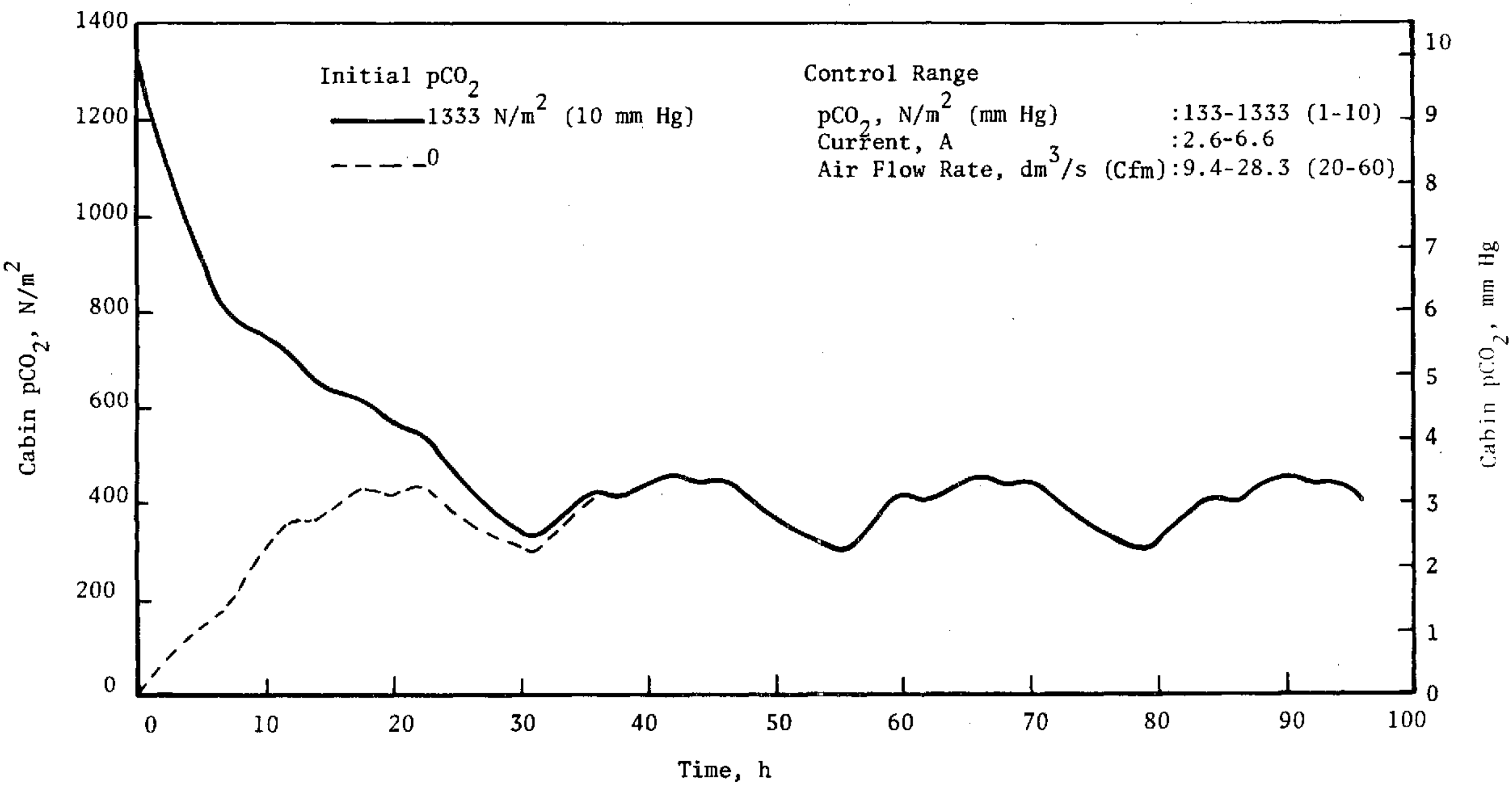

FIGURE 27 CABIN pCO_2 SIMULATION PROFILE FOR CONTROL MODE B(3)

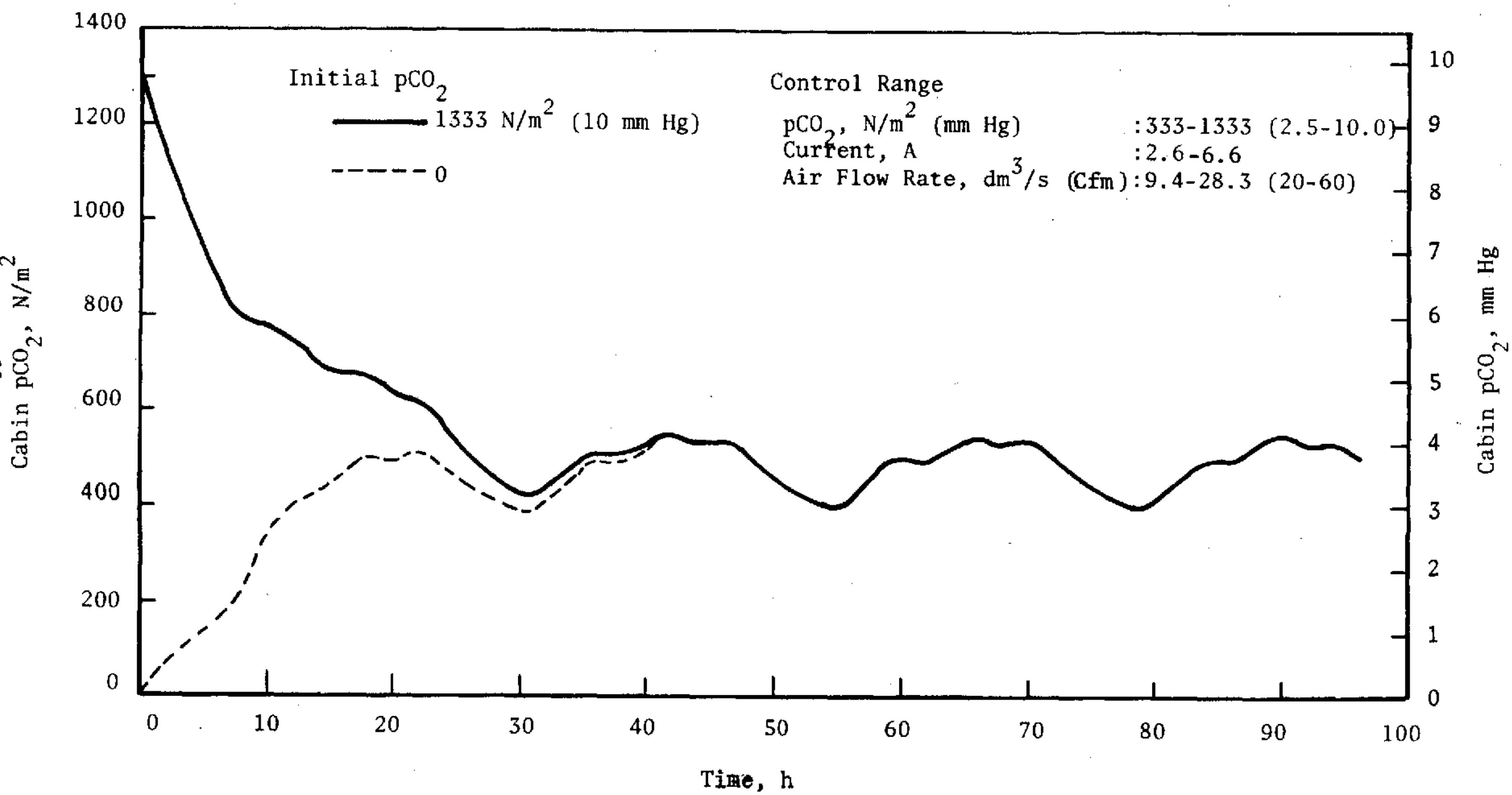

FIGURE 28 CABIN pCO_2 SIMULATION PROFILE FOR CONTROL MODE B(4)

TABLE 11 INPUT VARIABLES FOR SAMPLE MODE B PROBLEMS

Cabin Atmosphere	
Total Pressure, PØPSA	14.7 Psia
pCO_2, PCØ	0.001, 10 mm Hg
pO_2, POØPSA	3.1 Psia
Temperature, TØ	70F
Volume, VOLUME	8000 Ft^3
Process Air Outlet	
Total Pressure, P8PSA	14.75 Psia
Process Air Inlet	
Temperature, T7	55F
Flow Rate, V7	265 Scfm[(a)]
Dew Point Temperature, DW7	50F
Anode H_2/CO_2 Outlet	
Total Pressure, P4PSA	20 Psia
System H_2 Inlet	
Temperature, T9	72F
Flow Rate, V9SL	10 Scfm[(a)]
Dew Point Temperature, DW9	69F
Modules	
Number in Circuit, N	96
Current, I	N/A[(b)]
DELT1[(c)]	22F
Cathode Air Flow Rate, V1	N/A
Penalty Weight Factors	
Power, PWPEN	0.591 Lb/Watt
Heat Rejection to Ambient, HTPEN	0.128 Lb/Btu/Hr
Water Vapor Rejection to Ambient, H2OPEN	134 Lb/Lb H_2O/Hr
Oxygen Consumption, OXPEN	1536 Lb/Lb O_2/Hr
Program Control	
KMODE[(d)]	1
NFLAG[(e)]	1
Number of Days to be Simulated, DAYS	4 Days
Integration Time Increment, DT	15 Min[(f)]
Output Table Time Increment, DPRINT	60 Min[(g)]

(a) Reference conditions for standard flow units: 70F, 14.7 Psia
(b) N/A = Not Applicable
(c) DELT1 = Module temperature - cathode air inlet dew point temperature
(d) KMODE = 0 - Mode A; 1 - Mode B
(e) NFLAG = 0 - Out-of-tolerance moisture conditions do not stop program
1 - Out-of-tolerance moisture conditions do stop program
(f) DT must be chosen so that the length of each time step in the CO_2 generation rate table is a whole multiple of DT
(g) DPRINT must be a whole multiple of DT

In control Mode A, subsystem equivalent weight and O_2 consumption remain constant. In control Mode B, however, these two parameters vary with time. The steady-state daily equivalent weight and O_2 consumption profiles for the four control Mode B runs are presented in Figures 29 through 36. Subsystem power consumption profiles and any other subsystem performance variable profiles can likewise be predicted, depending upon the specific interests of the program user. In this manner, control Mode A and control Mode B can then be compared on the basis of the important performance parameters for a given application.

CONCLUSIONS

The following conclusions were reached as a direct result of the math model development effort:

1. The CS-6 Base Program developed accurately predicts the performance characteristics of the CS-6 as a subsystem over its typical range in operating conditions.

2. The Cabin pCO_2 Simulation Program developed predicts cabin pCO_2 as a function of a given CO_2 generation profile and spacecraft cabin volume for the CS-6 as the CCS.

3. The Cabin pCO_2 Simulation Program provides a tool for the system designer for use in trade studies to determine subsystem equivalent weight, O_2 consumption, power consumption, and cabin pCO_2 as a function of a CO_2 generation profile for both control Mode A and control Mode B.

4. The CS-6 Base Program and Cabin pCO_2 Simulation Program can be upgraded for use as a hardware design tool. Hardware limitations such as cooling air damper leakage and blower capacity could be eliminated from the program. The result of the upgrading would be a hardware design tool specifically aimed at sizing and designing an EDC CO_2 removal subsystem for general spacecraft application.

5. The experimental work completed provided the necessary data to model the performance of the CS-6 and to verify the model's predictability.

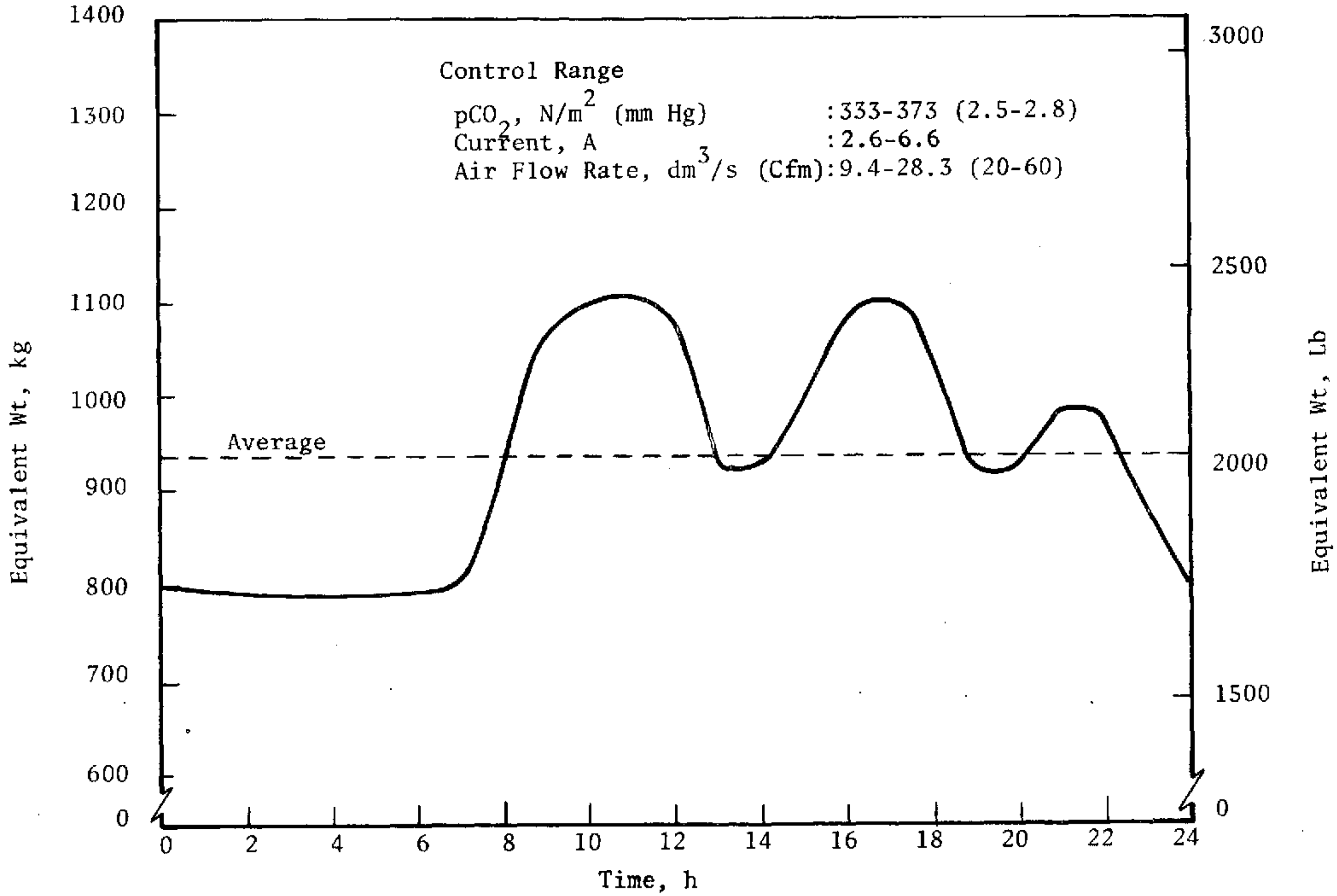

FIGURE 29 STEADY-STATE DAILY EQUIVALENT WEIGHT PROFILE FOR CONTROL MODE B(1)

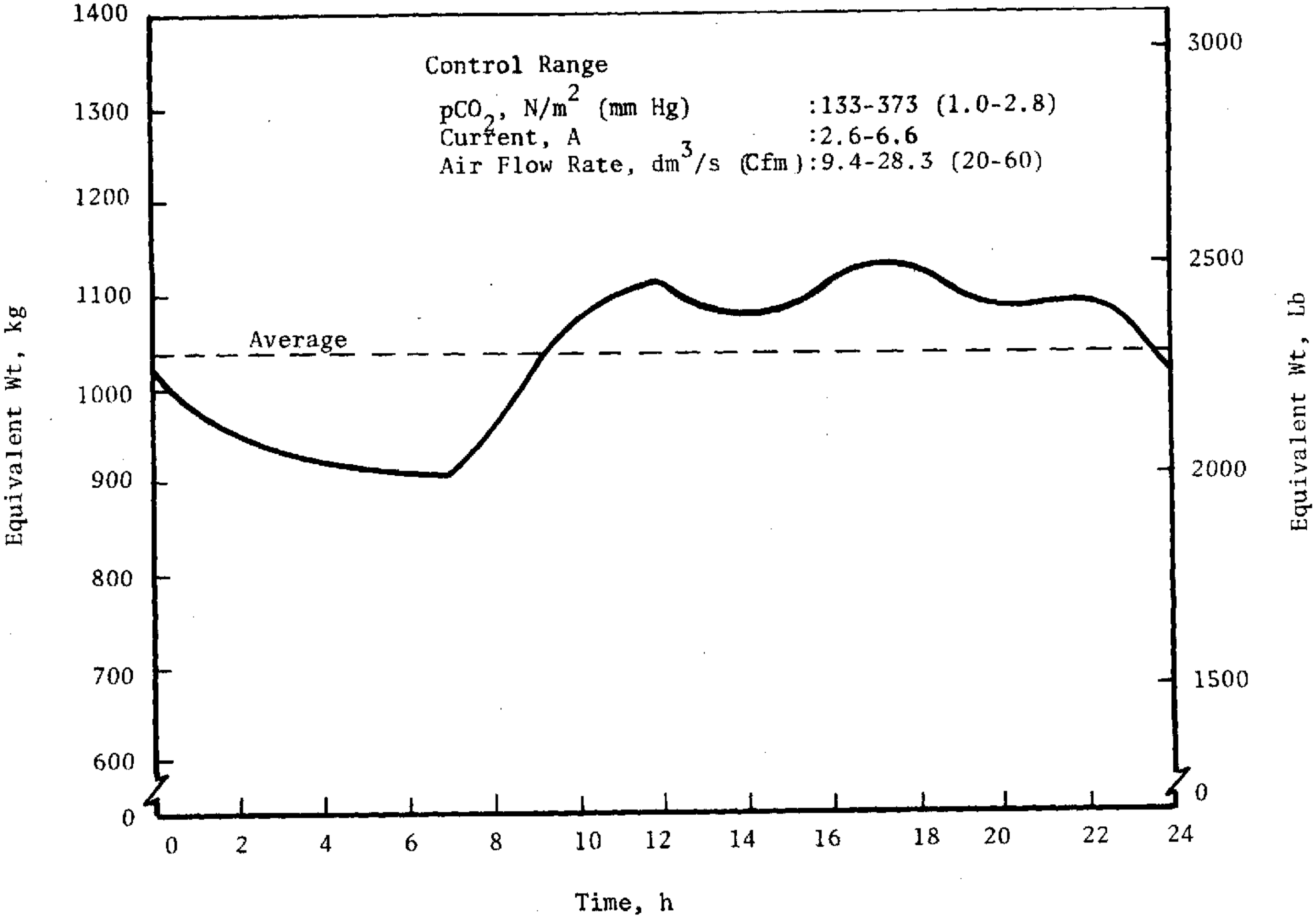

FIGURE 30 STEADY-STATE DAILY EQUIVALENT WEIGHT PROFILE FOR CONTROL MODE B(2)

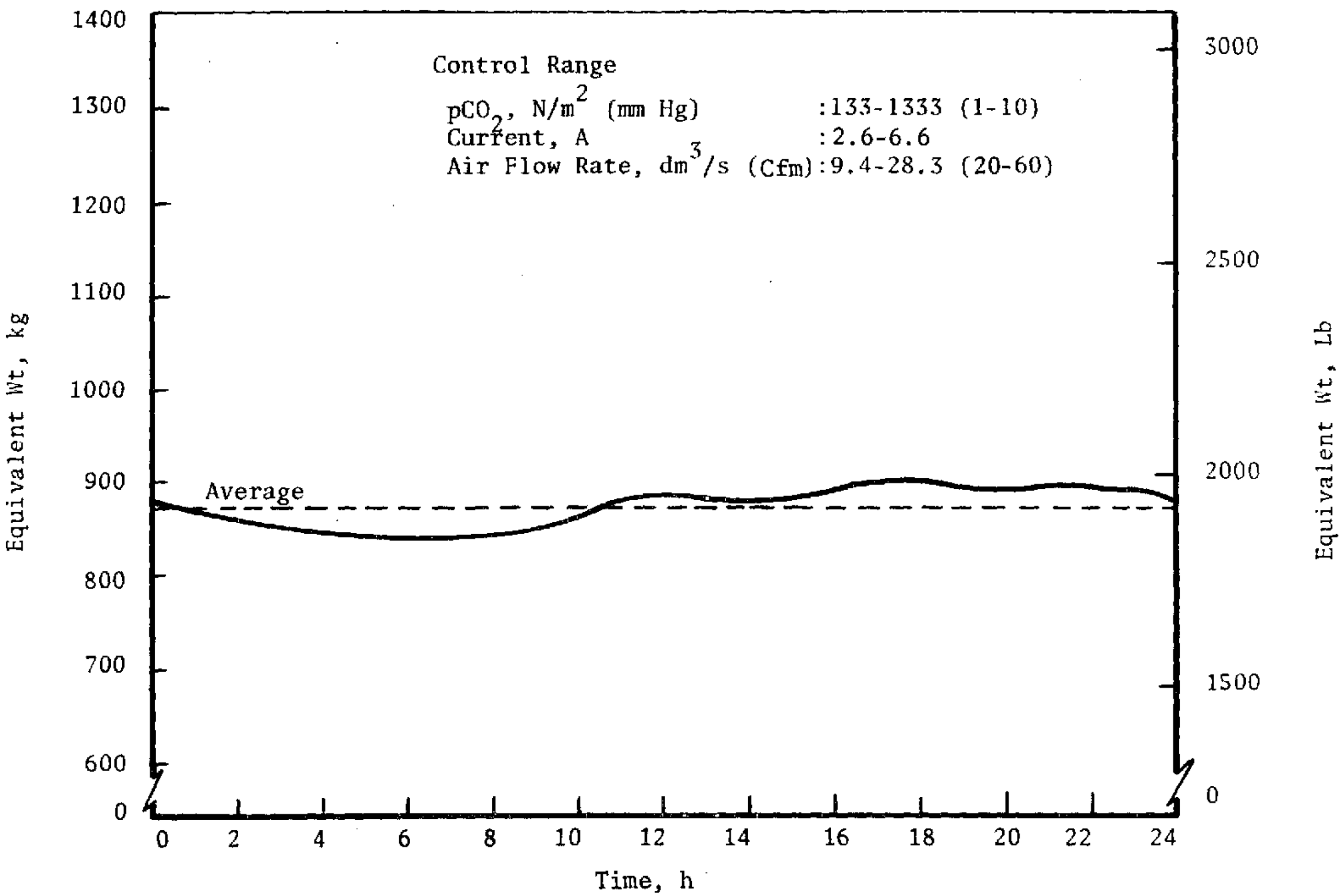

FIGURE 31 STEADY-STATE DAILY EQUIVALENT WEIGHT PROFILE FOR CONTROL MODE B(3)

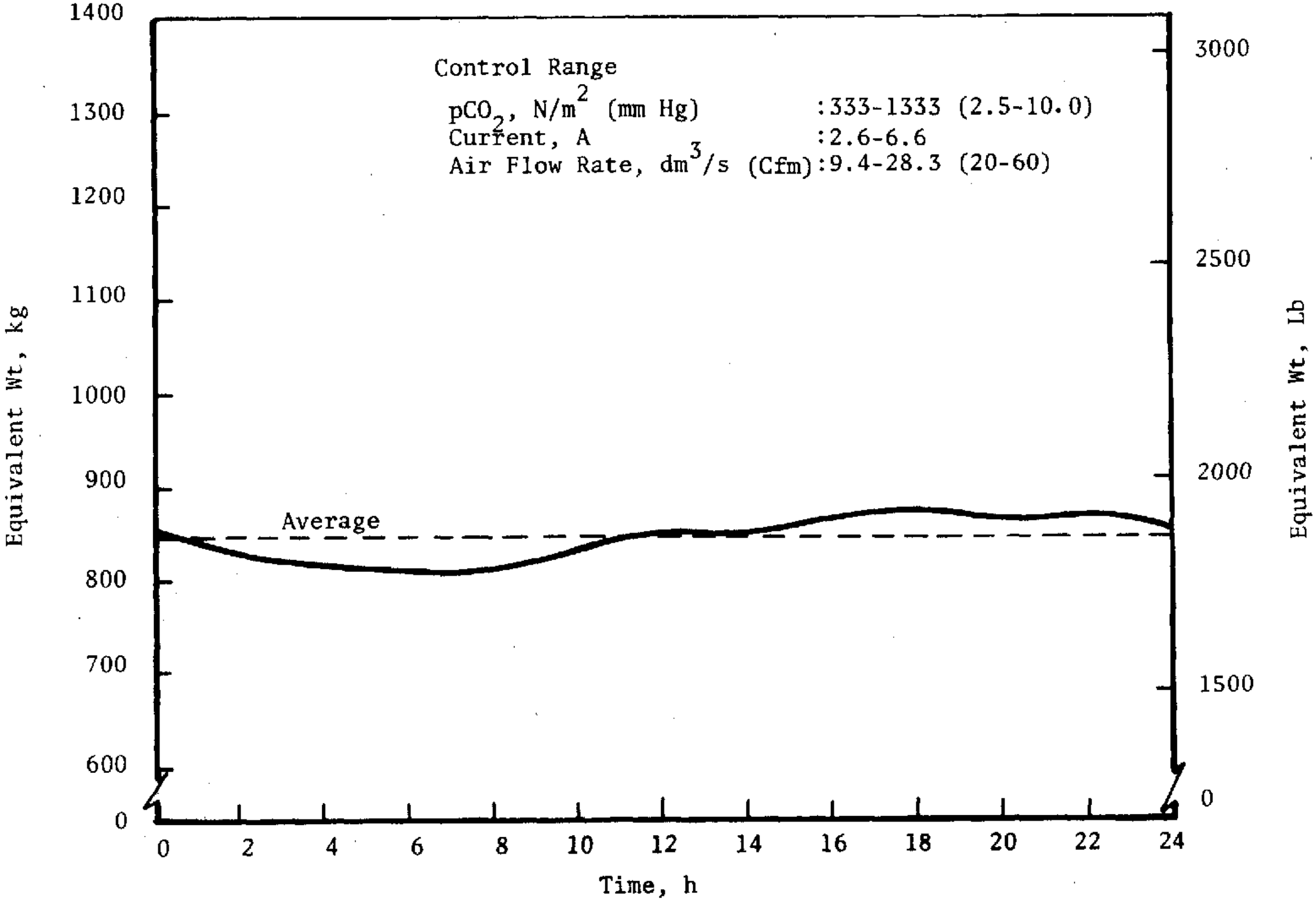

FIGURE 32 STEADY-STATE DAILY EQUIVALENT WEIGHT PROFILE FOR CONTROL MODE B(4)

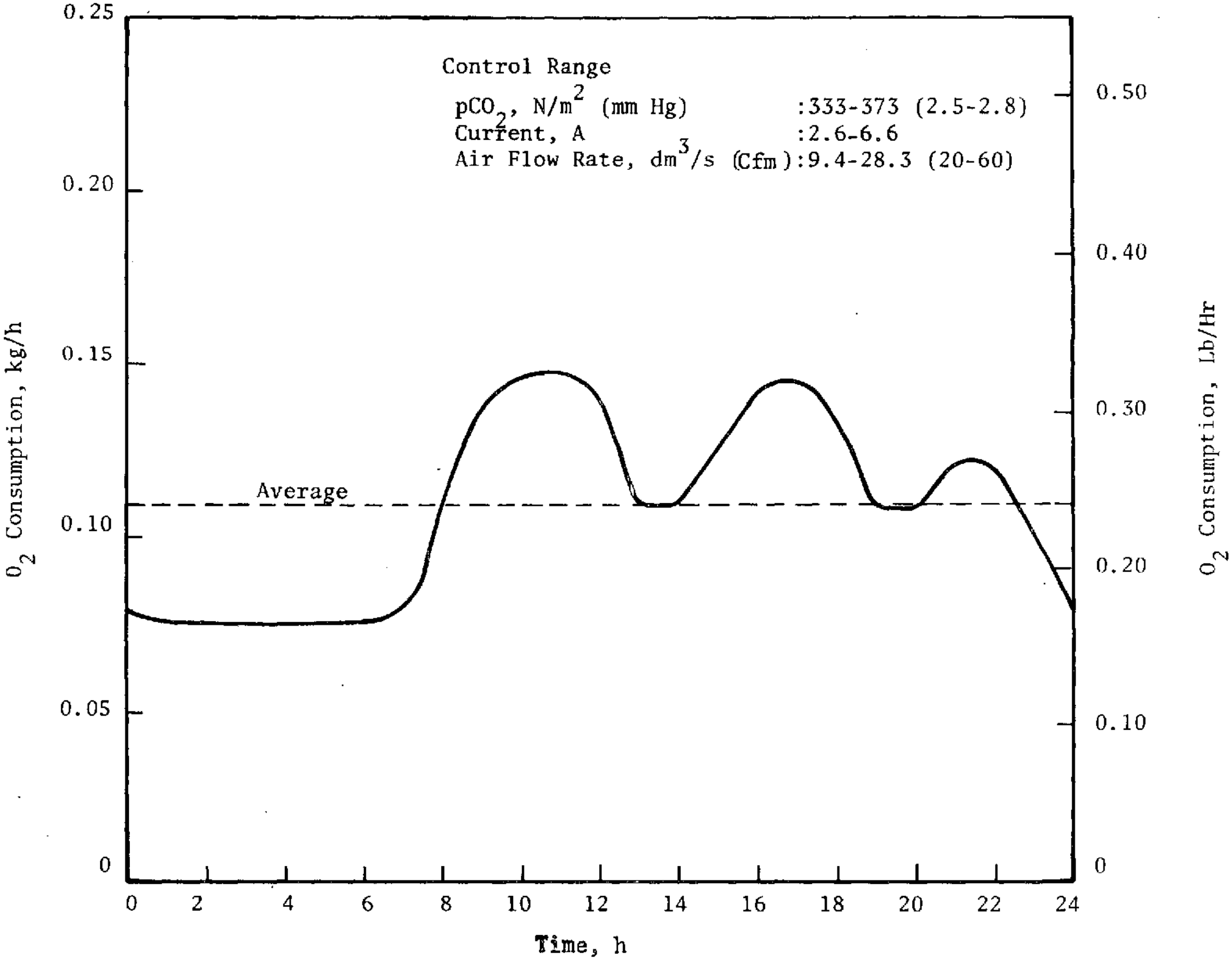

FIGURE 33 STEADY-STATE DAILY O_2 CONSUMPTION PROFILE FOR CONTROL MODE B(1)

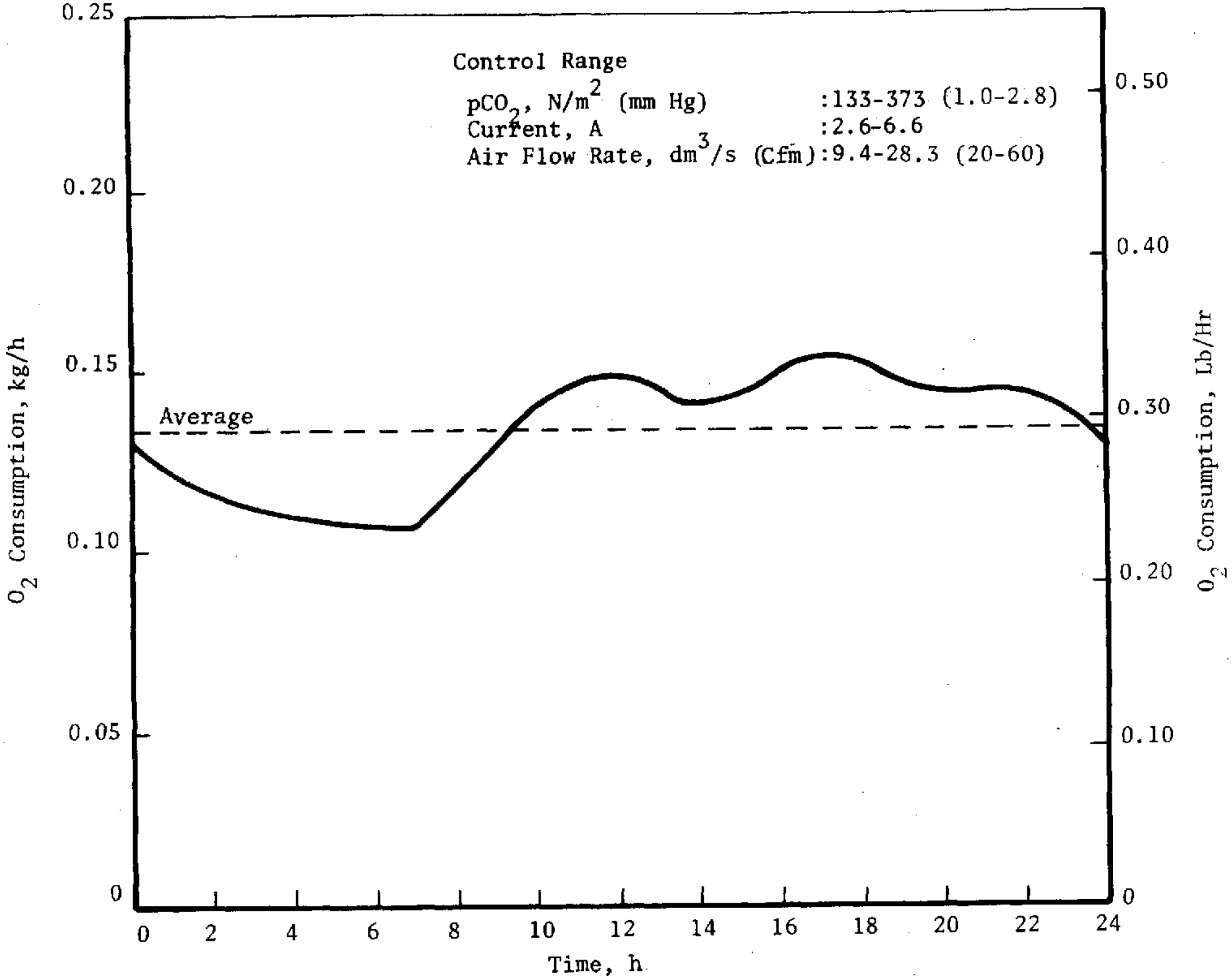

FIGURE 34 STEADY-STATE DAILY O_2 CONSUMPTION PROFILE FOR CONTROL MODE B(2)

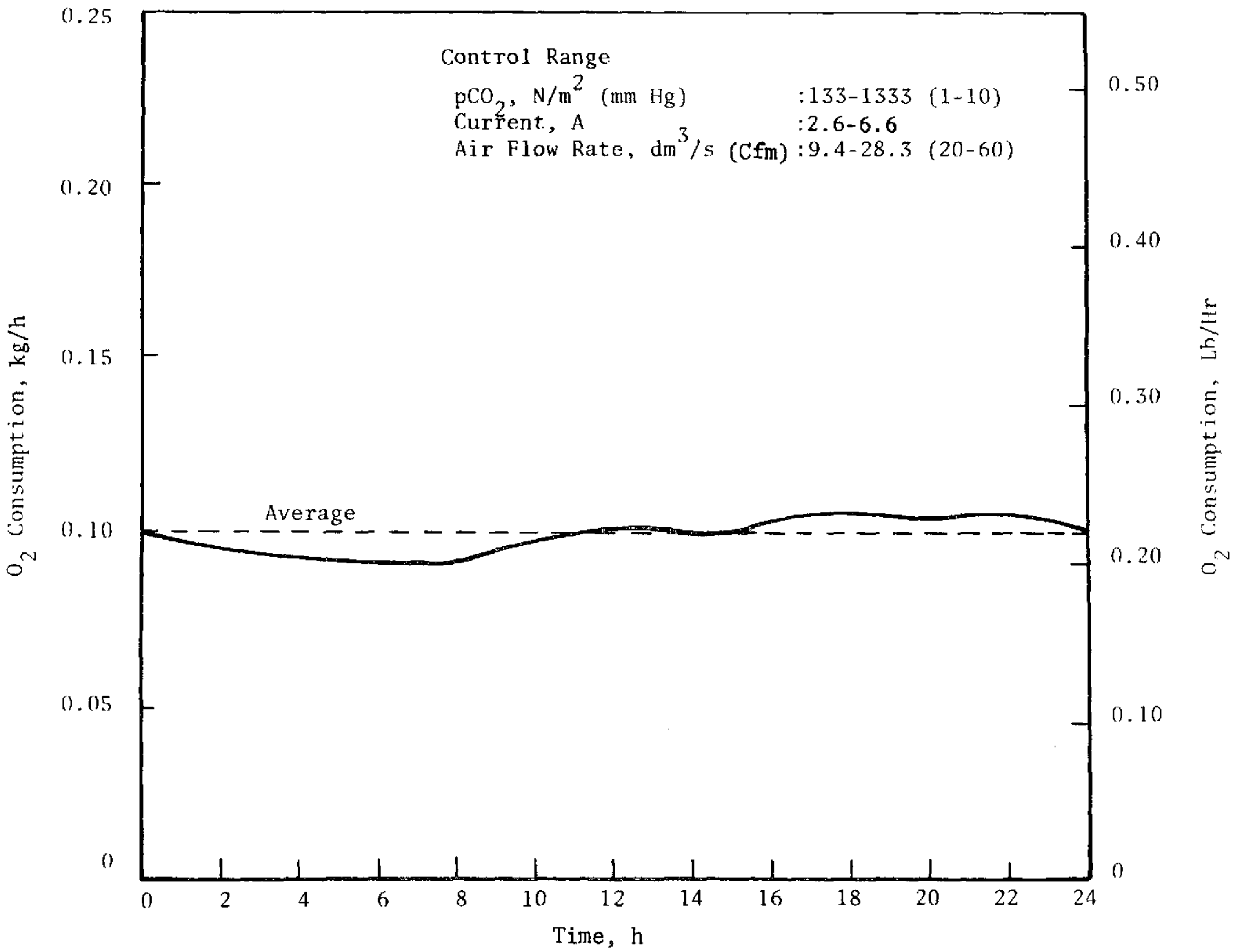

FIGURE 35 STEADY-STATE DAILY O_2 CONSUMPTION PROFILE FOR CONTROL MODE B(3)

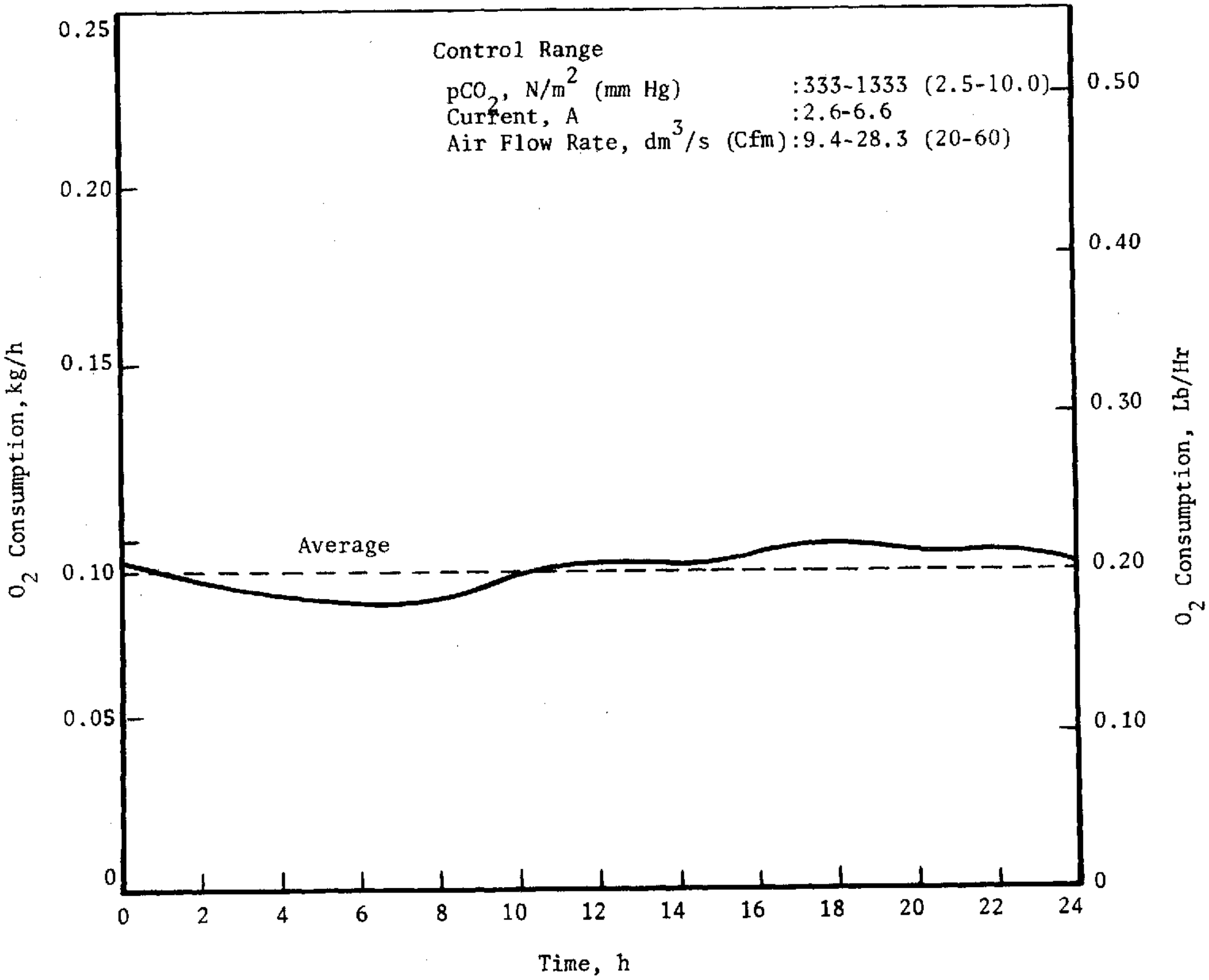

FIGURE 36 STEADY-STATE DAILY O_2 CONSUMPTION PROFILE FOR CONTROL MODE B(4)

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2. Kostell, G. D., Schubert, F. H., Shumar, J. W., Hallick, T. M. and Jensen, F. C., "Six-Man, Self-Contained Carbon Dioxide Concentrator Subsystem for Space Station Prototype (SSP) Application," Final Report, ER-170-34, NASA CR 114742, Contract NAS2-6478, Life Systems, Inc., Cleveland, Ohio, May, 1974.

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4. Shubert, F. H. and Quattrone, P. D., "Development of a Six-Man, Self-Contained Carbon Dioxide Collection Subsystem for Spacecraft Application," ASME Publication 74-ENAs-16, presented at the Intersociety Conference on Environmental Systems, Seattle, Washington, July 29-August 1, 1974.

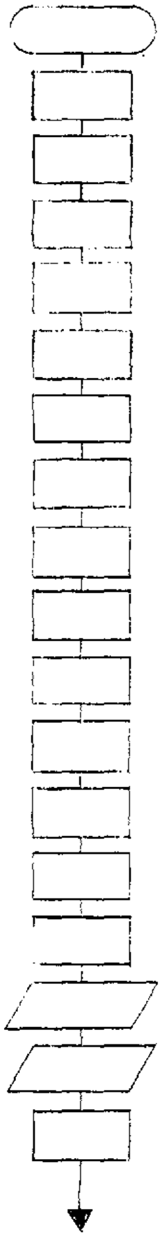
5. Schubert, F. H. and Schneider, J. J., "Six-Man, Self-Contained CO_2 Concentrator Extension: New Technology Tasks," First Quarterly Report, ER-170E-2a, Contract NAS2-6478, Life Systems, Inc., Cleveland, Ohio, December, 1973.

6. Bird, R. Byron, Stewart, Warren E. and Lightfoot, Edwin N., "Transport Phenomena," John Wiley & Sons, Inc., New York, 1960.

7. Welty, James R., Wicks, Charles E. and Wilson, Robert E., "Fundamentals of Momentum, Heat and Mass Transfer," John Wiley & Sons, Inc., New York, 1969.

APPENDIX A CS-6 BASE PROGRAM DOCUMENTATION

TABLE 1 MAIN PROGRAM FLOW CHART

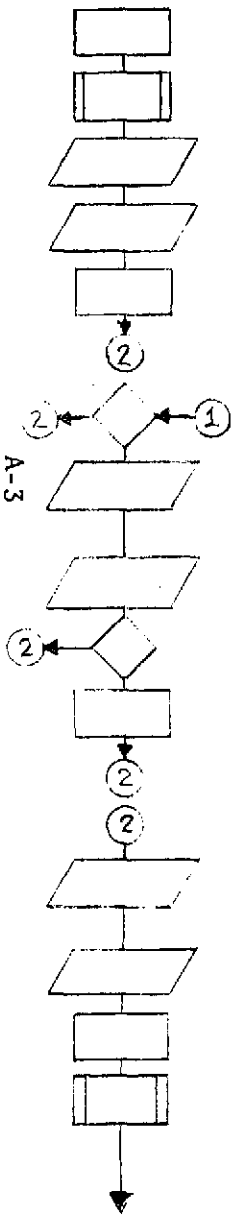


Symbol	Program Line Numbers	Description	Comments
		START	
	190	CPA = 1.0765	Initialize Constant Btu/Hr/Scfm-F
	190	CPH = 1.0666	Initialize Constant Btu/Hr/Scfm-F
	200	U1 = 51.7	Initialize Constant mm Hg/Psi
	200	U2 = 386.7	Initialize Constant Scfm/Lb-Mol/Hr
	200	U3 = 3.419	Initialize Constant Btu/Hr/Watt
	200	U4 = 28.32	Initialize Constant $1/Ft^3$
	210	$C782 = 2.25 \times 10^{-5}$	
	210	$C562 = 1.303 \times 10^{-5}$	Initialize Constants For Pressure Drop Equations
	210	$C561 = 1.01 \times 10^{-2}$	
	210	$C6132 = 8.611 \times 10^{-4}$	
	220	C5132 = C562 + C6132	
	230	C5131 = C561	
	240	QA = C5132 - C782	
	250	IOUT = 1	Initialize output file device code
	260	PRINT, "FILE INPUT (T OR F)	
	270	READ, QFIN	
	280	INP = 50	

-continued-

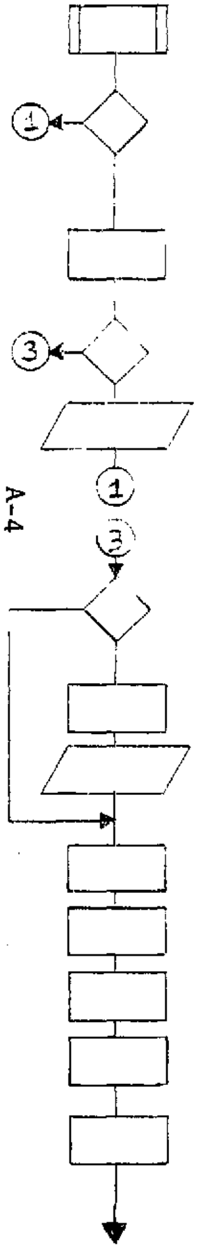
Table 1 - continued

Symbol



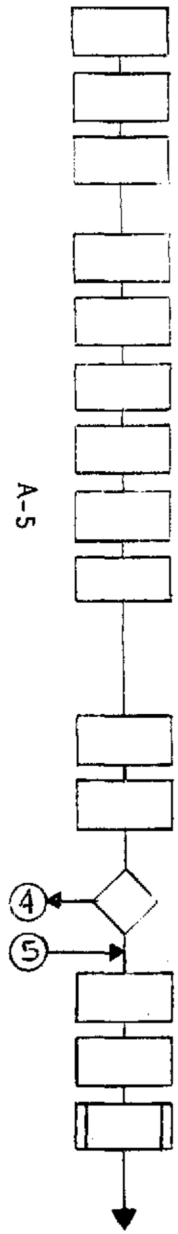
Program Line Numbers	Description	Comments
290	IF (QFIN) INP=2	Open input file if desired
300	IF (QFIN) OPEN INPUT FILE	
310	PRINT, "FILE OUTPUT (T OR F)"	Should output be written into a file? If not, correct the output device code for direct terminal output.
320	READ, QFOUT	
330	IF (NOT QFOUT) IOUT = 66	
360	IF (NOT QFOUT) BRANCH	If file output was used, read in the file name. If the file is completed, close it and assign the name to it.
370	IF (NOT QFIN) PRINT, "FILE FOR OUTPUT"	
380-390	READ (INP, 48) FNAME	
400	IF (FNAME = "WAIT") BRANCH	
410-430	END, CLOSE AND REWIND FILE	
450-470	READ: POPSA, PCO, POOPSA, P8PSA, T7, V7, DW7, P4PSA, T9, V9SL, DW9, N, I, DELT1, V1, PWPEN, HTPEN, H2OPEN, OXPEN, NFLAG	Read in and write out input variables
510-750	WRITE INPUT VARIABLES	
790	IR=0	Initialize out of range input variable counter
800	CALL T ("POPSA," POPSA, 13.7, 15.7, IR)	Subroutine T checks each input variable against its allowable range. Out of range variables are printed and cause IR to be incremented.
810-990		

Table 1 - continued



Symbol	Program Line Numbers	Description	Comments
	1000	CALL T ("NFLAG,", FLAG, 0, 1, IR)	
	1010	IF (IR > 0) BRANCH	If the counter shows that one or more input variables is out-of-range, abort the simulation and read in next set of data.
	1050	$V9MSL = (1.3)(N)(I)(7.058 \times 10^{-3})$	Calc. required H_2 flow
	1060	IF V9MSL < V9SL THEN BRANCH	Check for sufficient H_2 Flow
	1070-1080	WRITE "INSUFFICIENT H_2," V9MSL, "IS REQUIRED"	Write error message and required H_2 flow Return for new inputs
	1140	IF V1 $\leq$ 70 THEN BRANCH	Check that V1 is less than the process air blower capacity
	1150	V1 = 70	Set V1 to maximum blower capacity
	1160-1180	WRITE "AIRFLOW CHANGE TO 70 SCFM"	Print error message
	1220	V7M1 = V7 - V1	Calculate bypass cooling air flow with cooling blowers off; i.e., calculate minimum cooling air flow rate
	1230	$QB = C5131 + 2(V7M1)^2$	
	1240	$QC = C782\ (V7M1)^2$	
	1250	$V5MIN = \dfrac{-QB + QB^2 + 4(QA)(QC)}{2(QA)}$	
	1290	DW1 = DW7	

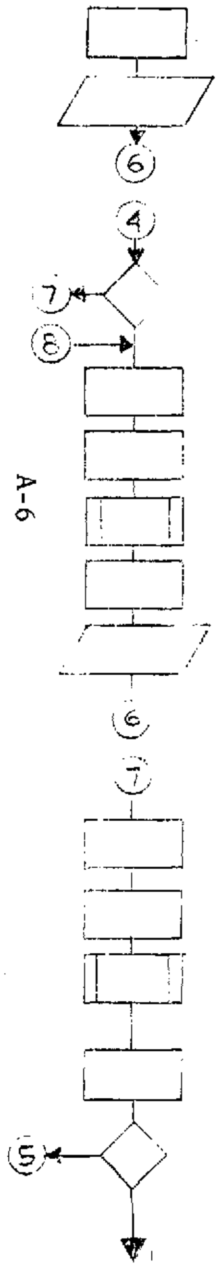
Table 1 - continued



Symbol	Program Line Numbers	Description	Comments
	1300	T2 = DW1 + DELT1	Calculate cell temperature
	1310	T2INP = T2	Store input T2
	1320	E = 0.729 - 0.22 InI + 0.008I + 0.005 (T2-78)	Calculate cell voltage
	1330	HEATLD = (1.25-E)(N)(I)(U3)	Calculate modules' heatload
	1340	T1 = T7	
	1350	T3 = T9	
	1360	V3 = V9SL/U4	
	1370	T5 = T1	
	1380	DHA = V1 (CPA)(T2 - T1)	Calculate heat removed by cathode air flow
	1390	DHH = V3 (CPH)(T2-T3)	Calculate heat removed by H_2
	1400	DHC = HEATLD-DHA-DHC	Calculate heat removed by cooling air
	1440	If DHC > 0 THEN BRANCH	Check to see if cooling air is required
	1490	V5 = V5MIN	Set cooling air flow to minimum
	1500	V5A = (N)(V5MIN)/96	Calculate flow thru active cells
	1510	CALL TDRIFT	Calculate T2 for subcooled condition

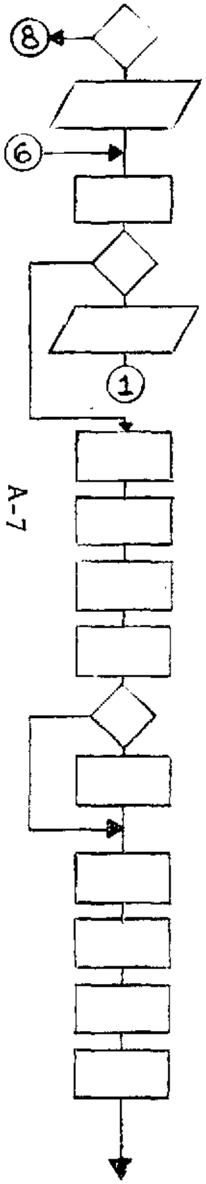
Table 1 - continued

Symbol



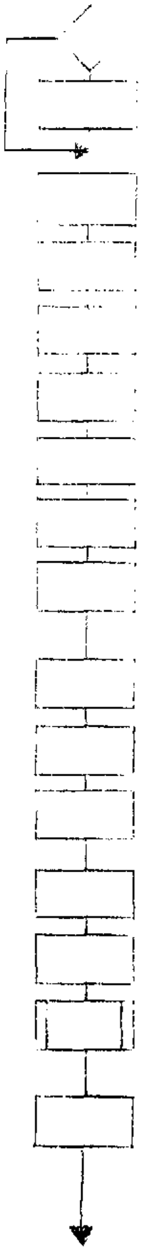
Program Line Numbers	Description	Comments
1520	DROP = T2INP-T2	Calculate temperature, T2, drop
1530-1560	WRITE "V5MIN," V5MIN "COOLING BLOWERS OFF," "MODULE TEMPERATURE FALLS," DROP, "NEW T2," T2	Print out new conditions
1630	IF $T2-T5 \geq \frac{(0.376)DHC}{N}$ THEN BRANCH	Check if there is sufficient ΔT to conduct heat up fins
1680	V5 = 440	Set V5 to maximum blower capacity
1690	V5A = V5(N)/96	Calculate flow thru active cells
1700	Call TDRIFT	Calculate T2
1710	RISE = T2-T2INP	Call rise in module temperature
1720-1740	WRITE "COOLING BLOWERS ON FULL," "MODULE TEMPERATURE RISES," RISE, "NEW T2," T2	Print out new conditions
1800	VA = 1.01 x DHC/CPA (N)(T2-T5)	Calculate minimum and maximum cooling air flow to set range for iterative subroutine "ROOT"
1810	VB = 2(VA)	
1820	V5A = (N) · ROOT (VA, VB, ERT, 0, 0.005, 0.001, 20)	Calculate cooling air flow past active cell
1830	V5 = 96(V5A)/N	Calculate total cooling air flow
1880	If V5 < V5MIN THEN BRANCH	Check for subcooling

Table 1 - continued



Program Line Numbers	Description	Comments
1890	If V5 > 440 THEN BRANCH	Check for heatup
1900-1920	WRITE "COOLING BLOWERS IN RANGE"	Print clarifying statement
1970	V10 = V7-V1-V5	Calculate plenum bypass flow
2020	IF V10 $\geq$ 0.005 (V8) THEN BRANCH	Check for sufficient plenum bypass
2030-2060	WRITE "INSUFFICIENT AIR FLOW, RECIRCULATION OF AIR FROM OUTLET TO INLET"	Print error message
2120	$COR34 = \left(\frac{14.1}{P4PSA}\right)^{0.8}$	
2130	P4 = P4PSA (V1)	Calculate module H_2 cavity pressure drop
2140	V3SL = V9SL	
2150	DP34 = (0.3822)(COR34)(V3SL)	
2150	IF V3SL $\leq$ 22 THEN BRANCH	
2150	$DP\ 34 = COR34\ (8.3183 + 0.4187\ (V3SL-21.5801)^{1.75})$	
2170	P3 = P4 + DP34	Calculate module H_2 inlet pressure
2180	P3PSA = P3/U1	
2190	$COR93 = \left(\frac{14.1}{P3PSA}\right)^{0.8}$	
2200	DP93 = (COR93)(10.64)(V3SL)	Calculate H_2 distribution block pressure drop

Table 1 - continued

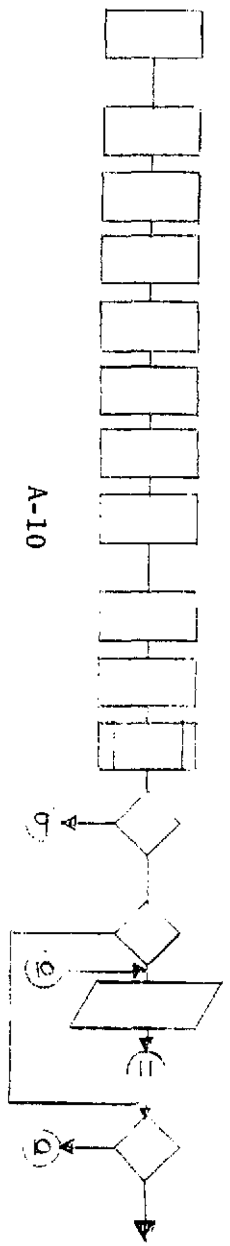


Symbol	Program Line Numbers	Description	Comments
	2210	IF V3SL $\leq$ 6.2 THEN BRANCH	
	2210	$DP93 = COR93\,[35.64\,V3SL - 195.25 + e^{(7.75-0.6537V3SL)}]$	
	2220	P9 = P3 + DP93	Calculate H_2 inlet pressure
	2230	P9PSA = P9/U1	
	2240	$DP78 = 2.25 \times 10^{-5}(V10)^2$	Calculate process air inlet pressure using plenum pressure drop correlation
	2250	P8 = P8PSA(U1)	
	2260	P7 = P8 + DP78	
	2270	P7PSA = P7/U1	
	2280	$DP12 = 0.001903(V1)^2 + 0.04877(V1)$	Calculate cathode air pressure drop
	2290	P1 = P7	
	2300	P2 = P1-DP12	Calculate cathode air out pressure
	2310	$PC1 = PCO\,\frac{P7PSA}{POPSA}$	Calculate cathode inlet pCO_2
	2320	CURDEN = I/0.244	Calculate current density
	2330	DELT1E = T2-DW1	Calculate actual humidity ΔT
	2340	TI = TICOR (PC1, V1/96, CURDEN, DELTIE)	Calculate TI
	2350	$OCON = 6.5803 \times 10^{-4}(N)(I)$	Calculate O_2 consumed

Table 1 - continued

Symbol	Program Line Numbers	Description	Comments
	2360	CTRANS = TI (OCON)	Calculate CO_2 transferred
	2370	$HCON = OCON \frac{2.016}{16}$	Calculate H_2 consumed
	2380	WPROD = HCON + OCON	Calculate water produced
	2390	$VC4 = CTRANS \frac{V2}{44.01 \times 60}$	
	2400	PW9 = PHTO (DW9)	
	2410	$PW3 = P3 \frac{PW9}{P9}$	Calculate anode gas stream parameters
	2420	$VH3 = V3(1 - \frac{PW3}{P3})$	
	2430	$VH4 = VH3\text{-}HCON \frac{U2}{2.016 \times 60}$	
	2450	PW4 = PHTO (T2-6)	
	2460	$VW4 = \frac{PW4}{P4\text{-}PW4} (VC4 + VH4)$	
	2470	DW1 = DW7	
	2480	PW1 = PHTO (DW1)	Calculate cathode air water balance parameters
	2490	$VW1 = V1 \frac{PW1}{P1}$	
	2500	VW3 = V3-VH3	
	2510	$VWPROD = WPROD \frac{V2}{18.01 \times 60}$	
	2520	VW2 = VW1 + VW3 - VW4	
	2530	POO = POOPSA/U1	
	2540	PO7 = POO (P7/PO)	

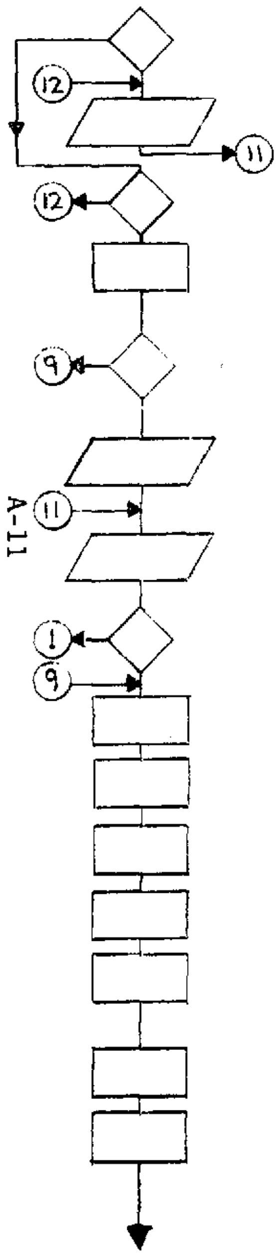
Table 1 - continued



Symbol	Program Line Numbers	Description	Comments
	2550	PO1 = PO7	Calculate cathode air inlet stream parameters
	2560	PN1 = P1-PO1-PW1-PC1	
	2570	VN1 = V1 (PN1/P1)	
	2580	VO1 = V1 (PO1/P1)	
	2590	VC1 = V1 (PC1/P1)	
	2600	VN2 = VN1	Calculate cathode air outlet stream parameters
	2610	VO2 = VO1 - OCON (U2/32 x 60)	
	2620	VC2 = VC1 - VC4	
	2630	V2 = VO2 + VN2 + VW2 + VC2	
	2640	$PW2 = \frac{VW2}{V2} P2$	
	2650	DW2 = DEWT (PW2)	
	2710	IF T1-DW1 = 11.25 ± 1.75 AND T2-DW2 = 11.25 ± 1.75 THEN BRANCH	
	2720	IF T1-DW1 $\geq$ 4 THEN BRANCH	
	2850-2860	WRITE "INLET AIR HUMIDITY OUT-OF-RANGE"	
	2730	IF T1-DW1 $\leq$ 14 THEN BRANCH	

C-2

Table 1 - continued



Symbol	Program Line Numbers	Description	Comments
	2740	IF T2-DW2 ≥ 7 THEN BRANCH	Perform moisture balance checks
	2880-2890	WRITE "OUTLET AIR HUMIDITY OUT-OF-RANGE"	
	2750	IF T2-DW2 ≤ 19 THEN BRANCH	
	2760	DPTDAV = ½ (T1-DW1+T2-DW2)	
	2770	IF DPTDAV = 11±1.5 AND EITHER T2-DW2 ≥ 13 OR DPTDAV ≥ 0 THEN BRANCH	
	2780-2790	WRITE "AVE DEW PT DEPRESSION OUT-OF-RANGE	
	2800-2820	WRITE "ELECTROLYTE MOISTURE BALANCE NOT MAINTAINED"	
	2830	IF NFLAG = 1 THEN BRANCH	Check NFLAG for program abort
	2950	DELT1P = 22-T1 + DW2	Calculate preferred ΔT
	2960	T2P = DP1 + DELT1P	
	2970	PW7 = PW1	
	2980	PN7 = PN1	
	2990	PC7 = PC1	Complete definition of process air inlet stream
	3000	$VC7 = \frac{PC7}{P7} (V7)$	
	3010	$VW7 = \frac{PW7}{P7} (V7)$	

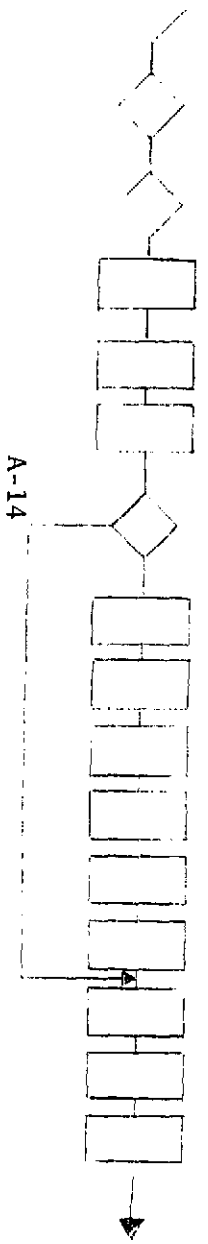
Table 1 - continued

Symbol	Program Line Numbers	Description	Comments
	3020	$PO7 = PO1$	
	3030	$VO7 = \frac{PO7}{P7}(V7)$	
	3040	$VN7 = \frac{PN7}{P7}(V7)$	
	3050	$RH7 = 100\left(\frac{PW7}{PHTO(T7)}\right)$	
	3060	$FC1 = VC1\left(\frac{44.01 \times 60}{U2}\right)$	Complete cathode air inlet stream definition
	3070	$FW1 = VW1\left(\frac{18.01 \times 60}{U2}\right)$	
	3080	$RH1 = RH7$	Complete cathode air inlet def.
	3090	$PH3 = P3 - PW3$	Complete definition of H_2 inlet
	3100	$FH3 = VH3\left(\frac{2.016 \times 60}{U2}\right)$	
	3110	$EMOD = 16(E)$	
	3120	$POWER = (N)(I)(E)$	Calculate remaining module parameters
	3130	$TE = TI/0.0275$	
	3140	$PC2 = VC2\left(\frac{P2}{V2}\right)$	
	3150	$FC2 = FC1 - CTRANS$	
	3160	$FW2 = VW2\left(\frac{18.01 \times 60}{U2}\right)$	Complete definition of cathode air outlet
	3170	$RH2 = 100\left(\frac{PW2}{PHTO(T2)}\right)$	
	3180	$T4 = T2$	

Table 1 - continued

Symbol	Program Line Numbers	Description	Comments
	3190	$V9 = V3$	
	3200	$DW4 = 0.77\left(\frac{DW1 + DW2}{2}\right) + 0.23T2$	Refined H_2 dew point correlation
	3210	$PW4 = PHTO(DW4)$	
	3220	$VW4 = \frac{PW4}{P4-PW4}(VH4 + VC4)$	Complete definition of anode gas outlet
	3230	$V4 = VH4 + VC4 + VW4$	
	3240	$V4SL = V4(U4)$	
	3250	$VC4SL = VC4(U4)$	
	3260	$VH4SL = VH4(U4)$	
	3270	$FC4 = CTRANS$	Complete definition of anode gas outlet
	3280	$FH4 = VH4\left(\frac{2.016 \times 60}{U2}\right)$	
	3290	$FW4 = VW4\left(\frac{18.01 \times 60}{U2}\right)$	
	3300	$F4 = FC4 + FH4 + FW4$	
	3310	$CHWRTO = FC4/FH4$	
	3320	$HCVRTO = VHR/VC4$	
	3330	$P5 = P7$	
	3340	$DP56 = (V5)^2 C562 + V5(C561)$	Calculate cooling air pressure drop
	3350	$P6 = P5-DP56$	Calculate cooling air outlet pressure
	3360	$T6 = \frac{(V5A)T6A + (V5-V5A)T5}{V5}$	Calculate cooling air out temperature

Table 1 - continued



Symbol	Program Line Numbers	Description	Comments
	3370	IF VI $\leq$ 62 THEN PWRCTB = 2.8V + 153.8	
	3380	IF 62 < V1 $\leq$ 65 THEN PWRCTB = 40V1 - 2150	Calculate cathode air blower power
	3390	IF 65 < V1 $\leq$ 70 THEN PWRCTB = -34V± + 2660	
	3400	$T11 = T2 + \frac{PWRCTB(U3)}{V1 \cdot CPA}$	
	3410	V11 = V2	Define stream after cathode blower
	3420	P11 = P8	
	3430-3450	IF V5-V5MIN < 0.001(V5MIN) THEN PWRCLB = 0, $DP1213 = C12132(V5)^2$ AND BRANCH	Check if cooling blower is off
	3460	$DP1213 = C12132\ (V5MIN)^2$	
	3470	$TR = \left(\frac{DP78}{1.869} + 0.05\right)/1.3$	
	3480	$TR = TR^{(0.128 + 0.102(\frac{DP78}{1.869}))}$	Calculate cooling blower power
	3490	$PWH = 410 - 0.00396\ (V5-368)^2$	
	3500	$PWL = 410 - 0.00178\ (V5 - 306)^2$	
	3510	PWRCLB = TR (PWH) + (1-TR)(PWL)	
	3530	P12 = P8 + DP1213	
	3540	$+12 = T6 + \frac{PWRCTB(U3)}{V5(CPA)}$	
	3550	T13 = T12	Define cooling blower exit stream

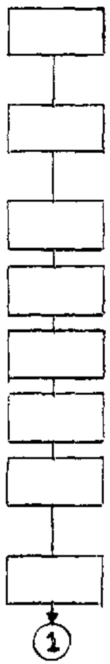
Table 1 - continued

Symbol	Program Line Numbers	Description	Comments
	3560	$V12 = V5$	
	3570	$P13 = P8$	
	3580	$V13 = V5$	
	3590	$V8 = V10 + V2 + V5$	
	3600	$VW8 = VW7 + VW2 - VW1$	
	3610	$VC8 = VC7 - VC4$	
	3620	$PC8 = \left(\frac{VC8}{V8}\right)P8$	Calculate plenum exit conditions
	3630	$VN8 = VN7$	
	3640	$PN8 = \left(\frac{VN8}{V8}\right) P8$	
	3650	$VO8 = VO7 - \frac{1}{2}(VH3 - VH4)$	
	3660	$PW8 = \left(\frac{VW8}{V8}\right) P8$	
	3670	$DW8 = DEWT\ (PW8)$	
	3680	$T8 = \frac{T11(V11) + T13(V13)}{V8} + \frac{T7(V10) + POWER\ \frac{U3}{CPA}}{V8}$	
	3690	$RH8 = \frac{100 \times PW8}{PHTO\ (T8)}$	
	3700	$AV7 = \frac{V7(T7 + 460)}{P7}\left(\frac{760}{530}\right)$	

Table 1 - continued

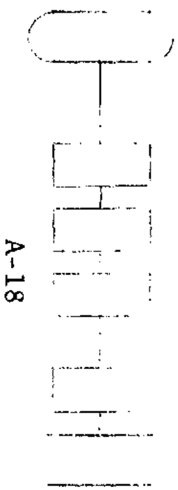
Symbol	Program Line Numbers	Description	Comments
	3710	$AV1 = V1\ (AV7/V7)$	Calculate actual stream flow rates
	3720	$AV2 = \frac{V2(T2 + 460)}{P2} \times 1.434$	
	3730	$AV11 = \frac{V11(T11 + 460)}{P11}\ (1.434)$	
	3740	$AV9 = \frac{V9(T9 + 460)}{P9}\ (1.434)$	
	3750	$AV3 = \frac{V3(T3 + 460)}{P3}\ (1.434)$	
	3760	$AV4 = \frac{V4(T4 + 460)}{P4}\ (1.434)$	
	3770	$AV5 = V5\ AV7/V7$	Calculate actual stream flow rates
	3780	$AV6 = \frac{V6(T6 + 460)}{P6}\ (1.434)$	
	3790	$V6A = V5A$	
	3800	$AV6A = \frac{V6A(T6A + 460)}{P6}\ (1.434)$	
	3810	$AV12 = \frac{V12(T12 + 460)}{P12}\ (1.434)$	
	3820	$AV13 = \frac{V13(T13 + 460)}{P13}\ (1.434)$	
	3830	$AV10EX = \frac{V10(T7 + 460)}{P8}\ (1.434)$	
	3840	$AV8 = \frac{V8(T8 + 460)}{P8}\ (1.434)$	
	3880	HRDWGT = 817.9	
	3890	PWRPC = 136	Calculate equivalent weight penalty
	3900	PWREC = 45	
	3910	PWRDAU = 100	

Table 1 - continued



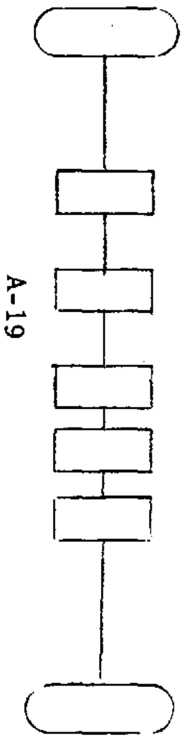
Symbol	Program Line Numbers	Description	Comments
	3920	PWRTOT = PWRPC + PWREC + PWRCLB + PWRCTB + PWRDAU	
	3930	HTTOT = HEATLD + U3(PWRTOT + POWER)	
	3940	PWRWGT = PWPEN(PWRTOT)	Calculate equivalent weight penalty
	3950	HTWGT = HTPEN(HTTOT)	
	3960	H2OWGT = H2OPEN(WPROD)	
	3970	OXWGT = OXPEN(OCON)	
	3980	EQWGT = PWRWGT + HTWGT + H_2OWGT + OXWGT + HRDWGT	
	3990-4710	WRITE OUT ALL OUTPUTS	
		END OF PROGRAM	

TABLE 2 WATER VAPOR PRESSURE FUNCTION



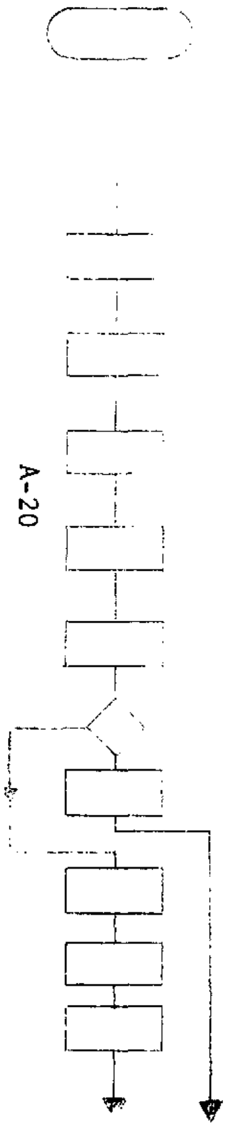
Symbol	Program Line Numbers	Description	Comments
	4750	FUNCTION PHTO(TF)	The input parameter is the Fahrenheit dew point temperature. The output parameter is pH_2O, in millimeters of mercury.
	4760-4770		Initialize constants A-G.
	4780	TC=(TF-32) 1.8	Calculate Centigrade dew point temperature.
	4790	X = 374.11 - TC	Calculate the temperature span from the dew point to the critical temperature.
	4800	$PHTO=10^{\left(EE-\frac{X}{TC+F} \times \frac{A+BX+CX^3}{1+DX}\right)}$	Calculate water vapor pressure
	4810	RETURN	

TABLE 3 DEW POINT TEMPERATURE FUNCTION



Symbol	Program Line Numbers	Description	Comments
	4840	FUNCTION DEWT(P)	The input parameter P is the water vapor pressure in millimeters of mercury. The output parameter DEWT is the Fahrenheit dew point temperature
	4850	EXTERNAL ROOT, PHTO	Functions ROOT and PHTO are used by function DEWT
	4860	X=ALOG(P)	Calculate two trial values for the dew point temperature
	4870	TA=-2.4 + 20.25X + 1.522X^2	
	4880	TB=TA + 0.1	
	4890	DEWT=ROOT(TA,TB,PHTO,P,0.005, 0.005, 5)	Function ROOT will call function PHTO starting with dew points equal to TA and TB until the water vapor pressure is equal to P with temperature and vapor pressure tolerances of point .005 but not exceeding five trials.
	7700	RETURN	

TABLE 4 TRANSFER INDEX FUNCTION



Program Line Numbers	Description	Comments
4930	FUNCTION TICOR(PC,AF,CD,DEL)	Input parameters are CO_2 partial pressure in millimeters of mercury, cathode air flow in Cfm/cell, current density in Amp/Ft^2, and module temperature - inlet cathode air dew point temperature. The output parameter is TICOR in Lb CO_2/Lb O_2.
4940-5010		Initialize the correlation parameters in array S.
5020	$PA=PC\ (\frac{AF}{.44})^{(1+.84P)^{-.84P}}$	PA is the effective inlet pCO_2 corrected for nonbaseline cathode air flow.
5030	$J=\frac{CD}{5} - 1$	Calculate the J index which corresponds to current density.
5040	IF(J < 1)J=1	For current densities less than 10 ASF, extrapolate from 15 and 10 ASF.
5050	$TI1= \sum_{i=1}^{5} S_{ij}PA^i$	Calculate TI at the current density just below the actual current density.
5060	If (J < 7) BRANCH	Current density should not exceed 40 ASF.
5070	TICOR = TI1	
5090	J = J + 1	Calculate TI at the current density just above the actual current density.
5100	$TI2 = \sum_{i=1}^{5} S_{ij}PA^i$	
5110	AII=J	Interpolate between the two current densities.

-continued-

Table 4 - continued

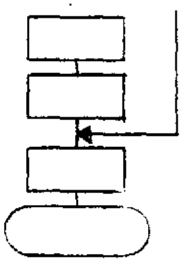
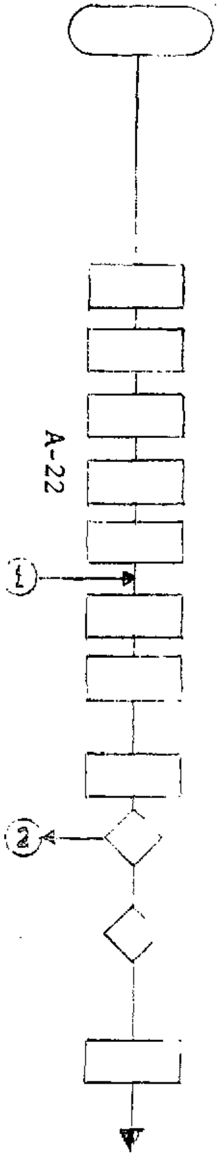
Symbol	Program Line Numbers	Description	Comments
	5120	TERP = $\frac{CD}{5}$ - AII	
	5130	TICOR=TI2xTERP+TI1(1-TERP)	
	5140	TICOR=TICOR(1+.03536(DEL-18.33))	Correct TI for moisture conditions.
	5050	RETURN	

TABLE 5 ROOT FUNCTION



Symbol	Program Line Numbers	Description	Comments
	5180	FUNCTION ROOT(X1,X2,YFCN,W,XTOL, YTOL,K)	Input parameters are the first and second trial root values, the function to be called which returns the function of X, the value of the function at the desired root, X tolerance, Y tolerance, and maximum trials. The output value, ROOT, is the value of X when the function equals W.
	5190-5200		Initialize common and external statements.
	5210	XA=X1	Isolate X1 and X2.
	5220	XB=X2	
	5230	FA=YCFN(XA) - W	Find the error values at XA and XB.
	5240	FB=YCFN(XB)-W	
	5250	BEGIN LOOP	
	5260	$XN=\frac{FA \cdot XB-FB \cdot XA}{FA-FB}$	Extrapolate from the previous two trial values.
	5270	FN=YFCN(XN)-W	Calculate the error at the next X value.
	5280-5290	IF(|FN| < YTOL and |XN-XB| < XTOL) BRANCH	BRANCH when the X and Y values are within tolerance.
	5300-5320	IF(Kth TIME THRU LOOP) DUMP VARIABLES & PRINT MESSAGE "NONCONVERGENCE IN LOOP"	If the root has not been found within K trials, print a message.
	5330	XA=XB	Drop the oldest trial value and add the new trial value.

-continued-

Table 5 - continued

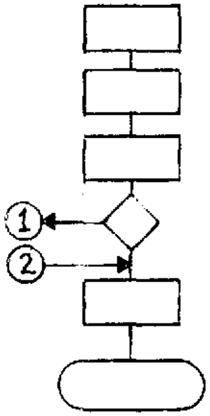
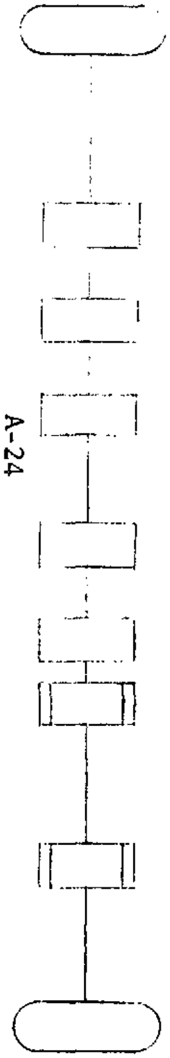
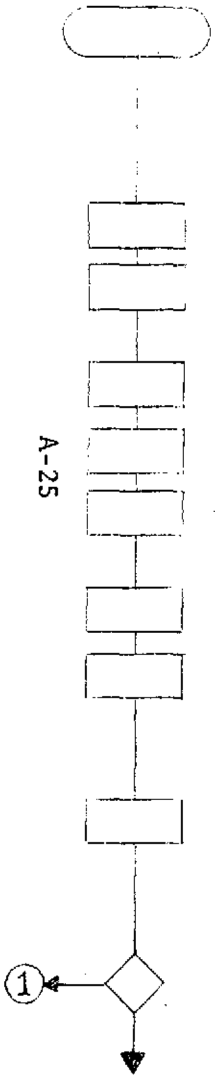
Symbol	Program Line Numbers	Description	Comments
	5340	XB=XN	
	5350	FA=FB	
	5360	FB=FN	
	5370	IF(<Kth TIME THRU LOOP)BRANCH	
	5380	ROOT = XN	The root of the function returned is the latest trial value.
	5390	RETURN	

TABLE 6 MODULE TEMPERATURE SUBROUTINE



Symbol	Program Line Numbers	Description	Comments
	5420	SUBROUTINE TDRIFT	Subroutine TDRIFT calculates the module temperature when the cooling air flow rate is specified. All inputs are through common storage. All outputs except P2 are also through common storage.
	5430-5460		Initialize type, common, and external statements.
	5470	ENTHPR=VI·CPA·T1+V3·CPH·T3	Calculate enthalpy entering the modules in the cathode air and inlet hydrogen streams.
	5480	$T2HIGH=\frac{ENTHPR+.99\cdot HEATLD}{V1\cdot CPA+V3\cdot CPH}$	Calculate maximum possible module temperature. This is the temperature the module would rise to with no cooling air.
	5490	$T2LOW=\frac{EHTHPR+V5A\cdot CPA\cdot T5+HEATLD}{V1\cdot CPA+V3\cdot CPA+V5A\cdot CPA}$	Calculate the minimum module temperature which would occur with no heat transfer resistance.
	5500	T2=T2HIGH	Call subroutine ERT to determine values of the heat transfer coefficient and the cooling fin efficiency, neither of which depends upon module temperature but only upon cooling air flow rate which is constant when subroutine TDRIFT is called.
	5510	DUMMY=ERT(V5A/N)	
	5520	T2=ROOT(T2HIGH,T2LOW,ERT1,0, 0.005, 0.005, 0.20)	Start with trial values T2HIGH and T2LOW and use function ERT1 to find the module temperature which yields a heat balance for the specified cooling air flow rate.
	5530	RETURN	

TABLE 7. HEAT BALANCE FUNCTION WITH VARIABLE MODULE TEMPERATURE



Symbol	Program Line Numbers	Description	Comments
	5560	FUNCTION ERT1(T)	The input parameter is the module temperature. The output parameter, ERT1, is the difference between the available module cooling air temperature drop and the required module cooling air temperature drop.
	5570-5590		Initialize type, common statements.
	5600	$E = 0.729 - 0.221 \ln I + 0.0081 + 0.005(T-78)$	Calculate module voltage and heat load at the given temperature.
	5610	HEATLD=N·I·(1.25-E)·3.419	
	5620	DHA=V1(CPA)(T-T1)	Calculate the enthalphy change for the cathode air process hydrogen and cooling air flow, respectively, at the given module temperature.
	5630	DHH=V3(CPH)(T-T3)	
	5640	DHC=HEATLD-DHA-DHH	
	5650	$T6A=T5 + \frac{DHC}{V5A(CPA)}$	Calculate the outlet cooling air temperature from the inlet cooling air temperature and the enthalpy increase.
	5660	$DTREQ=DHC\left(0.376 + 3.876\frac{HC \cdot ETA}{N}\right)$	The required module cooling air temperature difference depends upon the cooling air enthalpy change x the resistance in the fin roots + the gas film resistance.
1	5670	IF(T6A < T)BRANCH	If the cooling air temperature at the exit is less than the module temperature, then the log mean temperature difference can be calculated.

-continued

Table 7 - continued

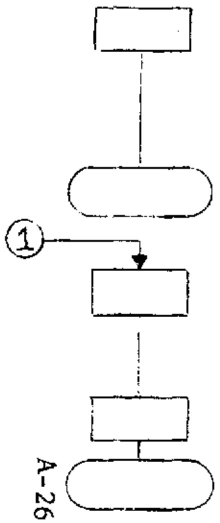
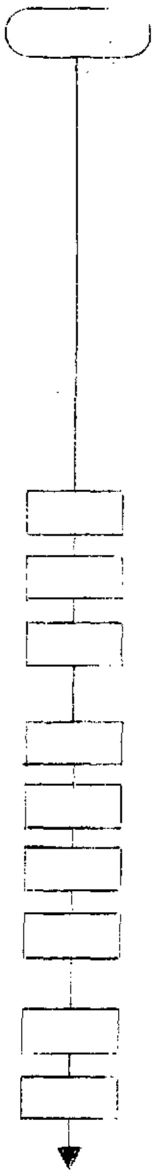
Symbol	Program Line Numbers	Description	Comments
	5680	ERT1 = -DTREQ	If it is not, then assume that the available temperature difference is zero and the error is equal to the required temperature difference.
	5690	RETURN	
	5700	$DTAVA = \frac{T6A-T5}{\ln\frac{T-T5}{T-T6A}}$	The available temperature drop is the log mean of the module cooling air temperature difference at the inlet and the outlet of the cooling air passages.
	5710	ERT1 = DTAVA-DTREQ	
	5720	RETURN	

TABLE 8 HEAT BALANCE FUNCTION WITH VARIABLE COOLING AIR FLOW RATE



Symbol	Program Line Numbers	Description	Comments
	5750	FUNCTION ERT(V)	The input parameter is the cooling air flow rate, Cfm/cell. The output parameter ERT is the difference between the available and required module-cooling air temperature differences. Inputs taken from common storage include the inlet cooling air and cathode air temperature, the cooling air heat load, the cooling air specific heat, the number of active cells, and the module temperature. Outputs through common storage include the heat transfer coefficient, the fin efficiency, the outlet cooling air temperature, the available temperature difference, and the required temperature difference.
	5760-5780		
	5790	IF $(V \leq 1) HC=1.97V^{0.3333}$	Calculate the heat transfer coefficient.
	5800	IF $(1 < V < 2.9883) HC=1.21 + 0.34V + 0.42V^2$	
	5810	If $(2.9883 \leq V \leq 4) HC=2V$	
	5820	IF $(4 < V) HC=2.639016V^{.8}$	
	5830	ETA=1	Calculate the fin efficiency.
	5840	IF $(0.32194 < V \leq 24.72) ETA= 1.0644 - 0.1135V^{0.5}$	
	5850	IF $(24.72 \leq V) ETA=2.486V^{-0.5}$	
	5860	$T6A=T5 + \frac{DHC}{V(CPA)N}$	

-continued-

Table 8 - continued

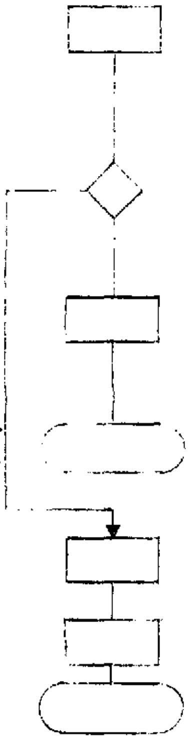
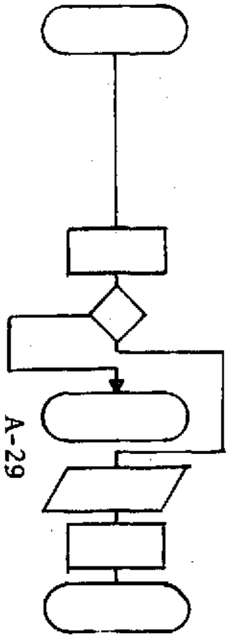
Symbol	Program Line Numbers	Description	Comments
	5870	$DTREQ=\frac{DHC}{N}\left(0.376+\frac{3.876}{HC(ETA)}\right)$	Calculate the required temperature difference from the cooling air heat load, resistance in the fins, and resistance in the stagnant air film.
	5880	IF (T6A < T2) BRANCH	Branch and calculate the log mean temperature difference only if the outlet cooling air temperature is less than the module temperature
	5890	ERT = -DTREQ	There is no available temperature difference. The error ERT is minus the required temperature difference.
	5900	RETURN	
	5910	$DTAVA=\dfrac{T6A-T5}{\ln\frac{T2-T5}{T2-T6A}}$	Log mean module cooling air temperature difference.
	5920	ERT=DTAVA-DTREQ	
	5930	RETURN	

TABLE 9 RANGE TEST SUBROUTINE



Symbol	Program Line Numbers	Description	Comments
	5960	SUBROUTINE T(VARNAM,VAR,BOT, TOP,I)	Subroutine input parameters are the variable, value, the lower and upper limits, and the out-of-range counter. The subroutine simply prints a message containing the first four parameters when the variable is out-of-range.
	5970	COMMON IOUT	The message is printed on output device IOUT.
	5980	IF (BOT ≤ VAR ≤ TOP) BRANCH	The subroutine ends immediately if the variable is in range.
	5980	RETURN	
	5990	WRITE, VARNAM, VAR, BOT, TOP	
	6000	I=I+1	
	6010	RETURN	

TABLE 10 BASE PROGRAM LISTING

BASE

```
100C
110C      *** CS-6 MATH MODEL BASE PROGRAM ***
120C
130$TTY,84
140$NDM
150 REALN,I
160 COMMON IOUT,CPA,CPH,DHC,DHA,DHH,HEATLD,DTREQ,DTAVA,N,I,E,
170&HC,ETA,V1,V3,V5A,T6A,T5,T3,T1,T2
180 EXTERNAL ERT,ERT1,PHTO
190 DATA CPA,CPH/1.0765,1.0666/
200&,U1,U2,U3,U4/51.7007,386.7,3.419,28.32/
210&,C782,C562,C561,C12132/2.25E-5,1.303E-5,.0101,8.6118E-4/
220 C5132=C562+C12132
230 C5131=C561
240 QA=C5132-C782
250 IOUT=1
260 PRINT,"FILE INPUT (T OR F)",:*
270 READ,?FIN
280 INP=50
290 IF(?FIN)INP=2
300 IF(?FIN)CALL OPENF(2,"MATHIN")
310 PRINT,"FILE OUTPUT (T OR F)",:*
320 READ,?FOUT
330 IF(.NOT.?FOUT)IOUT=66
340 GOTO6
350 1 CONTINUE
360 IF(.NOT.?FOUT)GOTO6
370 IF(.NOT.?FIN)PRINT,"FILE FOR OUTPUT",:*
380 READ(INP,48)FNAME
390 48 FORMAT(A6)
400 IF(FNAME.EQ."WAIT")GOTO6
410 END FILE 1
420 CALL CLOSEF(1,FNAME,?)
430 REWIND 1
440 6 CONTINUE
450 IF(.NOT.?FIN)PRINT,"INPUT DATA",:*
460 READ(INP,)POPSA,PCO,POOPSA,P8PSA,T7,V7,DW7,P4PSA,T9,V9SL,DW9,
470&N,I,DELT1,V1,PWPEN,HTPEN,H2OPEN,OXPEN,NFLAG
480C
490C   INPUT DATA PLAYBACK:
500C
510 WRITE(IOUT;4)
520 WRITE(IOUT;230)
530 4 FORMAT(/////)
540 230FORMAT(" **********INPUT DATA**********")
550 WRITE(IOUT;1017)
560 1017FORMAT(" CABIN ATMOSPHERE:")
570 WRITE(IOUT;944)"POPSA",POPSA,"PCO",PCO,"POOPSA",POOPSA
580 WRITE(IOUT;1032)
590 1032FORMAT(" PROCESS AIR OUTLET/INLET:")
```


continued-

Table 10 - continued

```
600 WRITE(IOUT;944)"P8PSA",P8PSA,"T7 ",T7,"V7 ",V7,"DW7",DW7
610 WRITE(IOUT;1031)
620 1031FORMAT(" H2 OUTLET/INLET:")
630 WRITE(IOUT;944)"P4PSA",P4PSA,"T9 ",T9,"V9SL",V9SL,"DW9",DW9
640 WRITE(IOUT;1020)
650 1020FORMAT(" MODULES:")
660 WRITE(IOUT;944)"N   ",N,"I   ",I,"DELT1",DELT1,"V1 ",V1
670 WRITE(IOUT;1021)
680 1021FORMAT(" PENALTY WEIGHT FACTORS:")
690 WRITE(IOUT;944)"PWPEN",PWPEN,"HTPEN",HTPEN,"H2OPEN",H2OPEN,
700&"OXPEN",OXPEN
710 WRITE(IOUT;1022)
720 1022FORMAT(" PROGRAM CONTROL:")
730 WRITE(IOUT;944)"NFLAG",NFLAG
740 WRITE(IOUT;220)
750 220 FORMAT(" ***********RESULTS************")
760C
770C   CHECK INPUTS:
780C
790 IR=0
800 CALLT("POPSA ",POPSA,13.7,15.7,IR)
810 CALLT("PCO   ",PCO,.5,10.,IR)
820 CALLT("POOPSA",POOPSA,2.,4.,IR)
830 CALLT("P8PSA ",P8PSA,13.7,15.7,IR)
840 CALLT("T7    ",T7,44.,80.,IR)
850 CALLT("V7    ",V7,0.,600.,IR)
860 CALLT("DW7   ",DW7,41.,70.,IR)
870 CALLT("P4PSA ",P4PSA,14.8,21.2,IR)
880 CALLT("T9    ",T9,65.,75.,IR)
890 CALLT("V9SL  ",V9SL,0.,18.,IR)
900 CALLT("DW9   ",DW9,10.,75.,IR)
910 CALLT("N     ",N,90.,96.,IR)
920 CALLT("I     ",I,2.44,9.76,IR)
930 CALLT("DELT1 ",DELT1,10.,25.,IR)
940 CALLT("V1    ",V1,19.2,76.8,IR)
950 CALLT("PWPEN ",PWPEN,0.,2.,IR)
960 CALLT("HTPEN ",HTPEN,0.,2.,IR)
970 CALLT("H2OPEN",H2OPEN,0.,500.,IR)
980 CALLT("OXPEN ",OXPEN,0.,3000.,IR)
990 FLAG=NFLAG
1000 CALLT("NFLAG ",FLAG,0.,1.,IR)
1010 IF(IR.GT.0)GOTO1
1020C
1030C   CHECK FOR SUFFICIENT H2:
1040C
1050 V9MSL=1.3*N*I*7.508E-3
1060 IF(V9SL.GE.V9MSL)GOTO1213
1070 WRITE(IOUT;213)V9MSL
1080 213 FORMAT(" INSUFFICIENT H2.",G10.4," SLPM IS REQUIRED")
1090 GOTO1
```


continued-

Table 10 - continued

```
1213 CONTINUE
C
C   CHECK CATHODE AIR CAPACITY:
C
IF(V1.LE.70)GOTO9001
V1=70.
WRITE(IOUT;9000)
9000FORMAT(" V1 HAS BEEN CHANGED TO 70 SCFM, BLOWER CAPACITY.")
9001 CONTINUE
C
C   CALC. COOLING AIR FLOW WITH COOLING BLOWERS OFF:
C
V7M1=V7-V1
QB=C5131+2.*C782*V7M1
QC=C782*V7M1**2
V5MIN=(-QB+SQRT(QB*QB+4.*QA*QC))/(2.*QA)
C
C   CALC. COOLING AIR HEAT LOAD, ETC. FOR INPUT MODULE TEMP:
C
DW1=DW7
T2=DW1+DELT1
T2INP=T2
E=.729-.22*ALOG(I)+.008*I+.005*(T2-78.)
HEATLD=N*I*(1.25-E)*U3
T1=T7
T3=T9
V3=V9SL/U4
T5=T1
DHA=V1*CPA*(T2-T1)
DHH=V3*CPH*(T2-T3)
DHC=HEATLD-DHA-DHH
C
C   CHECK NEED FOR COOLING:
C
IF(DHC.GT.0)GOTO898
C
C   CALC. NEW MODULE TEMP IF COOLING BLOWERS ARE OFF:
C
888 CONTINUE
V5=V5MIN
V5A=N*V5MIN/96.
CALL TDRIFT
DROP=T2INP-T2
WRITE(IOUT;944)"V5MIN",V5MIN
WRITE(IOUT;469)DROP,T2INP,T2
469 FORMAT(" COOLING BLOWERS ARE OFF."/" MODULE TEMPERATURE FALLS",
&F6.2,"F BELOW THE DESIRED",F6.2,"F TO",F6.2,"F.")
GOTO766
C
C   CHECK THAT MODULE TEMP IS HIGH ENOUGH TO TRANSFER HEAT
```


continued-

Table 10 - continued

```
1600C   AT LEAST TO COOLING FIN ROOTS:
1610C
1620 898 CONTINUE
1630 IF(T2-T5.GE..376*DHC/N)GOTO765
1640C
1650C   CALC. NEW MODULE TEMP IF COOLING BLOWERS ARE ON FULL:
1660C
1670 886 CONTINUE
1680 V5=440.
1690 V5A=V5*N/96.
1700 CALL TDRIFT
1710 RISE=T2-T2INP
1720 WRITE(IOUT;479)RISE,T2INP,T2
1730 479 FORMAT(" COOLING BLOWERS ARE ON FULL."/" MODULE TEMPERATURE RISES",
1740&F6.2,"F ABOVE THE DESIRED",F6.2,"F TO",F6.2,"F.")
1750 GOTO766
1760C
1770C   CALC. COOLING AIR FLOW FOR INPUT MODULE TEMPERATURE:
1780C
1790 765 CONTINUE
1800 VA=1.01*DHC/(CPA*N*(T2-T5))
1810 VB=2.*VA
1820 V5A=N*ROOT(VA,VB,ERT,0.,.005,.001,20)
1830 V5=96.*V5A/N
1840 V5INP=V5
1850C
1860C   ARE COOLING BLOWERS OUT OF RANGE:
1870C
1880 IF(V5.LT.V5MIN)GOTO888
1890 IF(V5.GT.440.)GOTO886
1900 WRITE(IOUT;3950)
1910 3950 FORMAT(" DESIRED MODULE TEMPERATURE IS MAINTAINED WITH",
1920&" COOLING BLOWERS AT PARTIAL CAPACITY.")
1930C
1940C   MODULE HEAT BALANCE IS MAINTAINED WITH COOLING BLOWERS IN RANGE:
1950C
1960 766 CONTINUE
1970 V10=V7-V1-V5
1980 WRITE(IOUT;944)"V5INP",V5INP
1990C
2000C   CHECK PLENUM BYPASS FLOW:
2010C
2020 IF(V10.GE..05*V7)GOTO244
2030 WRITE(IOUT;242)
2040 WRITE(IOUT;944)"V10",V10
2050 242FORMAT(" INSUFFICIENT INLET PROCESS AIR TO ",
2060&"PREVENT BACKMIXING THROUGH PLENUM BYPASS.")
2070 GOTO1
2080C
2090C   CALC. STREAM PARAMETERS REQUIRED FOR MOISTURE BALANCE CHECKS:
```


continued-

Table 10 - continued

```
2100C
2110 244 CONTINUE
2120 COR34=(14.1/P4PSA)**.8
2130 P4=P4PSA*U1
2140 V3SL=V9SL
2150 DP34=.3822*COR34*V3SL
2160 IF(V3SL.GT.22.)DP34=COR34*(8.3183+.4187*(V3SL-21.5801)**1.75)
2170 P3=P4+DP34
2180 P3PSA=P3/U1
2190 COR93=(14.1/P3PSA)**.8
2200 DP93=COR93*10.64*V3SL
2210 IF(V3SL.GT.6.2)DP93=COR93*(35.14*V3SL-195.25+EXP(7.75-.6537*V3SL))
2220 P9=P3+DP93
2230 P9PSA=P9/U1
2240 DP78=C782*V10*V10
2250 P8=P8PSA*U1
2260 P7=P8+DP78
2270 P7PSA=P7/U1
2280 DP12=V1*(.001903*V1+.04877)
2290 P1=P7
2300 P2=P1-DP12
2310 PC1=PC0*P7PSA/P0PSA
2320 CURDEN=I/.244
2330 DELT1E=T2-DW1
2340 TI=TICOR(PC1,V1/96.,CURDEN,DELT1E)
2350 OCON=6.5803E-4*N*I
2360 CTRANS=TI*OCON
2370 HCON=OCON*2.016/16.
2380 WPROD=OCON+HCON
2390 VC4=CTRANS*U2/(44.01*60.)
2400 PW9=PHTO(DW9)
2410 PW3=P3*PW9/P9
2420 VH3=V3*(1.-PW3/P3)
2430 VH4=VH3-HCON*U2/(2.016*60.)
2440C TRIAL VALUE OF H2+CO2 OUTLET WATER VAPOR PRESSURE:
2450 PW4=PHTO(T2-6.)
2460 VW4=PW4*(VC4+VH4)/(P4-PW4)
2470 DW1=DW7
2480 PW1=PHTO(DW1)
2490 VW1=V1*PW1/P1
2500 VW3=V3-VH3
2510 VWPROD=WPROD*U2/(18.01*60.)
2520 VW2=VW1+VW3-VW4+VWPROD
2530 PO0=PO0PSA*U1
2540 PO7=PO0*P7PSA/P0PSA
2550 PO1=PO7
2560 PN1=P1-PO1-PW1-PC1
2570 VN1=V1*PN1/P1
2580 VO1=V1*PO1/P1
2590 VC1=V1*PC1/P1
```


continued-

Table 10 - continued

```
VN2=VN1
VO2=VO1-OCON*U2/(32.*60.)
VC2=VC1-VC4
V2=VO2+VN2+VW2+VC2
PW2=VW2*P2/V2
DW2=DEWT(PW2)
C
C   CHECK MODULE MOISTURE BALANCE:
C
DDP1=T1-DW1
DDP2=T2-DW2
IF(ABS(DDP1-11.25).LE.1.75 .AND.ABS(DDP2-11.25).LE.1.75)GOTO30
IF(DDP1.LT.4.)GOTO1210
IF(DDP1.GT.14.)GOTO1210
IF(DDP2.LT.7.)GOTO1211
IF(DDP2.GT.19.)GOTO1211
DPTDAV=.5*(DDP1+DDP2)
IF(ABS(DPTDAV-11.).LE.1.5 .AND. (DDP2.GE.13. .OR. DPTDAV.GE.10.))GOTO30
WRITE(IOUT;654)
654FORMAT(" AVERAGE CATHODE AIR DEWPOINT DEPRESSION OUT OF RANGE.")
28 WRITE(IOUT;543)
WRITE(IOUT;944)"T1 ",T1,"DDP1",DDP1,"T2 ",T2,"DDP2",DDP2
543FORMAT(" ELECTROLYTE MOISTURE BALANCE IS NOT MAINTAINED.")
IF(NFLAG.EQ.1)GOTO1
GOTO30
1210 WRITE(IOUT;432)
432FORMAT(" INLET CATHODE AIR DEWPOINT DEPRESSION OUT OF RANGE.")
GOTO28
1211 WRITE(IOUT;321)
321FORMAT(" OUTLET CATHODE AIR DEWPOINT DEPRESSION OUT OF RANGE.")
GOTO28
C
C   COMPLETE ALL STREAM DEFINITIONS:
C
30 CONTINUE
DELT1P=22.-T1+DW2
T2P=DW1+DELT1P
PW7=PW1
PN7=PN1
PC7=PC1
VC7=PC7*V7/P7
VW7=PW7*V7/P7
PO7=PO1
VO7=PO7*V7/P7
VN7=PN7*V7/P7
RH7=100.*PW7/PHTO(T7)
FC1=VC1*44.01*60./U2
FW1=VW1*18.01*60./U2
RH1=RH7
PH3=P3-PW3
```


continued-

Table 10 - continued

```
3100 FH3=VH3*2.016*60./U2
3110 EMOD=16.*E
3120 POWER=N*I*E
3130 TE=TI/.0275
3140 PC2=VC2*P2/V2
3150 FC2=FC1-CTRANS
3160 FW2=VW2*18.01*60./U2
3170 RH2=100.*PW2/PHTO(T2)
3180 T4=T2
3190 V9=V3
3200 DW4=.77*(DW1+DW2)/2. + .23*T2
3210 PW4=PHTO(DW4)
3220 VW4=PW4*(VH4+VC4)/(P4-PW4)
3230 V4=VH4+VC4+VW4
3240 V4SL=V4*U4
3250 VC4SL=VC4*U4
3260 VH4SL=VH4*U4
3270 FC4=CTRANS
3280 FH4=VH4*2.016*60./U2
3290 FW4=VW4*18.01*60./U2
3300 F4=FC4+FH4+FW4
3310 CHWRTO=FC4/FH4
3320 HCVRTO=VH4/VC4
3330 P5=P7
3340 DP56=V5*(V5*C562+C561)
3350 P6=P5-DP56
3360 T6=(V5A*T6A+(V5-V5A)*T5)/V5
3370 IF(V1.LE.62.)PWRCTB=2.8*V1+153.8
3380 IF(V1.GT.62. .AND. V1.LE.65.)PWRCTB=40.*V1-2150.
3390 IF(V1.GT.65.)PWRCTB=-34.*V1+2660.
3400 T11=T2+PWRCTB*U3/(V1*CPA)
3410 V11=V2
3420 P11=P8
3430 PWRCLB=0.
3440 DP1213=C12132*V5*V5
3450 IF(V5.LT.1.01*V5MIN)GOTO14
3460 DP1213=C12132*V5MIN*V5MIN
3470 TR=(DP78/1.869+.05)/1.3
3480 TR=TR**(.128+.102*DP78/1.869)
3490 PWH=410.-.00396*(V5-368)**2
3500 PWL=410.-.00178*(V5-306.)**2
3510 PWRCLB=TR*PWH+(1.-TR)*PWL
3520 14CONTINUE
3530 P12=P8+DP1213
3540 T12=T6+PWRCLB*U3/(V5*CPA)
3550 T13=T12
3560 V12=V5
3570 P13=P8
3580 V13=V5
3590 V8=V10+V2+V5
```

continued-

Table 10 - continued

```
3600 VW8=VW7+VW2-VW1
3610 VC8=VC7-VC4
3620 PC8=VC8*P8/V8
3630 VN8=VN7
3640 PN8=VN8*P8/V8
3650 VO8=VO7-.5*(VH3-VH4)
3660 PW8=P8*VW8/V8
3670 DW8=DEWT(PW8)
3680 T8=(T11*V11+T13*V13+T7*V10+POWER*U3/CPA)/V8
3690 RH8=100.*PW8/PHTO(T8)
3700 AV7=V7*(T7+460.)*1.434/P7
3710 AV1=V1*AV7/V7
3720 AV2=V2*(T2+460.)*1.434/P2
3730 AV11=V11*(T11+460.)*1.434/P11
3740 AV9=V9*(T9+460.)*1.434/P9
3750 AV3=V3*(T3+460.)*1.434/P3
3760 AV4=V4*(T4+460.)*1.434/P4
3770 AV5=V5*AV7/V7
3780 AV6=V5*(T6+460.)*1.434/P6
3790 V6A=V5A
3800 AV6A=V6A*(T6A+460.)*1.434/P6
3810 AV12=V12*(T12+460.)*1.434/P12
3820 AV13=V13*(T13+460.)*1.434/P13
3830 AV10EX=V10*(T7+460.)*1.434/P8
3840 AV8=V8*(T8+460.)*1.434/P8
3850C
3860C   EQUIVALENT WEIGHT CALCULATIONS:
3870C
3880 HRDWGT=817.9
3890 PWRPC=136.
3900 PWREC=45.
3910 PWRDAU=100.
3920 PWRTOT=PWRPC+PWREC+PWRCLB+PWRCTB+PWRDAU
3930 HTTOT=HEATLD+U3*(PWRTOT+POWER)
3940 PWRWGT=PWPEN*PWRTOT
3950 HTWGT=HTPEN*HTTOT
3960 H2OWGT=H2OPEN*WPROD
3970 OXWGT=OXPEN*OCON
3980 EQWGT=PWRWGT+HTWGT+H2OWGT+OXWGT+HRDWGT
3990C
4000C   MAJOR OUTPUT SATEMENTS
4010C
4020 WRITE(IOUT;456)DELT1P,T2P,DW1,DELT1P
4030 456 FORMAT(" PREFERRED VALUE OF DELT1 IS",F6.2,
4040&" UNDER THESE CONDITIONS"/" SO THAT",F6.2,
4050&" = T2 = DW1 + DELT1 =",F6.2," +",F6.2,".")
4060C
4070 944FORMAT(5X,A6,G10.4,3("  !  ",A6,G10.4))
4080C
4090 WRITE(IOUT;1020)
```


continued-

Table 10 - continued

```
4100 WRITE(IOUT;944)"TI ",TI,"TE ",TE,"E  ",E,"EMOD",EMOD,
4110&"CTRANS",CTRANS,"OCON",OCON,"HCON",HCON,"WPROD",WPROD,
4120&"CURDEN",CURDEN,"HEATLD",HEATLD,"POWER",POWER
4130C
4140 WRITE(IOUT;1014)
4150 1014FORMAT(" CATHODE AIR INLET:")
4160 WRITE(IOUT;944)"P1 ",P1,"PC1",PC1,
4170&"PW1",PW1,"FC1",FC1,"FW1",FW1,"VC1",VC1,"VW1",VW1,
4180&"VO1",VO1,"VN1",VN1,"T1 ",T1,"DW1",DW1,"RH1",RH1
4190C
4200 WRITE(IOUT;1024)
4210 1024FORMAT(" CATHODE AIR OUTLET:")
4220 WRITE(IOUT;944)"P2 ",P2,"DP12",DP12,"PC2",PC2,
4230&"PW2",PW2,"V2 ",V2,"VC2",VC2,"VW2",VW2,
4240&"VO2",VO2,"VN2",VN2,"FC2",FC2,"FW2",FW2,"T2 ",T2,"DW2",DW2,"RH2",RH2
4250&,"P11",P11,"V11",V11,"T11",T11
4260C
4270 WRITE(IOUT;1010)
4280 1010FORMAT(" PROCESS AIR INLET:")
4290 WRITE(IOUT;944)"P7 ",P7,"PW7",PW7,"PN7",PN7,"VC7",VC7,"VW7",VW7,"VO7",VO7,
4300&"VN7",VN7,"DW7",DW7,"RH7",RH7
4310C
4320 WRITE(IOUT;1015)
4330 1015FORMAT(" PROCESS AIR OUTLET:")
4340 WRITE(IOUT;944)"P8 ",P8,"PC8",PC8,"V10",V10,"DP78",DP78,
4350&"V8 ",V8,"VW8",VW8,"VC8",VC8,"VO8",VO8,"PW8",PW8,"T8 ",T8,
4360&"DW8",DW8,"RH8",RH8
4370C
4380 WRITE(IOUT;1019)
4390 1019FORMAT(" H2 INLET:")
4400 WRITE(IOUT;944)"P9 ",P9,"PW9",PW9,"DP93",DP93,"P3 ",P3
4410&,"PW3",PW3,"PH3",PH3,"V3 ",V3,"VH3",VH3,"VW3",VW3,"FH3",FH3,"V9MSL",V9MSL
4420C
4430 WRITE(IOUT;1013)
4440 1013FORMAT(" H2 OUTLET:")
4450 WRITE(IOUT;944)"P4 ",P4,"DP34",DP34,"PW4",PW4,"V4 ",V4,"VC4",VC4,
4460&"VH4",VH4,"VW4",VW4,"V4SL",V4SL,"VC4SL",VC4SL,"VH4SL",VH4SL,"F4 ",F4,
4470&"FC4",FC4,"FH4",FH4,"FW4",FW4,"DW4",DW4,"CHWRTO",CHWRTO,"HCVRTO",HCVRTO
4480C
4490 WRITE(IOUT;1023)
4500 1023FORMAT(" HEAT BALANCE, MODULES:")
4510 WRITE(IOUT;944)"HEATLD",HEATLD,"DHA",DHA,"DHH",DHH,"DHC",DHC
4520C
4530 WRITE(IOUT;1012)
4540 1012FORMAT(" COOLING AIR:")
4550 WRITE(IOUT;944)"P5 ",P5,"DP56",DP56,"P6 ",P6
4560&,"V5 ",V5,"T5 ",T5,"T6 ",T6,"HC ",HC,"ETA",ETA
4570&,"V5A",V5A,"T6A",T6A
4580&,"P12",P12,"V12",V12,"T12",T12,"DP1213",DP1213,"V5MIN",V5MIN
4590C
```

continued-

Table 10 - continued

```
WRITE(IOUT;1041)
1041FORMAT(" ACTUAL VOLUMETRIC FLOW RATES:")
WRITE(IOUT;944)"AV1",AV1,"AV2",AV2,"AV3",AV3,"AV4",AV4,"AV5",AV5,
&"AV6",AV6,"AV6A",AV6A,"AV7",AV7,"AV8",AV8,"AV9",AV9,
&"AV10EX",AV10EX,"AV11",AV11,"AV12",AV12,"AV13",AV13
C
WRITE(IOUT;1016)
1016FORMAT(" EQUIVALENT WEIGHT:")
WRITE(IOUT;944)"PWRCLB",PWRCLB,"PWRCTB",PWRCTB,"PWRPC",PWRPC,
&"PWREC",PWREC,"PWRDAU",PWRDAU,"PWRTOT",PWRTOT,"HTTOT",HTTOT,
&"PWRWGT",PWRWGT,"HTWGT",HTWGT,"H2OWGT",H2OWGT,"OXWGT",OXWGT,
&"HRDWGT",HRDWGT,"EQWGT",EQWGT
GOTO1
END
C
FUNCTIONPHTO(TF)
DATA A,B,C,D,EE,F,G/3.2437814,.00586826,1.1702379E-8,
& .0021878462,5.219603,273.16,2.3025851/
TC=(TF-32.)/1.8
X=374.11-TC
PHTO=EXP(G*(EE-(X/(TC+F))*(A+B*X+C*X**3)/(1.0+D*X)))
RETURN
END
C
FUNCTION DEWT(P)
EXTERNAL ROOT,PHTO
XX=ALOG(P)
TA=-2.4+20.25*XX+1.522*XX**2
TB=TA+.1
DEWT=ROOT(TA,TB,PHTO,P,.005,.005,5)
RETURN
END
C
FUNCTION TICOR(P,AF,CD,DEL)
REAL S(5,7)
DATA S/1.75187,-.511449,.0775073,-.00592584,.000179862,
& 1.42306,-.271935,.0210187,-.00034839,-1.8475E-5,
& 1.08190,-.110821,-.0081408,.00196359,-8.5832E-5,
&  .90258,-.105068,.0025161,.00028694,-1.3673E-5,
&  .71551,-.072213,.0024297,9.08E-6,-3.48E-7,
&  .61612,-.055237,.0003803,.00028605,-1.5623E-5,
&  .52087,-.035109,-.0014939,.00035115,-1.4808E-5/
PA=P*(AF/.44)**((.84*P+1.)*EXP(-.84*P))
J=CD/5.-1.
IF(J.LT.1)J=1
TI1=PA*(S(1,J)+PA*(S(2,J)+PA*(S(3,J)+PA*(S(4,J)+PA*S(5,J)))))
IF(J.LT.7)GO TO 8
TICOR=TI1
GOTO9
8 J=J+1
```


continued-

Table 10 - continued

```
TI2=PA*(S(1,J)+PA*(S(2,J)+PA*(S(3,J)+PA*(S(4,J)+PA*S(5,J)))))
AII=J
TERP=CD/5.-AII
TICOR=TI2*TERP+TI1*(1.-TERP)
9 TICOR=TICOR*(1.+.03536*(DEL-18.33))
RETURN
END
C
FUNCTION ROOT(X1,X2,YFCN,W,XTOL,YTOL,K)
COMMON IOUT
EXTERNAL YFCN
XA=X1
XB=X2
FA=YFCN(XA)-W
FB=YFCN(XB)-W
DO 91 IROOT=1,K
XN=(FA*XB-FB*XA)/(FA-FB)
FN=YFCN(XN)-W
IF(ABS(FN).LT.YTOL .AND.
&   ABS(XN-XB).LT.XTOL)GO TO 99
IF(IROOT.GE.K)WRITE(IOUT;200)X1,X2,W,XTOL,YTOL,IROOT,
& XA,XB,XN,FA,FB,FN
200 FORMAT( " NONCONVERGENCE IN ROOT",5G11.4,I3/7G11.4)
XA=XB
XB=XN
FA=FB
FB=FN
91 CONTINUE
99 ROOT=XN
RETURN
END
C
SUBROUTINE TDRIFT
REAL N,I
COMMON IOUT,CPA,CPH,DHC,DHA,DHH,HEATLD,DTREQ,DTAVA,N,I,E,
&HC,ETA,V1,V3,V5A,T6A,T5,T3,T1,T2
EXTERNAL ERT,ROOT,ERT1
ENTHPR=V1*CPA*T1+V3*CPH*T3
T2HIGH=(ENTHPR+.99*HEATLD)/(V1*CPA+V3*CPH)
T2LOW=(ENTHPR+V5A*CPA*T5+HEATLD)/(V1*CPA+V3*CPH+V5A*CPA)
T2=T2HIGH
DUMMY=ERT(V5A/N)
T2=ROOT(T2HIGH,T2LOW,ERT1,0.,.005,.005,20)
RETURN
END
C
FUNCTION ERT1(T)
REAL N,I
COMMON IOUT,CPA,CPH,DHC,DHA,DHH,HEATLD,DTREQ,DTAVA,N,I,E,
&HC,ETA,V1,V3,V5A,T6A,T5,T3,T1,T2
```

continued-

Table 10 - continued

```
E=.729-.22*ALOG(I)+.008*I+.005*(T-78.)
HEATLD=N*I*(1.25-E)*3.419
DHA=V1*CPA*(T-T1)
DHH=V3*CPH*(T-T3)
DHC=HEATLD-DHA-DHH
T6A=T5+DHC/(V5A*CPA)
DTREQ=DHC*(.376+3.876/(HC*ETA))/N
IF(T6A.LT.T)GOTO 1086
ERT1=-DTREQ
RETURN
1086 DTAVA=(T6A-T5)/ALOG((T-T5)/(T-T6A))
ERT1=DTAVA-DTREQ
RETURN
END
C
FUNCTION ERT(V)
REAL N,I
COMMON IOUT,CPA,CPH,DHC,DHA,DHH,HEATLD,DTREQ,DTAVA,N,I,E,
&HC,ETA,V1,V3,V5A,T6A,T5,T3,T1,T2
IF(V.LE.1.)HC=1.97*V**(.3333)
IF(V.GT.1. .AND. V.LT.2.9883)HC=1.21+V*(.34+.42*V)
IF(V.GE.2.9883 .AND. V.LE.4.)HC=2.*V
IF(V.GT.4.)HC=2.639016*V**(.8)
ETA=1.
IF(V.GT..32194 .AND. V.LT.24.72)ETA=1.0644-.1135*SQRT(V)
IF(V.GE.24.72)ETA=2.486/SQRT(V)
T6A=T5+DHC/(V*CPA*N)
DTREQ=DHC*(.376+3.876/(HC*ETA))/N
IF(T6A.LT.T2)GO TO 86
ERT=-DTREQ
RETURN
86 DTAVA=(T6A-T5)/ALOG((T2-T5)/(T2-T6A))
ERT=DTAVA-DTREQ
RETURN
END
C
SUBROUTINET(VARNAM,VAR,BOT,TOP,I)
COMMON IOUT
IF(VAR.GE.BOT.AND.VAR.LE.TOP)RETURN
WRITE(IOUT;10)VARNAM,VAR,BOT,TOP
I=I+1
RETURN
10FORMAT(1X,A6,"=",G10.4," RANGE: ",2G10.4)
END
```

TABLE 11 CHECKS AND MESSAGES

1.	CONDITION:	An input variable is out of the prediction range.
	MESSAGE:	VARIABLE = XX.XX RANGE: XX.XX XX.XX
2.	CONDITION:	Less than 1.3 times stoichiometric amount of H_2 is supplied.
	MESSAGE:	INSUFFICIENT HYDROGEN. XXX.XX SLPM IS REQUIRED.
3.	CONDITION:	Cathode air blowers cannot supply the requested flow rate. Program sets the flow equal to blower capacity.
	MESSAGE:	V1 HAS BEEN CHANGED TO 70 SCFM, BLOWER CAPACITY.
4.	CONDITION:	Not enough heat is generated in the modules to attain the setpoint module temperature.
	MESSAGE:	COOLING BLOWERS ARE OFF. MODULE TEMPERATURE FALLS X.XXF BELOW THE DESIRED XX.XXF TO XX.XXF.
5.	CONDITION:	Process streams and cooling air cannot remove enough heat to maintain the setpoint module temperature.
	MESSAGE:	COOLING BLOWERS ARE ON FULL. MODULE TEMPERATURE RISES X.XXF ABOVE THE DESIRED XX.XXF TO XX.XXF.
6.	CONDITION:	Normal heat balance is attained.
	MESSAGE:	DESIRED MODULE TEMPERATURE IS MAINTAINED WITH COOLING BLOWERS AT PARTIAL CAPACITY.
7.	CONDITION:	Process air flow does not exceed cathode air plus cooling air flow by at least 5%.
	MESSAGE:	INSUFFICIENT PROCESS AIR TO PREVENT BACKMIXING THROUGH PLENUM BYPASS.
8.	CONDITION:	Inlet process air moisture conditions are out of tolerance and will not support steady state cell operation.
	MESSAGE:	INLET PROCESS AIR DEW POINT DEPRESSION OUT OF RANGE. ELECTROLYTE MOISTURE BALANCE IS NOT MAINTAINED.
9.	CONDITION:	Outlet process air moisture conditions are out of tolerance and will not support steady state cell operation.
	MESSAGE:	OUTLET PROCESS AIR DEW POINT DEPRESSION OUT OF RANGE. ELECTROLYTE MOISTURE BALANCE IS NOT MAINTAINED.

continued-

Table 11 - continued

10.	CONDITION:	Average of inlet and outlet process air moisture condition is out of tolerance and will not support steady state cell operation.
	MESSAGE:	AVERAGE PROCESS AIR DEW POINT DEPRESSION OUT OF RANGE. ELECTROLYTE MOISTURE BALANCE IS NOT MAINTAINED.
11.	CONDITION:	Convergence subroutine (ROOT) did not approach a solution within the specified number of iterations.
	MESSAGE:	NONCONVERGENCE IN ROOT (PRINT ROOT PARAMETERS)

TABLE 12 NOMENCLATURE AND UNITS

Composite Variable Names

First Prefix	P	(Partial) Pressure, mm Hg
	V	Volume Flow Rate, Scfm 70F, 760 mm Hg
	AV	Volume Flow Rate, Cfm
	F	Mass Flow Rate, Lb/Hr
	DP	Pressure Drop
	DW	Dew Point, F
	T	Temperature, F
	RH	Relative Humidity, %
Second Prefix	C	Carbon Dioxide (CO_2)
	O	Oxygen (O_2)
	N	Nitrogen (N_2)
	H	Hydrogen (H_2)
	W	Water (H_2O)
	(None)	Total Stream
Stream Number	Ø	Cabin Atmosphere
	1	Cathode Air Modules Inlet
	2	Cathode Air Modules Outlet
	3	H_2 Modules Inlet
	4	H_2 Modules Outlet
	5	Cooling Air Inlet
	5A	Cooling Air Inlet, Active Cells
	6	Cooling Air Outlet
	6A	Cooling Air Outlet, Active Cells
	7	Process Air Inlet
	8	Process Air Outlet
	9	H_2 System Inlet
	1Ø	Plenum Bypass
	11	Cathode Blowers Outlet
	12	Cooling Blowers Outlet
	13	Cooling Dampers Outlet
Units Suffix	(None)	Units of First Prefix
	PSA	Psia
	PSG	Psig
	SL	Slpm

Additional Variable Names

A,B,C,D,EE,F,G	Constants in pH_2O Dew Point Equation
All,J	Indices Determine S Constants
CD	Current Density
CHWRTO	CO_2/H_2 Weight Ratio, Lb CO_2/Lb H_2

continued-

Table 12 - continued

CJKN	Coefficient in Pressure Drop Equation J = Inlet Stream Subscript K = Outlet Stream Subscript N = Degree of Term
COR34,COR93	ΔP Correction Factors for Absolute Pressure
CPA	Volumetric Specific Heat, Air, Btu/Hr-Scfm-F
CPH	Volumetric Specific Heat, H_2, Btu/Hr-Scfm-F
CTRANS	CO_2 Transferred, Lb/Hr
CURDEN	Current Density, A/Ft^2
DELT1	Input Control Variable = T2-DP1, F
DELT1P	Preferred Value Control Variable = T2-DP1, F
DELIE	Actual Control Variable = T2-DP1, F
DHA	Enthalpy Gain of Inlet Process Air, Btu/Hr
DHC	Enthalpy Gain of Cooling Air, Btu/Hr
DHH	Enthalpy Gain of Inlet H_2, Btu/Hr
DDP1,DDP2	Dew Point Depression, Streams 1 and 2
DPTDAV	Process Air Dew Point Depression, Average, F
DROP,RISE	T2-(DWI + DELT1), Absolute Value of Module Temperature Offset
DTAVA	Log Mean Available Temperature Drop, F
DTREQ	Required Module - Cooling Air Temperature Drop, F
E	Cell Voltage, Volt
EMOD	Module (16 Cells) Voltage
EQWGT	Total System Equation Weight
ERT,ERT1	Difference Between DTREQ and DTAVA
ESTACK	Stack Voltage, Volt
ETA	Cooling Fin Efficiency, Dimensionless, 0-1
FA,FB,FN	Dependent Values Corresponding to XA,XB,XN
?FIN	File Input Indicator
FNAME	Variable Equal to Output File Name
?FOUT	File Output Indicator
HC	Cooling Fin Heat Transfer Coefficient, Btu/Hr-Ft^2-F
HCON	H_2 Consumption, Lb/Hr
HCVRTO	H_2/CO_2 Volume Ratio, Scfm H_2/Scfm CO_2
HEATLD	Net Heat Produced, Btu/Hr
HTPEN	Heat Rejection Penalty, Lb/Btu/Hr
HTTOT	Total Heat Rejection
HTWGT	Heat Rejection Penalty Weight
H2OPEN	H_2O Vapor Rejection Penalty, Lb/Lb/Hr
H2OWGT	H_2O Rejection Penalty Weight
I	Current, A
INP	Input Device Code: 2=File, 50=Terminal
IOUT	Output Device Code: 1=File, 66=Terminal
MATHIN	Name of Input Data File
N	Number of Cells in Circuit
NERROR	Check Violation Indicator 0 - No Violation 1 - Violation

continued-

Table 12 - continued

NFLAG,FLAG	Program Option Integer = 0 or 1
OCON	O_2 Consumption, Lb/Hr
OXPEN	O_2 Consumption Penalty, Lb/Lb/Hr
OXWGT	O_2 Consumption Penalty Weight
P	Inlet pCO_2
PA	Inlet pCO_2 Corrected for Effect of Air Flow
POWER	Electrical Power Produced, Watt
PWPEN	Power Penalty, Lb/Watt
PWRCLB	Cooling Blower Power, Watt
PWRCTB	Cathode Blower Power, Watt
PWRDAU	Data Acquisition Unit Power, Watt
PWREC	Emergency Controller Power, Watt
PWRPC	Primary Controller Power, Watt
PWRTOT	Total Power, Watt
PWRWGT	Power Penalty Weight
QA,QB,QC	Coefficients of V5 in Quadratic Formula
S	Array containing Coefficients of PA in TI Correlation
TA,TB	Trial Values of Dew Point, F
TC,TF	Dew Point, C, F, respectively
TE	Current Efficiency, %
TERP	Current Density Interpolation Variable
TI	Transfer Index, Lb CO_2/Lb O_2
T2INP	Set Point Value of T2
T2P	Preferred Value of T2
T11	TI at one of the seven current densities just below the desired current density
T12	TI at one of the seven current densities just above the desired current density
U1	Conversion Factor, mm Hg/Psi
U2	Conversion Factor, Scf/Lb Mol
U3	Conversion Factor, Btu/Hr-Watt
U4	Conversion Factor, $1/Ft^3$
V,TR	Dummy and Interpolation Variables
VA,VB	Trial Values for V5
V5INP	Cooling Flow for Set Point Module Temperature
V5MIN	Cooling Flow with Blowers Off
V7M1	Plenum Inlet Flow less Cathode Air Flow
V9MSL	Minimum Flow of H_2 Required
WAIT	Dummy File Name to Prevent Closing Output File
WPROD	Water Production, Lb/Hr
X1,X2,XA,XB,XN	Trial Values of Independent Variable in Subroutine Root

APPENDIX B CS-6 BASE PROGRAM SAMPLE OUTPUTS

TABLE 1   OUTPUT EXAMPLES

```
**********INPUT DATA***********
CABIN ATMOSPHERE:
     POPSA      14.70  !  PCO          2.800  !  POOPSA       3.100  !
PROCESS AIR OUTLET/INLET:
     P8PSA      14.05  !  T7           55.80  !  V7           444.0  !  DW7          48.00
H2 OUTLET/INLET:
     P4PSA      14.80  !  T9           75.00  !  V9SL         9.700  !  DW9          74.00
MODULES:
     N          96.00  !  I            4.880  !  DELT1        19.00  !  V1           54.00
PENALTY WEIGHT FACTORS:
     PWPEN     0.5910  !  HTPEN       0.1280  !  H2OPEN       134.0  !  OXPEN        1536.
PROGRAM CONTROL:
     NFLAG     0.0000  !
***********RESULTS************
DESIRED MODULE TEMPERATURE IS MAINTAINED WITH COOLING BLOWERS AT PARTIAL CAPACITY.
     V5INP      261.6  !
PREFERRED VALUE OF DELT1 IS 18.81 UNDER THESE CONDITIONS
SO THAT 66.81 = T2 = DW1 + DELT1 = 48.00 + 18.81.
MODULES:
     TI         2.184  !  TE           79.41  !  E           0.3643  !  EMOD         5.829
     CTRANS    0.6732  !  OCON        0.3083  !  HCON  0.3884E-01  !  WPROD       0.3471
     CURDEN     20.00  !  HEATLD       1419.  !  POWER        170.7  !
CATHODE AIR INLET:
     P1         726.8  !  PC1          2.678  !  PW1          8.549  !  FC1          1.359
     FW1        1.775  !  VC1         0.1989  !  VW1         0.6352  !  VO1          11.39
     VN1        41.78  !  T1           55.80  !  DW1          48.00  !  RH1          75.01
CATHODE AIR OUTLET:
     P2         718.6  !  DP12         8.183  !  PC2          1.336  !  PW2          10.14
     V2         53.97  !  VC2         0.1004  !  VW2         0.7619  !  VO2          11.33
     VN2        41.78  !  FC2         0.6853  !  FW2          2.129  !  T2           67.00
     DW2        52.61  !  RH2          59.89  !  P11          726.4  !  V11          53.97
     T11        84.94  !
PROCESS AIR INLET:
     P7         726.8  !  PW7          8.549  !  PN7          562.3  !  VC7          1.636
     VW7        5.223  !  VO7          93.63  !  VN7          343.5  !  DW7          48.00
     RH7        75.01  !
PROCESS AIR OUTLET:
     P8         726.4  !  PC8          2.515  !  V10          128.4  !  DP78        0.3711
     V8         444.0  !  VW8          5.350  !  VC8          1.537  !  VO8          93.57
     PW8        8.753  !  T8           64.85  !  DW8          48.63  !  RH8          55.67
H2 INLET:
     P9         912.2  !  PW9          21.49  !  DP93         143.5  !  P3           768.7
     PW3        18.11  !  PH3          750.6  !  V3          0.3425  !  VH3         0.3344
     VW3   0.8071E-02  !  FH3         0.1046  !  V9MSL        4.573  !
```

continued-

Table 1 - continued

```
H2 OUTLET:
    P4         765.2    !  DP34          3.566   !  PW4          10.73    !  V4          0.3132
    VC4   0.9859E-01    !  VH4          0.2103   !  VW4    0.4393E-02     !  V4SL         8.871
    VC4SL      2.792    !  VH4SL         5.955   !  F4          0.7513    !  FC4         0.0752
    FH4   0.6577E-01    !  FW4     0.1227E-01    !  DW4          54.14    !  CHWRTO       10.24
    HCVRTO     2.133    !
HEAT BALANCE, MODULES:
    HEATLD     1419.    !  DHA           651.1   !  DHH         -2.923    !  DHC          770.5
COOLING AIR:
    P5         726.8    !  DP56          3.533   !  P6           723.2    !  V5           261.6
    T5         55.80    !  T6            58.54   !  HC           5.255    !  ETA         0.8770
    V5A        261.6    !  T6A           58.54   !  P12          728.5    !  V12          261.6
    T12        63.08    !  DP1213        2.085   !  V5MIN        49.20    !
ACTUAL VOLUMETRIC FLOW RATES:
    AV1        54.96    !  AV2           56.75   !  AV3         0.3418    !  AV4         0.3094
    AV5        266.2    !  AV6           268.9   !  AV6A         268.9    !  AV7          451.9
    AV8        460.0    !  AV9          0.2881   !  AV10EX       130.8    !  AV11         58.06
    AV12       269.3    !  AV13          270.1   !
EQUIVALENT WEIGHT:
    PWRCLB     374.1    !  PWRCTB        305.0   !  PWRPC        136.0    !  PWREC        45.00
    PWRDAU     100.0    !  PWRTOT        960.1   !  HTTOT        5285.    !  PWRWGT       567.4
    HTWGT      676.5    !  H2OWGT        46.51   !  OXWGT        473.5    !  HRDWGT       817.9
    EQWGT      2582.    !

**********INPUT DATA**********
CABIN ATMOSPHERE:
    POPSA      14.70    !  PCO          0.6830   !  POOPSA       3.100    !
PROCESS AIR OUTLET/INLET:
    P8PSA      14.05    !  T7            55.80   !  V7           444.0    !  DW7          48.00
H2 OUTLET/INLET:
    P4PSA      14.80    !  T9            75.00   !  V9SL         9.700    !  DW9          74.00
MODULES:
    N          96.00    !  I             4.880   !  DELT1        19.00    !  V1           54.00
PENALTY WEIGHT FACTORS:
    PWPEN     0.5910    !  HTPEN        0.1280   !  H2OPEN       134.0    !  OXPEN        1536.
PROGRAM CONTROL:
    NFLAG     0.0000    !
***********RESULTS************
DESIRED MODULE TEMPERATURE IS MAINTAINED WITH COOLING BLOWERS AT PARTIAL CAPACITY.
    V5INF      261.6    !
PREFERRED VALUE OF DELT1 IS 18.82 UNDER THESE CONDITIONS
SO THAT 66.82 = T2 = DW1 + DELT1 = 48.00 + 18.82.
MODULES:
    TI        0.8224    !  TE            29.91   !  E           0.3643    !  EMOD         5.829
    CTRANS    0.2535    !  OCON         0.3083   !  HCON   0.3884E-01     !  WPROD       0.3471
    CURDEN     20.00    !  HEATLD        1419.   !  POWER        170.7    !
CATHODE AIR INLET:
    P1         726.8    !  PC1          0.6531   !  PW1          8.549    !  FC1         0.3314
    FW1        1.775    !  VC1     0.4853E-01    !  VW1         0.6352    !  VO1          11.39
    VN1        41.93    !  T1            55.80   !  DW1          48.00    !  RH1          75.01
```


continued

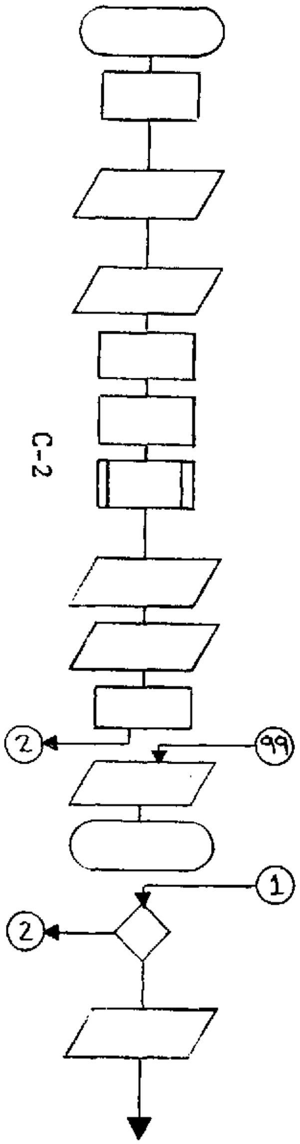
Table 1 - continued

```
CATHODE AIR OUTLET:
     P2        718.6  !  DP12         8.183  !  PC2         0.1516  !  PW2         10.15
     V2        54.03  !  VC2    0.1140E-01  !  VW2         0.7630  !  V02         11.33
     VN2       41.93  !  FC2    0.7786E-01  !  FW2          2.132  !  T2          67.00
     DW2       52.62  !  RH2          59.91  !  P11          726.4  !  V11         54.03
     T11       84.94  !
PROCESS AIR INLET:
     P7        726.8  !  PW7          8.549  !  PN7          564.3  !  VC7        0.3990
     VW7       5.223  !  V07          93.63  !  VN7          344.7  !  DW7         48.00
     RH7       75.01  !
PROCESS AIR OUTLET:
     P8        726.4  !  PC8         0.5920  !  V10          128.4  !  DP78       0.3711
     V8        444.0  !  VW8          5.351  !  VC8         0.3619  !  V08         93.57
     PW8       8.753  !  T8           64.85  !  DW8          48.63  !  RH8         55.67
H2 INLET:
     P9        912.2  !  PW9          21.49  !  DP93         143.5  !  P3          768.7
     PW3       18.11  !  PH3          750.6  !  V3          0.3425  !  VH3        0.3344
     VW3  0.8071E-02  !  FH3         0.1046  !  V9MSL        4.573  !
H2 OUTLET:
     P4        765.2  !  DP34         3.566  !  PW4          10.73  !  V4         0.2509
     VC4  0.3713E-01  !  VH4         0.2103  !  VW4     0.3520E-02  !  V4SL        7.106
     VC4SL     1.051  !  VH4SL        5.955  !  F4          0.3291  !  FC4        0.2535
     FH4  0.6577E-01  !  FW4     0.9835E-02  !  DW4          54.15  !  CHWRTO      3.855
     HCVRTO    5.663  !
HEAT BALANCE, MODULES:
     HEATLD    1419.  !  DHA          651.1  !  DHH         -2.923  !  DHC         770.5
COOLING AIR:
     P5        726.8  !  DP56         3.533  !  P6           723.2  !  V5          261.6
     T5        55.80  !  T6           58.54  !  HC           5.255  !  ETA        0.8770
     V5A       261.6  !  T6A          58.54  !  P12          728.5  !  V12         261.6
     T12       63.08  !  DP1213       2.085  !  V5MIN        49.20  !
ACTUAL VOLUMETRIC FLOW RATES:
     AV1       54.96  !  AV2          56.82  !  AV3         0.3418  !  AV4        0.2478
     AV5       266.2  !  AV6          268.9  !  AV6A         268.9  !  AV7         451.9
     AV8       460.1  !  AV9         0.2881  !  AV10EX       130.8  !  AV11        58.12
     AV12      269.3  !  AV13         270.1  !
EQUIVALENT WEIGHT:
     PWRCLB    374.1  !  PWRCTB       305.0  !  PWRPC        136.0  !  PWREC       45.00
     PWRDAU    100.0  !  PWRTOT       960.1  !  HTTOT        5285.  !  PWRWGT      567.4
     HTWGT     676.5  !  H2OWGT       46.51  !  OXWGT        473.5  !  HRDWGT      817.9
     EQWGT     2582.  !

OK
```

APPENDIX C CS-6 CABIN pCO_2 SIMULATION PROGRAM DOCUMENTATION

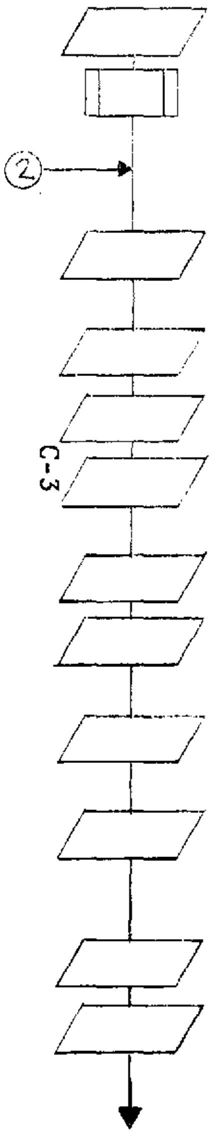
TABLE 1 MAIN PROGRAM FLOW CHART



Symbol	Program Line Numbers	Description	Comments
		START	
	150-720		Initialize type, common, equivalence, external and data statements
	760	PRINT, "FILE INPUT (T OR F)"	Indicate from terminal whether input will be from data file MATHIN (T), or from the terminal (F).
	770	READ, QFIN	
	780	INP = 50	
	790	IF (QFIN)INP=2	
	800	IF (QFIN) CALL OPEN F(2, "MATHIN")	
	810	PRINT, "FILE OUTPUT (T OR F)"	Indicate from terminal whether output will be on a file (T) or on the terminal (F).
	820	READ, QFOUT	
	830	IF (NOT, QFOUT)IOUT=66	
	850	PRINT, "END OF INPUT DATA FILE"	Program branches to this point and terminates when a file input statement is attempted (usually line 1050) but the input file has been exhausted.
	860	CALL EXIT	
	900	IF (NOT QFOUT) BRANCH	Obtain output file name if file output is in use.
	910	IF (NOT QFIN) PRINT, "FILE FOR INPUT	

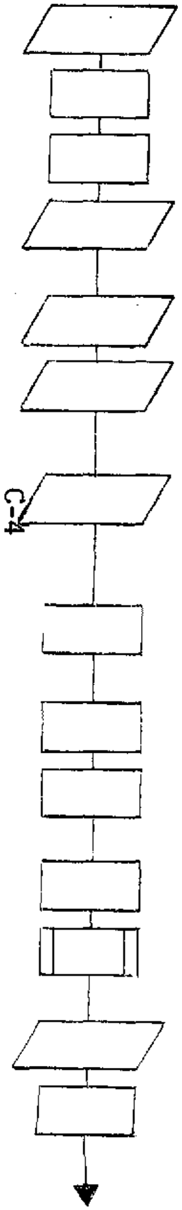
-continued-

Table 1 - continued



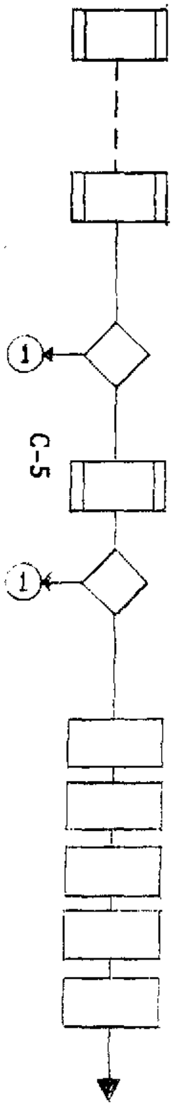
Symbol	Program Line Numbers	Description	Comments
	920-930	READ, FNAME	Assign the name to the file and close it unless the name is SAME, indicating that more output will be written into the same file.
	980	IF (FNAME ≠ "SAME") CALL CLOSEF(1, FNAME, 7)	
	1020-1040	IF (NOT QFIN) PRINT, "PROBLEM IDENTIFIER"	Read and write the problem identifier which may be any comments up to 84 characters long.
	1050	READ, IDENTIFIER	
	1060	IF (QFIN) PRINT, IDENTIFIER	
	1100	PRINT, "NEW CO2 GENERATION TABLE?"	Input and output new CO2 generation table if desired, or use the table stored in the program.
	1110	READ, QCO2GT	
	1120	IF(QCO2GT) READ, CO2 GENERATION TABLE	
	1130-1160	IF (QCO2GT) PRINT, CO2 GENERATION TABLE	
	1210	IF (NOT QFIN) PRINT, "INPUT DATA"	Read inputs for base, Mode B, and time intervals in the order and ranges specified in Table 1.
	1220	READ, POPSA, PCO,...,DT,DPRINT	
	1280	IF (NOT QFIN) PRINT, "PRINT BASE OUTPUT (T OR F)"	Indicate whether the base program output table should be printed (T) or omitted (F).

Table 1 - continued



Symbol	Program Line Numbers	Description	Comments
	1290	READ, QPRINT	
	1300	KBASE = 4	
	1310	IF (QPRINT) KBASE = 5	
	1320	IF (NOT QFIN) PRINT, "NEW CYCLIC OUTPUT SUBSCRIPTS?"	Read new cyclic table output item subscripts if they are to be changed.
	1330	READ, QSUBS	
	1340	IF (QSUBS) READ, NDEX, $INDEX_1, \ldots, INDEX_{NDEX}$	
	1350	IF (QFOUT) PRINT, "START PROBLEM"	Print message at terminal indicating that a set of inputs is complete and calculation is beginning.
	1390	$BK_9 = \frac{BK_1 - BK_4}{BK_2 - BK_3}$	
	1400	$BK_{10} = BK_1 - BK_9(BK_2)$	Calculate slopes and intercepts for Mode B current and cathode air flow curves.
	1410	$BK_{11} = \frac{BK_5 - BK_8}{BK_6 - BK_7}$	
	1420	$BK_{12} = BK_5 - BK_{11}(BK_6)$	
	1470	IF(KMODE=1)CALL BMODE	If Mode B is in effect, determine current and cathode air flow for the initial pCO_2.
	1480-1780	WRITE,POPSA,PCO,...,DT,DPRINT	Playback base, Mode B and time interval inputs with current and cathode air flow determined by Mode B if it is in effect.
	1820	IR=0	

Table 1 - continued



Symbol	Program Line Numbers	Description	Comments
	1830	CALL T("POPSA,"POPSA,13.7, 15.7,IR)	Initialize out-of-range input variable counter.
	1840-2170		
	2180	CALL T("DPRINT,",DPRINT,1, 100,IR)	Subroutine T checks each input variable against its allowable range. Out-of-range variables are printed and cause IR to be incremented.
	2190	IF(IR > 0) BRANCH	If the counter shows that one or more inputs is out-of-range, abort the simulations and read in next set of inputs.
	2230	CALL BASE(KMODE,KBASE,1, KERROR)	Call BASE to determine all system parameters at time zero, to print a base output table if indicated by KBASE=5, and to abort simulation if KERROR value returned by BASE indicates that certain inputs do not support steady-state. Also abort if no. of days to be simulated = 0.
	2240	IF(KERROR ≠0 OR DAYS =0) BRANCH	
	2280	NDT=DT	Initialize integer variables:integration time interval, day counter, minutes per cycle (day), limit on number of days, and printing time increment.
	2290	NDAY=0	
	2300	MINCYC=TMAX(NSTEPS)	
	2310	NDAYS=DAYS	
	2320	NPRINT=DPRINT	

Table 1 - continued

Symbol	Program Line Numbers	Description	Comments
	2330	$U5=\frac{(T\emptyset + 460)(386.7)(760)}{(530)(VOLUME)(60)(44.01)}$	Calculate proportionality constant between net CO_2 removal (Lb/Hr) and cabin pCO_2 change rate (mm Hg/Min).
	2340	MAXDEX=0	Determine the names (HDG) of the variables to be printed out in the table versus time, and find largest subscript (MAXDEX).
	2350	DO 110 MN=1,NDEX	
	2360	IN=INDEX(MN)	
	2370	HDG(MN)=HEAD(IN)	
	2380	110 IF (IN > MAXDEX)MAXDEX=IN	
	2390	IF (1 ≤ MAXDEX ≤ 52)KBASE=1	Calculate the parameter KBASE which indicates to the BASE subroutine which of its output variables must be calculated and which sections may be omitted for faster execution.
	2400	IF (53 ≤ MAXDEX ≤ 78)KBASE=2	
	2410	IF (79 ≤ MAXDEX ≤ 129)KBASE=3	
	2420	IF (130 ≤ MAXDEX ≤ 150)KBASE=4	
3	2470	QPRINT= .TRUE.	A line will be printed at time zero.
	2480	NT=0	
	2490	D0725 MN=1,NDEX	Clear the variable containing the average of the parameters, AVG.
	2500	725 AVG(MN)=0	
	2510	NDAY=NDAY + 1	Increment the day counter.
	2520	PCOI=PCO	Store the cabin pCO_2 for the beginning of the cycle.

Table 1 - continued

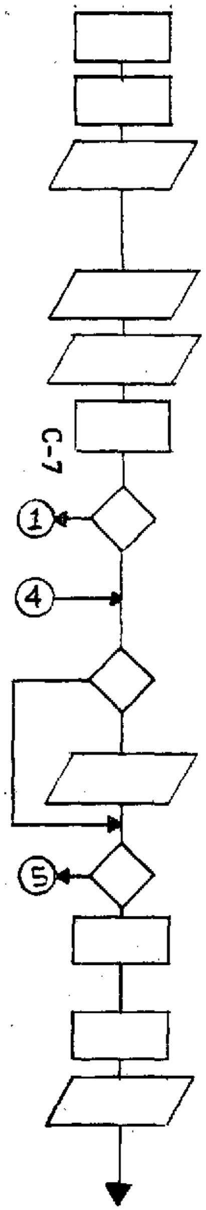
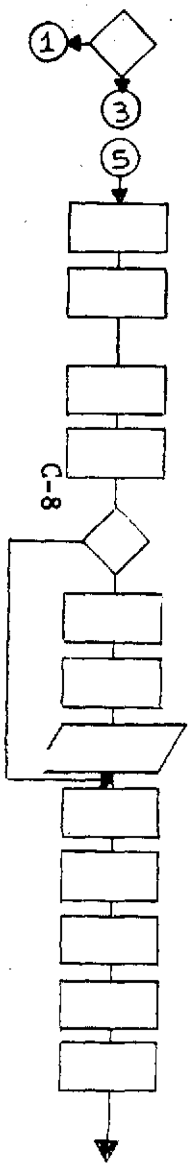
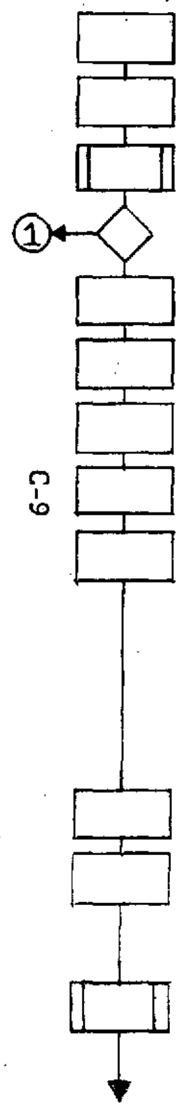
Symbol	Program Line Numbers	Description	Comments
	2530	IGEN=1	Initialize the CO_2 generation rate step counter and the CO_2 generation rate.
	2540	CO2GEN=CGEN(1)	
	2580	IF(QFOUT)PRINT, NDAY	If file output is being used, print the day counter on the terminal to indicate progress of the program to the operator.
	2590-2620	PRINT CYCLIC TABLE HEADINGS	
	2630	WRITE, 0,0	Print time at time zero.
	2640	CALL BASE(KMODE,KBASE,1,KERROR)	Call BASE to determine system parameters at time zero and to print any error messages.
	2650	IF(KERROR $\neq$ 0)BRANCH	If the variable KERROR indicates that conditions will not support the steady-state, then BRANCH to get the next set of input data.
	2700	IF (NOT QPRINT) BRANCH	Print a line in the cyclic table at the proper time.
	2710-2750	PRINT A LINE IN THE CYCLIC TABLE	
	2820	IF (NT < MINCYC) BRANCH	BRANCH if it is not the end of the day.
	2830	DO 726 MN=1,NDEX	Complete calculation of average system parameters.
	2840	726 $AVG(MN)=AVG(MN)\cdot\frac{DT}{MINCYC}$	
	2850-2870	PRINT AVERAGES	

Table I - continued



Symbol	Program Line Numbers	Description	Comments
	2880	IF (NDAY=NDAYS OR $\left\|\frac{PCO-PCOI}{PCO}\right\| <$ 0.0005) BRANCH	Start a new cycle unless either steady-state has been reached or maximum number of cycles has been reached.
	2940	NT=NT + NDT	Increment time.
	2950	QPRINT=MOD(NT,NPRINT).EQ.0	Determine whether a table line will be printed at this time.
	2960	IF(NT > TMAX(IGEN))IGEN=IGEN+1	Update CO_2 generation rate.
	2970	CO2GEN = CGEN(IGEN)	
	3010	IF(NOT QPRINT) BRANCH	Print the time if a line of table will be printed at this time.
	3020	NHRS = NT/60	
	3030	NMIN=NT - NHRS(60)	
	3040-3050	WRITE TIME	
	3100	XA=PCO	Calculate pCO_2 at the new time. First assume that pCO_2 has not changed during the latest time increment. Calculate the rate of pCO_2 change at the beginning of the time increment (SLOPEA). Calculate average rate of pCO_2 change during the time interval (SLOPE). Using the old pCO_2 and the average slope, recalculate the new pCO_2. The error associated with the first trial is YA.
	3110	SLOPEA=U5(CO2GEN-CTRANS)	
	3120	SLOPE=SLOPEA	
	3130	PCN=PCO + SLOPE x DT	
	3140	YA=XA - PCN	

Table 1 - continued



Symbol	Program Line Numbers	Description	Comments
	3150	XB=PCN	Use the improved pCO_2 value for the second guess (XB). Call BASE to find the CO_2 removal rate based on the latest value of pCO_2. Calculate the rate of pCO_2 change at the end of the time increment and the average rate of pCO_2 change during the time increment. Recalculate pCO_2 at the end of the time interval from the pCO_2 at the beginning of the interval and the rate of pCO_2 change. YB is the error associated with the second guess at cabin pCO_2
	3160	PCO=PCN	
	3170	CALL BASE(KMODE,0,0,KERROR)	
	3180	IF(KERROR $\neq$ 0)BRANCH	
	3190	SLOPEB=U5 x(CO2GEN-CTRANS)	
	3200	SLOPE = 0.5 x(SLOPEA+SLOPEB)	
	3210	PCN=XA + SLOPE x DT	
	3220	YB = XB - PCN	
	3230	$PCO=\frac{YAxXB-YBxXA}{YA-YB}$	The cabin pCO_2 at the end of the time increment is found with precision by finding the zero of the function defined by two points with coordinates (XA,YA), and (XB,YB). Linear interpolation is used because both points are already close to the root.
	3240	KPRINT=0	Calculate KPRINT, the parameter to BASE which determines when error messages can be printed by BASE. Error messages will not be printed unless it is time to print a line in the cyclic table.
	3250	IF(QPRINT)KPRINT=1	
	3290	CALL BASE(KMODE,KBASE,KPRINT, KERROR)	Call BASE to calculate system parameters at the new cabin pCO_2.

Table 1 - continued

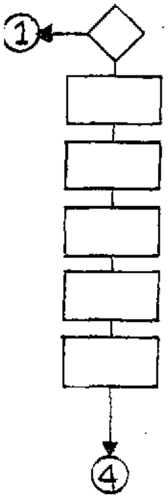
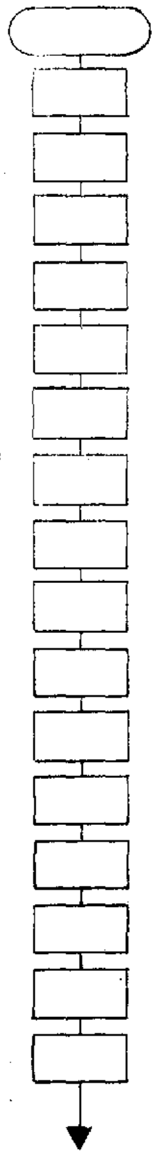
Symbol	Program Line Numbers	Description	Comments
	3300	IF (KERROR ≠ 0) BRANCH	
	3310-3330		Update the average system parameters.
	3360	SLOPEC=U5 x (CO2GEN-CTRANS)	Check for error in cabin pCO_2 and BRANCH to print a line of data in the cyclic table.
	3370	SLOPE = 0.5 x (SLOPEA+SLOPEC)	
	3380	PCN=XA - SLOPE x DT	
	3390	YC= PCO - PCN	

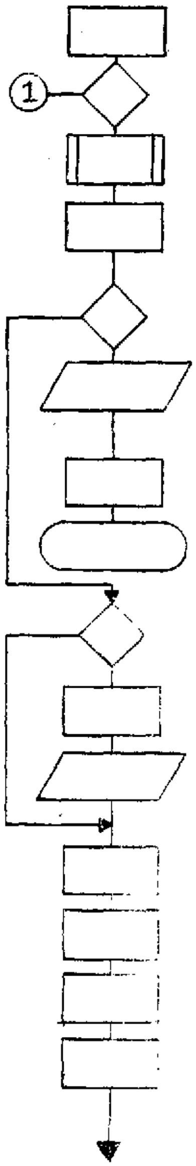
TABLE 2 BASE SUBROUTINE FLOW CHART



Symbol	Program Line Numbers	Description	Comments
		START	
	3680	CPA = 1.0765	Initialize Constant Btu/Hr/Scfm-F
	3680	CPH = 1.0666	Initialize Constant Btu/Hr/Scfm-F
	3690	U1 = 51.7	Initialize Constant mm Hg/Psi
	3690	U2 = 386.7	Initialize Constant Scfm/Lb-Mol/Hr
	3690	U3 = 3.419	Initialize Constant Btu/Hr/Watt
	3690	U4 = 28.32	Initialize Constant 1/Ft^3
	3700	C782 = 2.25×10^{-5}	
	3700	C562 = 1.303×10^{-5}	Initialize constants for pressure drop equations
	3700	C561 = 1.01×10^{-2}	
	3700	C6132 = 8.611×10^{-4}	
	3710	C5132 = C562 + C6132	
	3710	C5131 = C561	
	3710	QA = C5132 - C782	
	3720	HRDWGT = 817.9 Lb	Initialize weight and power constants
	3720	PWRPC = 136 WATTS	
	3720	PWREC = 45 WATTS	
	3720	PWRDAU = 100 WATTS	

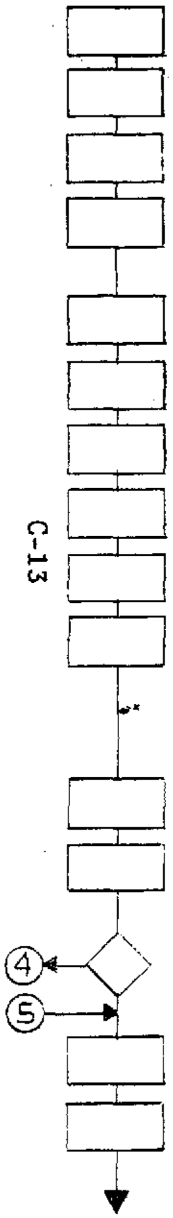
-continued-

Table 2 - continued



Program Line Numbers	Description	Comments
3730	KERROR = 0	Initialize error indicator
3740	IF (KMODE + KBASE=0)BRANCH	
3750	IF (KMODE=1)CALL BMODE	
3790	V9MSL = (1.3)(N)(I)(7.058 x 10^{-3})	Calc. required H_2 flow
3800	IF V9MSL $\leq$ V9SL THEN BRANCH	Check for sufficient H_2 Flow
3810-3820	WRITE "INSUFFICIENT H_2," V9MSL, "IS REQUIRED"	Write error message and required H_2 flow
3830	KERROR = 1	Return in error condition
3840	RETURN	
3890	IF V1$\leq$70 THEN BRANCH	Check that V1 is less than the process air blower capacity
3900	V1 = 70	Set V1 to maximum blower capacity
3910-3920	WRITE "AIRFLOW CHANGE TO 70 SCFM"	Print error message
3970	V7M1 = V7 - V1	Calculate bypass cooling air flow with cooling blowers off; i.e., calculate minimum cooling air flow rate
3980	QB = C5131 + 2$(V7M1)^2$	
3990	QC = C782 $(V7M1)^2$	
4000	$V5MIN = \frac{-QB + \sqrt{QB^2 + 4(QA)(QC)}}{2(QA)}$	

Table 2 - continued



Symbol	Program Line Numbers	Description	Comments
	4040	DW1 = DW7	
	4050	T2 = DW1 + DELT1	Calculate cell temperature
	4060	T2INP = T2	Store input T2
	4070	E = 0.729 - 0.22 lnI + 0.008I + 0.005 (T2-78)	Calculate cell voltage
	4080	HEATLD = (1.25-E)(N)(I)(U3)	Calculate modules' heatload
	4090	T1 = T7	
	4100	T3 = T9	
	4110	V3 = V9SL/U4	
	4120	T5 = T1	
	4130	DHA = V1 (CPA)(T2 - T1)	Calculate heat removed by cathode air flow
	4140	DHH = V3 (CPH)(T2-T3)	Calculate heat removed by H_2
	4150	DHC = HEATLD-DHA-DHC	Calculate heat removed by cooling air
	4190	If DHC > 0 THEN BRANCH	Check to see if cooling air is required
	4240	V5 = V5MIN	Set cooling air flow to minimum
	4250	V5A = (N)(V5MIN)/96	Calculate flow thru active cells

Table 2 - continued

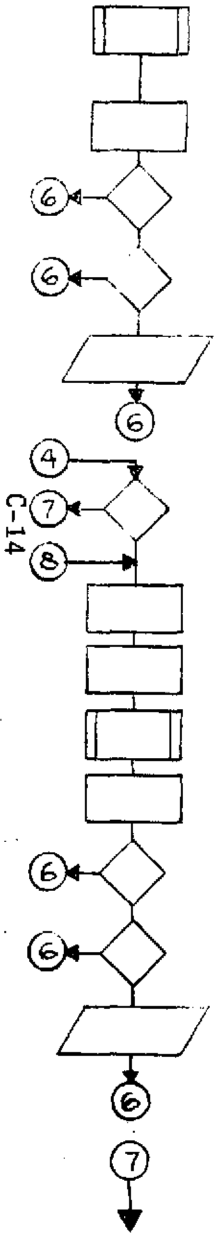
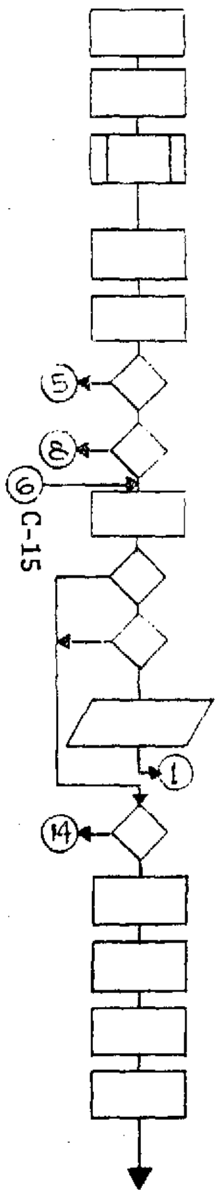
Symbol	Program Line Numbers	Description	Comments
	4260	CALL TDRIFT	Calculate T2 for subcooled condition
	4270	DROP = T2INP-T2	Calculate temperature, T2, drop
	4280	IF (DROP ≤ 3) BRANCH	
	4290	IF (KPRINT = 0) BRANCH	
	4300-4320	WRITE "V5MIN," V5MIN "COOLING BLOWERS OFF," "MODULE TEMPERATURE FALLS," DROP, "NEW T2," T2	Print out new conditions
	4390	IF $T2-T5 \geq \frac{(0.376)DHC}{N}$ THEN BRANCH	Check if there is sufficient ΔT to conduct heat up fins
	4440	V5 = 440	Set V5 to maximum blower capacity
	4450	V5A = V5(N)/96	Calculate flow thru active cells
	4460	Call TDRIFT	Calculate T2
	4470	RISE = T2-T2INP	Call rise in module temperature
	4480	IF (RISE ≤ 3) BRANCH	
	4490	IF (KPRINT = 0) BRANCH	
	4500-4520	WRITE "COOLING BLOWERS ON FULL," "MODULE TEMPERATURE RISES," RISE, "NEW T2," T2	Print out new conditions

Table 2 - continued



Symbol	Program Line Numbers	Description	Comments
	4580	VA = 1.01 x DHC/CPA (N)(T2-T5)	Calculate minimum and maximum cooling air flow to set range for iterative subroutine "ROOT"
	4590	VB = 2(VA)	
	4600	V5A = (N) · ROOT (VA, VB, ERT, 0, 0.005, 0.001, 20)	Calculate cooling air flow past active cells
	4610	V5 = 96(V5A)/N	Calculate total cooling air flow
	4620	V5INP = V5	
	4660	If V5 < V5MIN THEN BRANCH	Check for subcooling
	4670	If V5 > 440 THEN BRANCH	Check for heatup
	4720	V10 = V7-V1-V5	Calculate plenum bypass flow
	4760	IF V10 $\geq$ 0.05 (V8) THEN BRANCH	Check for sufficient plenum bypass
	4770	IF (KPRINT = 0) BRANCH	
	4780-4810	WRITE "INSUFFICIENT AIR FLOW, RECIRCULATION OF AIR FROM OUTLET TO INLET"	Print error message
	4880	IF(KBASE = 0) BRANCH	
	4890	COR34 = $\left(\frac{14.1}{P4PSA}\right)^{0.8}$	
	4900	P4 = P4PSA (V1)	Calculate module H_2 cavity pressure drop
	4910	V3SL = V9SL	
	4920	DP34 = (0.3822)(COR34)(V3SL)	

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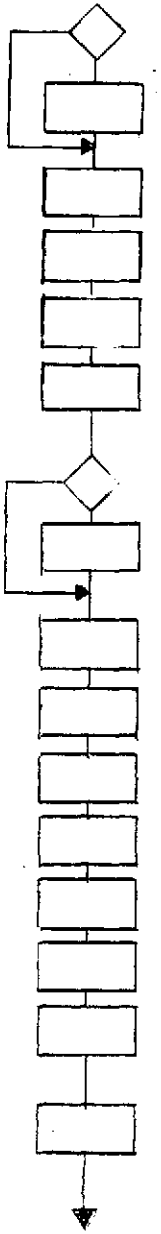
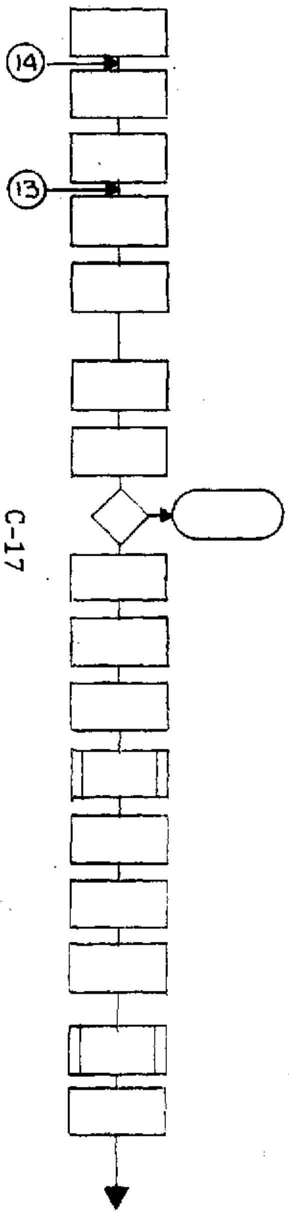
Table 2 - continued



Program Line Numbers	Description	Comments
4930	IF V3SL $\leq$ 22 THEN BRANCH	
4930	DP34 = COR34 $(8.3183\ 0.4187\ (V3SL-21.5801)^{1.75})$	
4940	P3 = P4 + DP34	Calculate module H_2 inlet pressure
4950	P3PSA = P3/U1	
4960	COR93 = $\left(\frac{14.1}{P3PSA}\right)^{0.8}$	
4970	DP93 = (COR93)(10.64)(V3SL)	Calculate H_2 distribution block pressure drop
4980	IF V3SL $\leq$ 6.2 THEN BRANCH	
4980	DP93 = COR93 $[35.64\ V3SL - 195.25 + e^{(7.75-0.6537V3SL)}]$	
4990	P9 = P3 + DP93	Calculate H_2 inlet pressure
5000	P9PSA = P9/U1	
5010	DP78 = $2.25 \times 10^{-5}(V10)^2$	Calculate process air inlet pressure using plenum pressure drop correlation
5020	P8 = P8PSA(U1)	
5030	P7 = P8 + DP78	
5040	P7PSA = P7/U1	
5050	DP12 = $0.001903(V1)^2 + 0.04877(V1)$	Calculate cathode air pressure drop
5060	P1 = P7	

Table 2 - continued

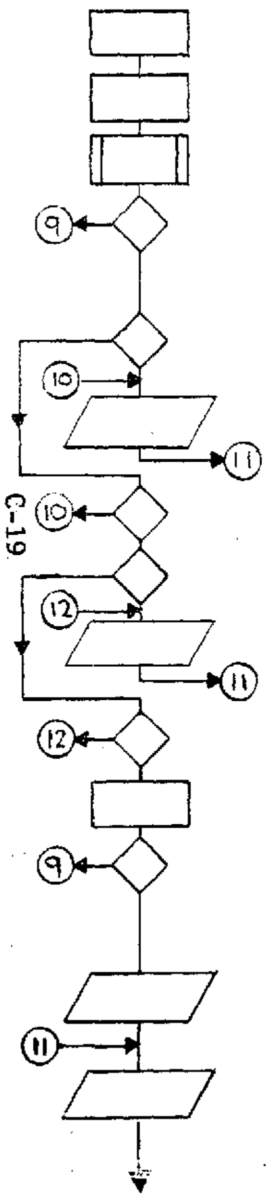


Symbol	Program Line Numbers	Description	Comments
	5070	P2 = P1-DP12	Calculate cathode air out pressure
	5080	CURDEN = I/0.244	Calculate current density
	5090	DELT1E = T2-DW1	Calculate actual humidity ΔT
	5110	$PC1 = PCO \frac{P7PSA}{POPSA}$	Calculate cathode inlet pCO_2
	5120	TI = TICOR (PC1, V1/96, CURDEN, DELTIE)	Calculate TI
	5130	$OCON = 6.5803 \times 10^{-4} (N)(I)$	Calculate O_2 consumed
	5140	CTRANS = TI (OCON)	Calculate CO_2 transferred
	5150	IF(KBASE $\leq$ 1) RETURN	
	5160	$HCON = OCON \frac{2.016}{16}$	Calculate H_2 consumed
	5170	WPROD = HCON + OCON	Calculate water produced
	5180	$VC4 = CTRANS \frac{V2}{44.01 \times 60}$	
	5190	PW9 = PHTO (DW9)	
	5200	$PW3 = P3 \frac{PW9}{P9}$	Calculate anode gas stream parameters
	5210	$VH3 = V3\left(1 - \frac{PW3}{P3}\right)$	
	5220	$VH4 = VH3-HCON \frac{U2}{2.016 \times 60}$	
	5240	PW4 = PHTO (T2-6)	
	5250	$VW4 = \frac{PW4}{P4-PW4} (VC4 + VH4)$	

Table 2 - continued

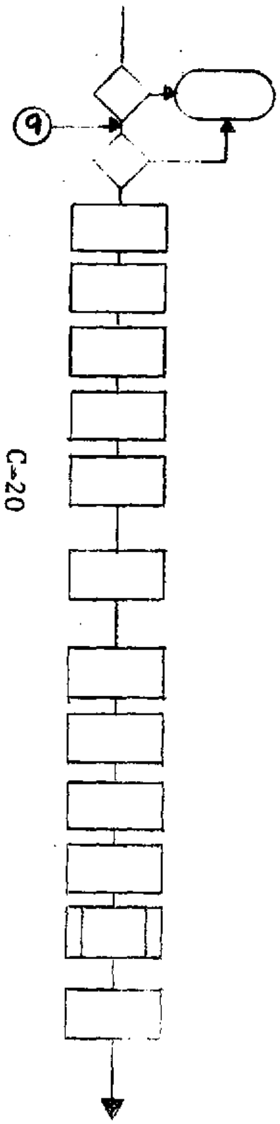
Symbol	Program Line Numbers	Description	Comments
	5260	DW1 = DW7	
	5270	PW1 = PHTO (DW1)	Calculate cathode air water balance parameters
	5280	$VW1 = V1 \frac{PW1}{P1}$	
	5290	VW3 = V3-VH3	
	5300	$VWPROD = WPROD \frac{V2}{18.01 \times 60}$	
	5310	VW2 = VW1 + VW3 - VW4	
	5320	POO = POOPSA/U1	
	5330	PO7 = POO (P7/PO)	
	5340	PO1 = PO7	Calculate cathode air inlet stream parameters
	5350	PN1 = P1-PO1-PW1-PC1	
	5360	VN1 = V1 (PN1/P1)	
	5370	VO1 = V1 (PO1/P1)	
	5380	VC1 = V1 (PC1/P1)	
	5390	VN2 = VN1	
	5400	VO2 = VO1 - OCON (U2/32 x 60)	
	5410	VC2 = VC1 - VC4	Calculate cathode air outlet stream parameters

Table 2 - continued



Symbol	Program Line Numbers	Description	Comments
	5420	V2 = VO2 + VN2 + VW2 + VC2	
	5430	PW2 = $\frac{VW2}{V2}$ P2	
	5440	DW2 = DEWT (PW2)	
	5500	IF T1-DW1 = 11.25 ± 1.75 AND T2-DW2 = 11.25 ± 1.75 THEN BRANCH	Perform moisture balance checks
	5510	IF T1-DW1 ≥ 4 THEN BRANCH	
	5640-5650	WRITE "INLET AIR HUMIDITY OUT-OF-RANGE"	
	5520	IF T1-DW1 ≤ 14 THEN BRANCH	
	5530	IF T2-DW2 ≥ 7 THEN BRANCH	
	5670-5680	WRITE "OUTLET AIR HUMIDITY OUT-OF-RANGE"	
	5540	IF T2-DW2 ≤ 19 THEN BRANCH	
	5550	DPTDAV = ½ (T1-DW1+T2-DW2)	
	5560	IF DPTDAV = 11±1.5 AND EITHER T2-DW2 ≥ 13 OR DPTDAV ≥ 0 THEN BRANCH	
	5570-5580	WRITE "AVE DEW PT DEPRESSION OUT OF-RANGE	
	5590-5610	WRITE "ELECTROLYTE MOISTURE BALANCE NOT MAINTAINED"	

Table 2 - continued

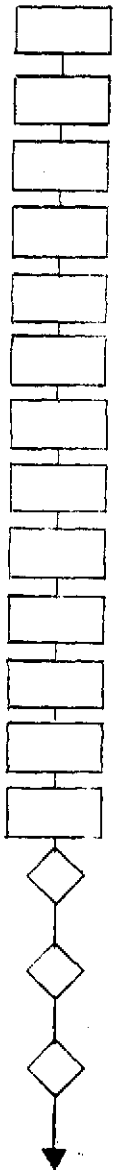


Program Line Numbers	Description	Comments
5620	KERROR = 3	
5630	IF NFLAG = 1 THEN RETURN	Check NFLAG for program abort
5740	IF (KBASE = 2) RETURN	
5750	DELT1P = 22-T1 + DW2	Calculate preferred ΔT
5760	T2P = DP1 + DELT1P	
5770	PW7 = PW1	
5780	PN7 = PN1	
5790	PC7 = PC1	Complete definition of process air inlet stream
5800	$VC7 = \frac{PC7}{P7}(V7)$	
5810	$VW7 = \frac{PW7}{P7}(V7)$	
5820	PO7 = PO1	
5830	$VO7 = \frac{PO7}{P7}(V7)$	
5840	$VN7 = \frac{PN7}{P7}(V7)$	
5850	$RH7 = 100 \frac{PW7}{PHTO(T7)}$	
5860	$FC1 = VC1 \frac{44.01 \times 60}{U2}$	Complete cathode air inlet stream definition

Table 2 - continued

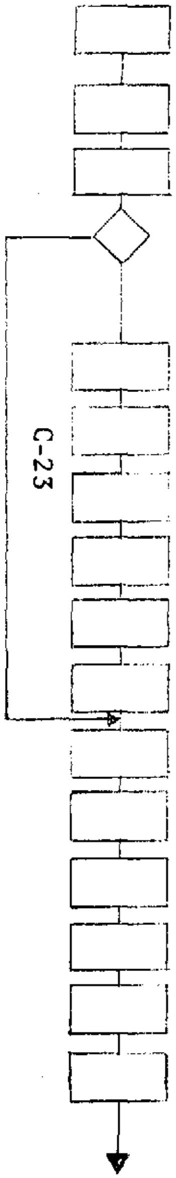
Symbol	Program Line Numbers	Description	Comments
	5870	$FW1 = VW1 \frac{18.01 \times 60}{U2}$	
	5880	RH1 = RH7	Complete cathode air inlet def.
	5890	PH3 = P3 - PW3	Complete definition of H_2 inlet
	5900	$FH3 = VH3 \frac{2.016 \times 60}{U2}$	
	5910	EMOD = 16(E)	
	5920	POWER = (N)(I)(E)	Calculate remaining module parameters
	5930	TE = TI/0.0275	
	5940	$PC2 = VC2 \frac{P2}{V2}$	
	5950	FC2 = FC1 - CTRANS	
	5960	$FW2 = VW2 \frac{18.01 \times 60}{U2}$	Complete definition of cathode air outlet
	5970	$RH2 = 100 \frac{PW2}{PHTO(T2)}$	
	5980	T4 = T2	
	5990	V9 = V3	
	6000	$DW4 = 0.77 \frac{DW1 + DW2}{2} + 0.23T2$	Refined H_2 dew point correlation
	6010	PW4 = PHTO(DW4)	
	6020	$VW4 = \frac{PW4}{P4-PW4} (VH4 + VC4)$	Complete definition of anode gas outlet
	6030	V4 = VH4 + VC4 + VW4	

Table 2 - continued



Symbol	Program Line Numbers	Description	Comments
	6040	V4SL = V4(U4)	
	6050	VC4SL = VC4(U4)	
	6060	VH4SL = VH4(U4)	
	6070	FC4 = CTRANS	
	6080	$FH4 = VH4 \ \frac{2.016 \times 60}{U2}$	
	6090	$FW4 = VW4 \ \frac{18.01 \times 60}{U2}$	
	6100	F4 = FC4 + FH4 + FW4	
	6110	CHWRTO = FC4/FH4	
	6120	HCVRTO = VHR/VC4	
	6130	P5 = P7	
	6140	$DP56 = (V5)^2 \ C562 + V5(C561)$	Calculate cooling air pressure drop
	6150	P6 = P5-DP56	Calculate cooling air outlet pressure
	6160	$T6 = \frac{(V5A)T6A + (V5-V5A)T5}{V5}$	Calculate cooling air out temperature
	6170	IF VI $\leq$ 62 THEN PWRCTB = 2.8V + 153.8	
	6180	IF 62 < V1 $\leq$ 65 THEN PWRCTB = 40V1 - 2150	Calculate cathode air blower power
	6190	IF 65 < V1 $\leq$ 70 THEN PWRCTB = -34V± + 2660	

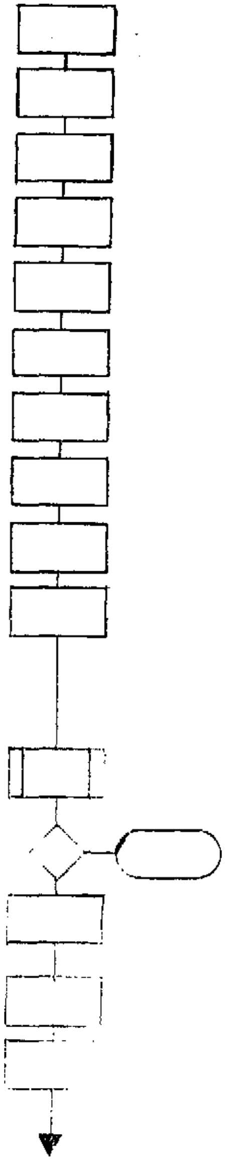
Table 2 - continued



Symbol	Program Line Numbers	Description	Comments
	6200	$T11 = T2 + \frac{PWRCTB(U3)}{V1 \cdot CPA}$	
	6210	$V11 = V2$	Define stream after cathode blower
	6220	$P11 = P8$	
	6240-6250	IF $V5-V5MIN < 0.001(V5MIN)$ THEN $PWRCLB = 0$, $DP1213 = C12132(V5)^2$ AND BRANCH	Check if cooling blower is off
	6260	$DP1213 = C12132\ (V5MIN)^2$	Calculate cooling blower power
	6270	$TR = (\frac{DP78}{1.869} + 0.05)/1.3$	
	6280	$TR = TR^{(0.128 + 0.102(\frac{DP78}{1.869}))}$	
	6290	$PWH = 410 - 0.00396\ (V5-368)^2$	
	6300	$PWL = 410 - 0.00178\ (V5 - 306)^2$	
	6310	$PWRCLB = TR\ (PWH) + (1-TR)(PWL)$	
	6330	$P12 = P8 + DP1213$	Define cooling blower exit stream
	6340	$T12 = T6 + \frac{PWRCTB(U3)}{V5(CPA)}$	
	6350	$T13 = T12$	
	6360	$V12 = V5$	
	6370	$P13 = P8$	
	6380	$V13 = V5$	

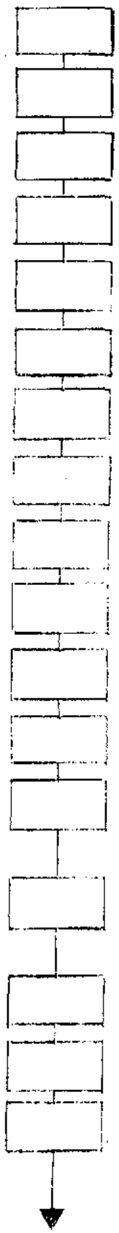
Table 2 - continued

Symbol



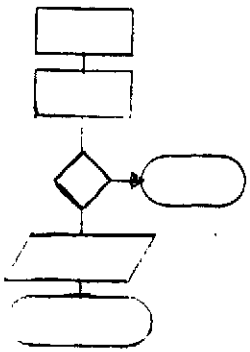
Program Line Numbers	Description	Comments
6390	$V8 = V10 + V2 + V5$	
6400	$VW8 = VW7 + VW2 - VW1$	
6410	$VC8 = VC7 - VC4$	
6420	$PC8 = \frac{VC8}{V8} P8$	Calculate plenum exit conditions
6430	$VN8 = VN7$	
6440	$PN8 = \frac{VN8}{V8} P8$	
6450	$VO8 = VO7 - \frac{1}{2}(VH3 - VH4)$	
6460	$PW8 = \frac{VW8}{V8} P8$	
6470	$DW8 = DEWT\ (PW8)$	
6480	$T8 = \frac{T11(V11) + T13(V13)}{V8} + \frac{T7(V10) + (POWER \frac{U3}{CPA})}{V8}$	
6490	$RH8 = \frac{100 \times PW8}{PHTO\ (T8)}$	
6500	IF (KBASE = 3) RETURN	
6510	$AV7 = \frac{V7(T7 + 460)}{P7} \frac{760}{530}$	
6520	$AV1 = V1\ (AV7/V7)$	
6530	$AV2 = \frac{V2(T2 + 460)}{P2} \times 1.434$	

Table 2 - continued



Symbol	Program Line Numbers	Description	Comments
	6540	$AV11 = \frac{V11(T11 + 460)}{P11} (1.434)$	
	6550	$AV9 = \frac{V9(T9 + 460)}{P9} (1.434)$	
	6560	$AV3 = \frac{V3(T3 + 460)}{P3} (1.434)$	
	6570	$AV4 = \frac{V4(T4 + 460)}{P4} (1.434)$	
	6580	AV5 = V5 AV7/V7	Calculate actual stream flow rates
	6590	$AV6 = \frac{V6(T6 + 460)}{P6} (1.434)$	
	6600	V6A = V5A	
	6610	$AV6A = \frac{V6A(T6A + 460)}{P6} (1.434)$	
	6620	$AV12 = \frac{V12(T12 + 460)}{P12} (1.434)$	
	6630	$AV13 = \frac{V13(T13 + 460)}{P13} (1.434)$	
	6640	$AV10EX = \frac{V10(T7 + 460)}{P8} (1.434)$	
	6650	$AV8 = \frac{V8(T8 + 460)}{P8} (1.434)$	
	6690	PWRTOT = PWRPC + PWREC + PWRCLB + PWRCTB + PWRDAU	
	6700	HTTOT = HEATLD + U3(PWRTOT + POWER)	
	6710	PWRWGT = PWPEN(PWRTOT)	Calculate equivalent weight penalty
	6720	HTWGT = HTPEN(HTTOT)	
	6730	H2OWGT = H2OPEN(WPROD)	

Table 2 - continued



Symbol	Program Line Numbers	Description	Comments
	6740	OXWGT = OXPEN(OCON)	
	6750	EQWGT = PWRWGT + HTWGT + H_2OWGT + OXWGT + HRDWGT	
	6760	IF (KBASE = 4) RETURN	
	6770-7510	WRITE OUT ALL OUTPUTS	
	7520	RETURN	

TABLE 3 WATER VAPOR PRESSURE FUNCTION

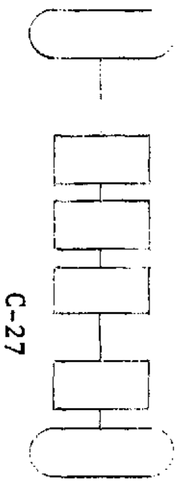
Symbol	Program Line Numbers	Description	Comments
	7550	FUNCTION PHTO(TF)	The input parameter is the Fahrenheit dew point temperature. The output parameter is pH_2O, in millimeters of mercury.
	7560-7570		Initialize constants A-G.
	7580	TC=(TF-32) 1.8	Calculate Centigrade dew point temperature.
	7590	X = 374.11 - TC	Calculate the temperature span from the dew point to the critical temperature.
	7600	$PHTO=10^{\left(EE-\frac{X}{TC+F} \times \frac{A+BX+CX^3}{1+DX}\right)}$	Calculate water vapor pressure
	7610	RETURN	

TABLE 4 DEW POINT TEMPERATURE FUNCTION

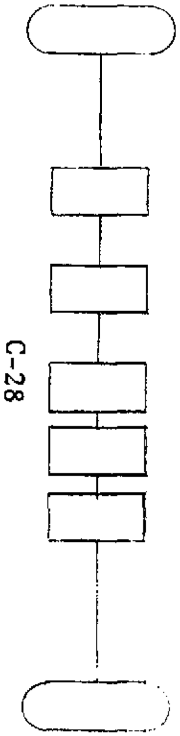
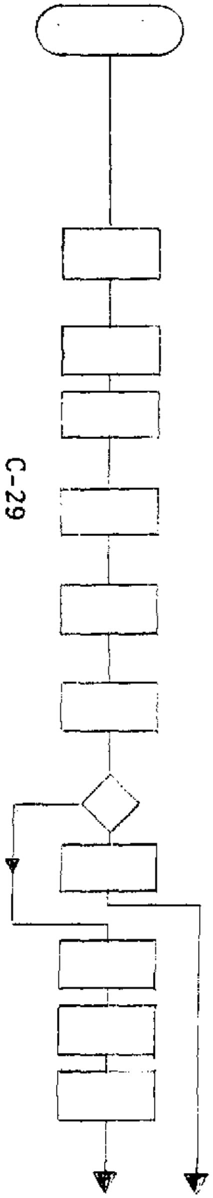
Symbol	Program Line Numbers	Description	Comments
	7640	FUNCTION DEWT(P)	The input parameter P is the water vapor pressure in millimeters of mercury. The output parameter DEWT is the Fahrenheit dew point temperature
	7650	EXTERNAL ROOT, PHTO	Functions ROOT and PHTO are used by function DEWT
	7660	X=ALOG(P)	Calculate two trial values for the dew point temperature
	7670	$TA=-2.4 + 20.25X + 1.522X^2$	
	7680	TB=TA + 0.1	
	4890	DEWT=ROOT(TA,TB,PHTO,P, 0.005, 0.005, 5)	Function ROOT will call function PHTO starting with dew points equal to TA and TB until the water vapor pressure is equal to P with temperature and vapor pressure tolerances of point .005 but not exceeding five trials.
	7700	RETURN	

TABLE 5 TRANSFER INDEX FUNCTION



Symbol	Program Line Numbers	Description	Comments
	7730	FUNCTION TICOR(PC,AF,CD,DEL)	Input parameters are CO_2 partial pressure in millimeters of mercury, cathode air flow in Cfm/cell, current density in Amp/Ft^2, and module temperature - inlet cathode air dew point temperature. The output parameter is TICOR in Lb CO_2/Lb O_2.
	7740-7810		Initialize the correlation parameters in array S.
	7820	P=AMIN1(PC,10)	pCO_2 should not exceed 10.
	7830	$PA = PC\left(\frac{AF}{.44}\right)^{(1+0.84P)^{-0.84P}}$	PA is the effective inlet pCO_2 corrected for nonbaseline cathode air flow.
	7840	$J = \frac{CD}{5} - 1$	Calculate the J index which corresponds to current density.
	7850	IF(J < 1)J=1	For current densities less than 10 ASF, extrapolate from 15 and 10 ASF.
	7860	$TI1 = \sum_{i=1}^{5} S_{ij} PA^i$	Calculate TI at the current density just below the actual current density.
	7870	If (J < 7) BRANCH	Current density should not exceed 40 ASF,
	7880	TICOR = TI1	
	7900	J = J + 1	Calculate TI at the current density just above the actual current density
	7910	$TI2 = \sum_{i=1}^{5} S_{ij} PA^i$	
	7920	AII=J	Interpolate between the two current densities.

-continued-

Table 5 - continued

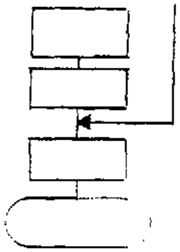
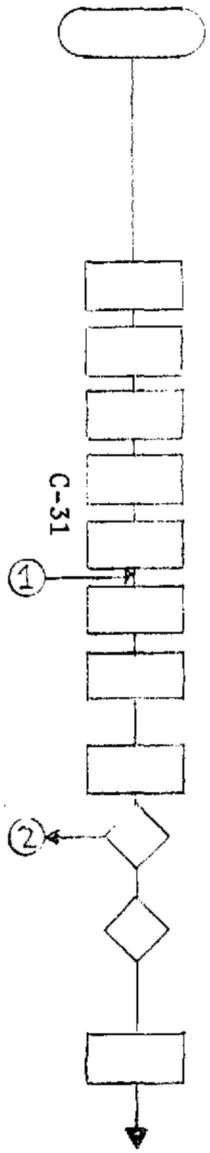
Symbol	Program Line Numbers	Description	Comments
	7930	TERP = $\frac{CD}{5}$ - AII	
	7940	TICOR=TI2xTERP+TI1(1-TERP)	
	7950	TICOR=TICOR(1+0.03536(DEL-18.33))	Correct TI for moisture conditions.
	7960	RETURN	

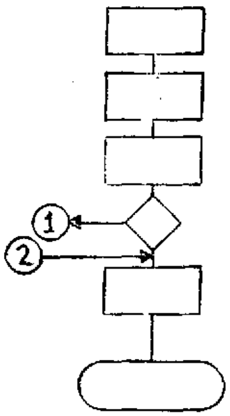
TABLE 6 ROOT FUNCTION



Symbol	Program Line Numbers	Description	Comments
	7990	FUNCTION ROOT(X1,X2,YFCN,W,XTOL, YTOL,K)	Input parameters are the first and second trial root values, the function to be called which returns the function of X, the value of the function at the desired root, X tolerance, Y tolerance, and maximum trials. The output value, ROOT, is the value of X when the function equals W.
	8000-8010		Initialize common and external statements.
	8020	XA=X1	Isolate X1 and X2.
	8030	XB=X2	
	8040	FA=YCFN(XA) - W	Find the error values at XA and XB.
	8050	FB=YCFN(XB)-W	
	8060	BEGIN LOOP	
	8070	$XN=\frac{FA\cdot XB-FB\cdot XA}{FA-FB}$	Extrapolate from the previous two trial values.
	8080	FN=YFCN(XN)-W	Calculate the error at the next X value.
	8090-8100	IF($\lvert FN\rvert$ < YTOL and $\lvert XN-XB\rvert$ < XTOL) BRANCH	BRANCH when the X and Y values are within tolerance.
	8110-8130	IF(Kth TIME THRU LOOP) DUMP VARIABLES & PRINT MESSAGE "NONCONVERGENCE IN LOOP"	If the root has not been found within K trials, print a message.
	8140	XA=XB	Drop the oldest trial value and add the new trial value.

-continued-

Table 6 - continued

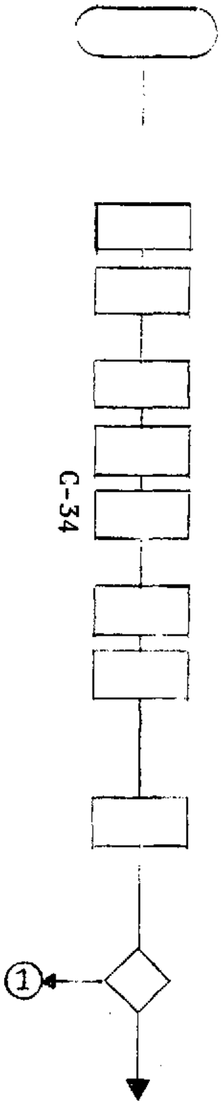


Symbol	Program Line Numbers	Description	Comments
	8150	XB=XN	
	8160	FA=FB	
	8170	FB=FN	
	8180	IF(<Kth TIME THRU LOOP)BRANCH	
	5260	ROOT=XN	The root of the function returned is the latest trial value.
	8190	RETURN	

TABLE 7 MODULE TEMPERATURE SUBROUTINE

Symbol	Program Line Numbers	Description	Comments
	8220	SUBROUTINE TDRIFT	Subroutine TDRIFT calculates the module temperature when the cooling air flow rate is specified. All inputs are through common storage. All outputs except P2 are also through common storage.
	8230-8280		Initialize type, common, and external statements.
	8290	ENTHPR=VI·CPA·T1+V3·CPH·T3	Calculate enthalpy entering the modules in the cathode air and inlet hydrogen streams.
	8300	$T2HIGH=\frac{ENTHPR+.99 \cdot HEATLD}{V1 \cdot CPA+V3 \cdot CPH}$	Calculate maximum possible module temperature. This is the temperature the module would rise to with no cooling air.
	8310	$T2LOW=\frac{EHTHPR+V5A \cdot CPA \cdot T5+HEATLD}{V1 \cdot CPA+V3 \cdot CPA+V5A \cdot CPA}$	Calculate the minimum module temperature which would occur with no heat transfer resistance.
	8320	T2=T2HIGH	Call subroutine ERT to determine values of the heat transfer coefficient and the cooling fin efficiency, neither of which depends upon module temperature but only upon cooling air flow rate which is constant when subroutine TDRIFT is called.
	8330	DUMMY=ERT(V5A/N)	
	8340	T2=ROOT(T2HIGH,T2LOW,ERT1,0,	Start with trial values T2HIGH and T2LOW and use function ERT1 to find the module temperature which yields a heat balance for the specified cooling air flow rate.
	8350	RETURN	

TABLE 8 HEAT BALANCE FUNCTION WITH VARIABLE MODULE TEMPERATURE



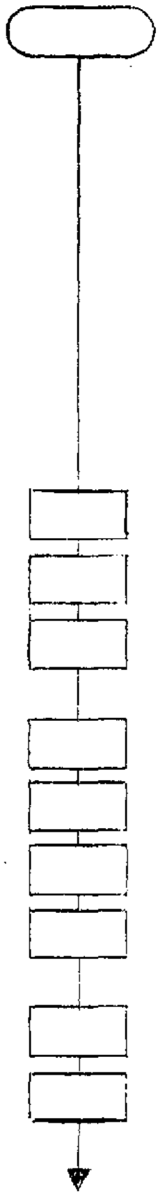
Symbol	Program Line Numbers	Description	Comments
	8380	FUNCTION ERT1(T)	The input parameter is the module temperature. The output parameter, ERT1, is the difference between the available module cooling air temperature drop and the required module cooling air temperature drop.
	8390-8430		Initialize type, common statements.
	8440	$E = 0.729 - 0.221 \ln I + 0.008I + 0.005(T-78)$	Calculate module voltage and heat load at the given temperature.
	8450	$HEATLD = N \cdot I \cdot (1.25-E) \cdot 3.419$	
	8460	DHA=V1(CPA)(T-T1)	Calculate the enthalphy change for the cathode air process hydrogen and cooling air flow, respectively, at the given module temperature.
	8470	DHH=V3(CPH)(T-T3)	
	8480	DHC=HEATLD-DHA-DHH	
	8490	$T6A = T5 + \frac{DHC}{V5A(CPA)}$	Calculate the outlet cooling air temperature from the inlet cooling air temperature and the enthalpy increase.
	8500	$DTREQ = DHC\left(0.376 + 3.876\frac{HC \cdot ETA}{N}\right)$	The required module cooling air temperature difference depends upon the cooling air enthalpy change x the resistance in the fin roots + the gas film resistance.
	8510	IF(T6A < T)BRANCH	If the cooling air temperature at the exit is less than the module temperature, then the log mean temperature difference can be calculated.

-continued-

Table 8 - continued

Symbol	Program Line Numbers	Description	Comments
	8520	ERT1 = -DTREQ	If it is not, then assume that the available temperature difference is zero and the error is equal to the required temperature difference.
	8530	RETURN	
1	8540	$DTAVA = \frac{T6A-T5}{\ln\frac{T-T5}{T-T6A}}$	The available temperature drop is the log mean of the module cooling air temperature difference at the inlet and the outlet of the cooling air passages.
	8550	ERT1 = DTAVA-DTREQ	
	8560	RETURN	

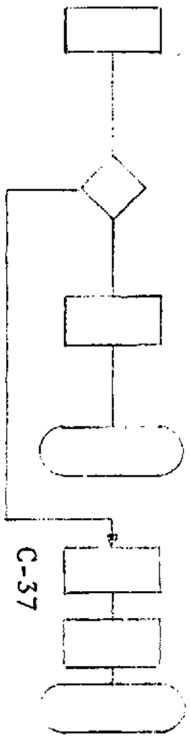
TABLE 9 HEAT BALANCE FUNCTION WITH VARIABLE COOLING AIR FLOW RATE



Symbol	Program Line Numbers	Description	Comments
	8590	FUNCTION ERT(V)	The input parameter is the cooling air flow rate, Cfm/cell. The output parameter ERT is the difference between the available and required module-cooling air temperature differences. Inputs taken from common storage include the inlet cooling air and cathode air temperature, the cooling air heat load, the cooling air specific heat, the number of active cells, and the module temperature. Outputs through common storage include the heat transfer coefficient, the fin efficiency, the outlet cooling air temperature, the available temperature difference, and the required temperature difference.
	8600-8640		
	8650	IF $(V \leq 1) HC = 1.97V^{0.3333}$	Calculate the heat transfer coefficient.
	8660	IF $(1 < V < 2.9883) HC = 1.21 + 0.34V + 0.42V^2$	
	8670	If $(2.9883 \leq V \leq 4) HC = 2V$	
	8680	IF $(4 < V) HC = 2.639016V^{.8}$	
	8690	ETA=1	Calculate the fin efficiency.
	8700	IF $(0.32194 < V \leq 24.72) ETA = 1.0644 - 0.1135V^{0.5}$	
	8710	IF $(24.72 \leq V) ETA = 2.486V^{-.5}$	
	8720	$T6A = T5 + \frac{DHC}{V(CPA)N}$	

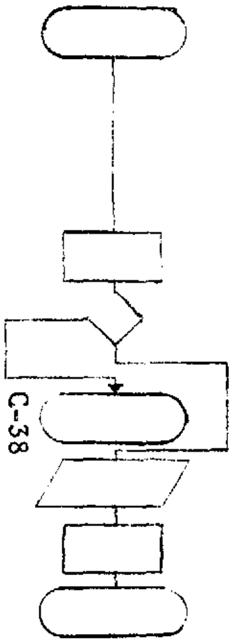
-continued-

Table 9 - continued



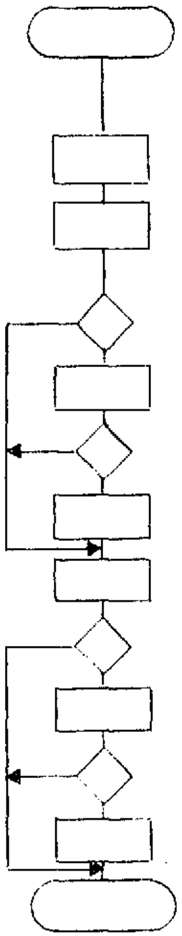
Program Line Numbers	Description	Comments
8730	$DTREQ=\frac{DHC}{N}\left(0.376+\frac{3.876}{HC(ETA)}\right)$	Calculate the required temperature difference from the cooling air heat load, resistance in the fins, and resistance in the stagnant air film.
8740	IF (T6A < T2) BRANCH	Branch and calculate the log mean temperature difference only if the outlet cooling air temperature is less than the module temperature.
8750	ERT = -DTREQ	There is no available temperature difference. The error ERT is minus the required temperature difference.
8760	RETURN	
8770	$DTAVA=\frac{T6A-T5}{\ln\frac{T2-T5}{T2-T6A}}$	Log mean module cooling air temperature difference.
8780	ERT=DTAVA-DTREQ	
8790	RETURN	

TABLE 10 RANGE TEST SUBROUTINE



Symbol	Program Line Numbers	Description	Comments
	8820	SUBROUTINE T(VARNAM,VAR,BOT, TOP,I)	Subroutine input parameters are the variable, value, the lower and upper limits, and the out-of-range counter. The subroutine simply prints a message containing the first four parameters when the variable is out-of-range.
	8830	COMMON IOUT	The message is printed on output device IOUT.
	8840	IF (BOT ≤ VAR ≤ TOP) BRANCH	The subroutine ends immediately if the variable is in range.
	8840	RETURN	
	8850	WRITE, VARNAM, VAR, BOT, TOP	
	8860	I=I+1	
	8870	RETURN	

TABLE 11 MODE B CURRENT AND CATHODE AIR FLOW SUBROUTINE



Symbol	Program Line Numbers	Description	Comments
	8910	SUBROUTINE BMODE	Subroutine BMODE takes the cabin pCO_2 and calculates the current and the cathode air flow based on BK, the Mode B parameters.
	8920-8940		Initialize type and common statements.
	8950	I = BK(1)	Calculate current.
	8960	IF (PCO ≤ BK(2)) BRANCH	
	8970	I = BK(4)	
	8980	IF (PCO ≥ BK(3)) BRANCH	
	8990	I = BK(9) · PCO + BK(10)	
	9000	V1 = BK(5)	Calculate cathode air flow.
	9010	IF (PCO ≤ BK(6)) BRANCH	
	9020	V1 = BK(8)	
	9030	IF (PCO ≥ BK(7)) BRANCH	
	9040	V1 = BK(11) · PCO + BK(12)	
	9050	RETURN	

TABLE 12 CYCLIC PROGRAM LISTING

```
100$SAV
110C    *** CYCLIC PROGRAM *** CS-6 MATH MODEL ***
120C
130$TTY,84
140$NDM
150 LOGICAL QFIN,QFOUT,QCO2GT,QSUBS,QPRINT
160 REAL N,I,HEAD(150),CGEN(200),HDG(150),A0(150),TAB(150),AVG(150)
170 INTEGER INDEX(150),TMAX(200)
180 COMMONIOUT,CPA,CPH,N,V3,T5,T3,T1,BK(12),
190&P0PSA,PO0PSA,T0,VOLUME,P8PSA,T7,V7,
200&DW7,P4PSA,T9,V9SL,DW9,PWPEN,HTPEN,H2OPEN,OXPEN,NFLAG,
210&PC0,I,V1,HEATLD,DHC,DHA,DHH,DTREQ,DTAVA,E,
220&HC,ETA,T2,V5A,T6A,DELT1,V9MSL,V7M1,V5MIN,V5,
230&DUM(5),YA,YB,YC,SLOPEC,CO2GEN,
240&V5INP,V10,COR34,DP34,P3,P3PSA,COR93,DP93,P9,P9PSA,
250&DP78,P7,P7PSA,DP12,P1,P2,CURDEN,DELT1E,PC1,TI,
260&OCON,CTRANS,HCON,WPROD,VC4,PW9,PW3,VH3,VH4,PW1,
270&VW1,VW3,VWPROD,VW2,PO0,PO7,PN1,VN1,VO1,VC1,
280&VO2,VC2,V2,PW2,DW2,DDP1,DDP2,DPTDAV,DELT1P,T2P,
290&VC7,VW7,VO7,VN7,RH7,FC1,FW1,PH3,FH3,EMOD,
300&POWER,TE,PC2,FC2,FW2,RH2,DW4,PW4,VW4,V4,
310&V4SL,VC4SL,VH4SL,FC4,FH4,FW4,F4,CHWRTO,HCVRTO,DP56,
320&P6,T6,PWRCTB,T11,DP1213,PWRCLB,P12,T12,V8,VW8,
330&VC8,PC8,VN8,PN8,VO8,PW8,DW8,T8,RH8,AV1,
340&AV2,AV3,AV4,AV5,AV6,AV6A,AV7,AV8,AV9,AV10EX,
350&AV11,AV12,AV13,PWRTOT,HTTOT,PWRWGT,HTWGT,H2OWGT,OXWGT,EQWGT
360 EQUIVALENCE(A0(1),PC0)
370 DATA IOUT,NSTEPS,(TMAX(MN),CGEN(MN),MN=1,21)/1,21,
380&405,.3530, 420,.4118, 435,.4706, 450,.5295, 465,.5687, 480,.7060,
390&705,.7452, 720,.6079, 780,.5295, 840,.5687, 900,.6667, 1020,.7452,
400&1080,.6667, 1140,.5295, 1200,.5687, 1290,.6471, 1320,.6079,
410&1365,.5295, 1380,.4706, 1395,.4118, 1440,.3530/
420 DATA HEAD/
430&"   PC0","     I","    V1","HEATLD","   DHC",
440&"   DHA","   DHH"," DTREQ"," DTAVA","     E",
450&"    HC","   ETA","    T2","   V5A","   T6A",
460&" DELT1"," V9MSL","  V7M1"," V5MIN","    V5",
470&"  DUM1","  DUM2","  DUM3","  DUM4","  DUM5",
480&"    YA","    YB","    YC","SLOPEC","CO2GEN",
490&" V5INP","   V10"," COR34","  DP34","    P3",
500&" P3PSA"," COR93","  DP93","    P9"," P9PSA",
510&"  DP78","    P7"," P7PSA","  DP12","    P1",
520&"    P2","CURDEN","DELT1E","   PC1","    TI",
530&"  OCON","CTRANS","  HCON"," WPROD","   VC4",
540&"   PW9","   PW3","   VH3","   VH4","   PW1",
550&"   VW1","   VW3","VWPROD","   VW2","   PO0",
560&"   PO7","   PN1","   VN1","   VO1","   VC1",
570&"   VO2","   VC2","    V2","   PW2","   DW2",
580&"  DDP1","  DDP2","DPTDAV","DELT1P","   T2P",
590&"   VC7","   VW7","   VO7","   VN7","   RH7",
```

continued-

Table 12 - continued

```
600&"   FC1","   FW1","   PH3","   FH3","  EMOD",
610&" POWER","    TE","   PC2","   FC2","   FW2",
620&"   RH2","   DW4","   PW4","   VW4","    V4",
630&"  V4SL"," VC4SL"," VH4SL","   FC4","   FH4",
640&"   FW4","    F4","CHWRTO","HCVRTO","  DP56",
650&"    P6","    T6","PWRCTB","   T11","DP1213",
660&"PWRCLB","   P12","   T12","    V8","   VW8",
670&"   VC8","   PC8","   VN8","   PN8","   VO8",
680&"   PW8","   DW8","    T8","   RH8","   AV1",
690&"   AV2","   AV3","   AV4","   AV5","   AV6",
700&"  AV6A","   AV7","   AV8","   AV9","AV10EX",
710&"  AV11","  AV12","  AV13","PWRTOT"," HTTOT",
720&"PWRWGT"," HTWGT","H2OWGT"," OXWGT"," EQWGT"/
730C
740C   DETERMINE I/O DEVICES:
750C
760 PRINT,"FILE INPUT (T OR F)",↑*
770 READ,QFIN
780 INP=50
790 IF(QFIN)INP=2
800 IF(QFIN)CALL OPENF(2,"MATHIN")
810 PRINT,"FILE OUTPUT (T OR F)",↑*
820 READ,QFOUT
830 IF(.NOT.QFOUT)IOUT=66
840 GOTO6
850 99 PRINT," END OF INPUT DATA FILE"
860 CALL EXIT
870C
880C   IF OUTPUT IS TO FILE, OBTAIN FILE NAME:
890C
900 1IF(.NOT.QFOUT)GOTO6
910 IF(.NOT.QFIN)PRINT,"FILE FOR OUTPUT",↑*
920 READ(INP,48,END=99)FNAME
930 48 FORMAT(14A6)
940C
950C   IF THE FILE NAME IS "SAME",KEEP FILE OPEN FOR MORE OUTPUT,
960C   OTHERWISE ASSIGN THE NAME AND CLOSE THE FILE:
970C
980 IF(FNAME.NE."SAME")CALL CLOSEF(1,FNAME,7)
990C
1000C   READ AND WRITE PROBLEM IDENTIFIER:
1010C
1020 6WRITE(IOUT;4)
1030 4 FORMAT(/////)
1040 IF(.NOT.QFIN)PRINT,"PROBLEM IDENTIFIER:"
1050 READ(INP,48,END=99)(HDG(J),J=1,14)
1060 IF(QFIN)WRITE(IOUT;48)(HDG(J),J=1,14)
1070C
1080C   INPUT AND OUTPUT NEW CO2 GENERATION TABLE IF DESIRED:
1090C
```

continued-

Table 12 - continued

```
IF(.NOT.QFIN)PRINT,"NEW CO2 GENERATION TABLE(T OR F)",+*
READ(INP,,END=99)QCO2GT
IF(QCO2GT)READ(INP,,END=99)NSTEPS,(TMAX(MN),CGEN(MN),MN=1,NSTEPS)
IF(QCO2GT)WRITE(IOUT;100)NSTEPS,(TMAX(MN),CGEN(MN),MN=1,NSTEPS)
100 FORMAT( /" CO2 GENERATION RATE TABLE:"/" NUMBER OF STEPS=",I3//
&"  ENDING          CO2"/"    TIME GENERATION"/" MINUTES       LB/HR"/
&(F8.0,F11.4))
C
C   INPUT FOR BASE, MODE B, NO. OF DAYS, SIZES OF TIME INTERVALS
C   FOR INTEGRATION AND PRINTING:
C
IF(.NOT.QFIN)PRINT,"INPUT DATA",+*
READ(INP,,END=99)POPSA,PCO,POOPSA,TO,VOLUME,P8PSA,T7,V7,DW7,P4PSA,T9,V9SL,DW9,
&N,I,DELT1,V1,PWPEN,HTPEN,H2OPEN,OXPEN,KMODE,NFLAG,(BK(MN),MN=1,8),DAYS,DT,DPRINT
C
C   DETERMINE WHETHER BASE OUTPUT IS TO BE PRINTED AND
C   INPUT THE SUBSCRIPTS OF THE DESIRED CYCLIC TABLE OUTPUT ITEMS:
C
IF(.NOT.QFIN)PRINT,"PRINT BASE OUTPUT(T OR F)",+*
READ(INP,,END=99)QPRINT
KBASE=4
IF(QPRINT)KBASE=5
IF(.NOT.QFIN)PRINT,"NEW CYCLIC OUTPUT SUBSCRIPTS(T OR F)",+*
READ(INP,,END=99)QSUBS
IF(QSUBS)READ(INP,,END=99)NDEX,(INDEX(MN),MN=1,NDEX)
IF(QFOUT)PRINT," START PROBLEM"
C
C   CALC. SLOPES AND INTERCEPTS FOR MODE B CURRENT AND AIRFLOW CURVES:
C
BK(9)=(BK(1)-BK(4))/(BK(2)-BK(3))
BK(10)=BK(1)-BK(9)*BK(2)
BK(11)=(BK(5)-BK(8))/(BK(6)-BK(7))
BK(12)=BK(5)-BK(11)*BK(6)
C
C   IF MODE B IS IN EFFECT, DETERMINE INITIAL VALUES OF I AND V1
C   BY CALLING SUBROUTINE "BMODE":
C
IF(KMODE.EQ.1)CALL BMODE
C
C   INPUT DATA PLAYBACK:
C
WRITE(IOUT;230)
230FORMAT(" **********INPUT DATA**********")
WRITE(IOUT;1017)
1017FORMAT(" CABIN ATMOSPHERE:")
944 FORMAT(5X,A6,G10.4,3("  !  ",A6,G10.4))
WRITE(IOUT;944)"POPSA",POPSA,"PCO",PCO,"POOPSA",POOPSA,"TO ",TO,"VOLUME",VOLUME
WRITE(IOUT;1032)
1032FORMAT(" PROCESS AIR OUTLET/INLET:")
WRITE(IOUT;944)"P8PSA",P8PSA,"T7 ",T7,"V7 ",V7,"DW7",DW7
```


continued-

Table 12 - continued

```
1600 WRITE(IOUT;1031)
1610 1031FORMAT(" H2 OUTLET/INLET:")
1620 WRITE(IOUT;944)"P4PSA",P4PSA,"T9 ",T9,"V9SL",V9SL,"DW9",DW9
1630 WRITE(IOUT;1020)
1640 1020FORMAT(" MODULES:")
1650 WRITE(IOUT;944)"N  ",N,"I  ",I,"DELT1",DELT1,"V1 ",V1
1660 WRITE(IOUT;1021)
1670 1021FORMAT(" PENALTY WEIGHT FACTORS:")
1680 WRITE(IOUT;944)"PWPEN",PWPEN,"HTPEN",HTPEN,"H2OPEN",H2OPEN,
1690&"OXPEN",OXPEN
1700 WRITE(IOUT;1022)
1710 1022 FORMAT(" CONTROL:")
1720 WRITE(IOUT;944)"KMODE",KMODE,"NFLAG",NFLAG
1730&,"IMIN",BK(1),"PCIMIN",BK(2),"PCIMAX",BK(3),"IMAX",BK(4),
1740&"VMIN",BK(5),"PCVMIN",BK(6),"PCVMAX",BK(7),"VMAX",BK(8)
1750&,"DAYS",DAYS,"DT ",DT,"DPRINT",DPRINT
1760 WRITE(IOUT;4)
1770 WRITE(IOUT;220)
1780 220 FORMAT(" ***********RESULTS************")
1790C
1800C   CHECK INPUTS:
1810C
1820 IR=0
1830 CALLT("POPSA ",POPSA,13.7,15.7,IR)
1840 CALLT("PCO",PCO,.0001,10.,IR)
1850 CALLT("POOPSA",POOPSA,2.,4.,IR)
1860 CALLT("TO ",TO,44.,80.,IR)
1870 CALLT("VOLUME",VOLUME,100.,100000.,IR)
1880 CALLT("P8PSA ",P8PSA,13.7,15.7,IR)
1890 CALLT("T7    ",T7,44.,80.,IR)
1900 CALLT("V7    ",V7,0.,600.,IR)
1910 CALLT("DW7   ",DW7,41.,70.,IR)
1920 CALLT("P4PSA ",P4PSA,14.8,21.2,IR)
1930 CALLT("T9    ",T9,65.,75.,IR)
1940 CALLT("V9SL  ",V9SL,0.,18.,IR)
1950 CALLT("DW9   ",DW9,10.,75.,IR)
1960 CALLT("N     ",N,90.,96.,IR)
1970 CALLT("I     ",I,2.44,9.76,IR)
1980 CALLT("DELT1 ",DELT1,10.,25.,IR)
1990 CALLT("V1    ",V1,5.,76.8,IR)
2000 CALLT("PWPEN ",PWPEN,0.,2.,IR)
2010 CALLT("HTPEN ",HTPEN,0.,2.,IR)
2020 CALLT("H2OPEN",H2OPEN,0.,500.,IR)
2030 CALLT("OXPEN ",OXPEN,0.,3000.,IR)
2040 FLAG=NFLAG
2050 CALLT("NFLAG ",FLAG,0.,1.,IR)
2060 AMODE=KMODE
2070 CALLT("KMODE ",AMODE,0.,1.,IR)
2080 CALLT("IMIN",BK(1),2.44,9.76,IR)
2090 CALLT("PCIMIN",BK(2),.0001,10.,IR)
```

continued-

Table 12 - continued

```
CALLT("PCIMAX",BK(3),.0001,10.,IR)
CALLT("IMAX",BK(4),2.44,9.76,IR)
CALLT("VMIN",BK(5),5.,76.8,IR)
CALLT("PCVMIN",BK(6),.0001,10.,IR)
CALLT("PCVMAX",BK(7),.0001,10.,IR)
CALLT("VMAX",BK(8),5.,76.8,IR)
CALLT("DAYS",DAYS,0.,10.,IR)
CALLT("DT ",DT,1.,15.,IR)
CALLT("DPRINT",DPRINT,1.,100.,IR)
IF(IR.GT.0)GOTO1
C
C   PRINT FULL BASE PROGRAM OUTPUT IF DESIRED:
C
CALL BASE(KMODE,KBASE,1,KERROR)
IF(KERROR.NE.0 .OR. DAYS.EQ.0.)GOTO1
C
C   INITIALIZE CONSTANTS:
C
NDT=DT
NDAY=0
MINCYC=TMAX(NSTEPS)
NDAYS=DAYS
NPRINT=DPRINT
U5=(T0+460.)*386.72*760./(530.*VOLUME*60.*44.01)
MAXDEX=0
DO 110 MN=1,NDEX
IN=INDEX(MN)
HDG(MN)=HEAD(IN)
110 IF(IN.GT.MAXDEX)MAXDEX=IN
KBASE=1
IF(MAXDEX.GT.52)KBASE=2
IF(MAXDEX.GT.78)KBASE=3
IF(MAXDEX.GT.129)KBASE=4
C
C   START A NEW CYCLE (DAY):
C
7800CONTINUE
QPRINT=.TRUE.
NT=0
DO 725 MN=1,NDEX
725AVG(MN)=0.
NDAY=NDAY+1
PCOI=PCO
IGEN=1
CO2GEN=CGEN(1)
C
C   PRINT CYCLIC TABLE HEADINGS:
C
IF(QFOUT)PRINT,NDAY
WRITE(IOUT;120)NDAY,(HDG(MN),MN=1,NDEX)
```

continued-

Table 12 - continued

```
120FORMAT(////" ************DAY",I3," ************"//"  TIME"/(7(5X,A6)))
WRITE(IOUT;121)
121FORMAT(/" ********************************"/)
WRITE(IOUT;135)0,0
CALL BASE(KMODE,KBASE,1,KERROR)
IF(KERROR.NE.0)GOTO1
C
C   PRINT A LINE IN THE TABLE:
C
7900CONTINUE
IF(.NOT.QPRINT)GOTO8000
DO 130 MN=1,NDEX
IN=INDEX(MN)
130 TAB(MN)=A0(IN)
WRITE(IOUT;140)(TAB(MN),MN=1,NDEX)
140FORMAT(7(G11.4))
C
C   START A NEW CYCLE AT THE END OF THE CURRENT CYCLE
C   UNLESS EITHER STEADY STATE HAS BEEN REACHED
C   OR MAXIMUM NUMBER OF CYCLES HAS BEEN REACHED
C
8000CONTINUE
IF(NT.LT.MINCYC)GOTO8100
DO 726MN=1,NDEX
726AVG(MN)=AVG(MN)*DT/MINCYC
WRITE(IOUT;122)
122FORMAT(" AVERAGES:")
WRITE(IOUT;140)(AVG(MN),MN=1,NDEX)
IF(NDAY.GE.NDAYS .OR. ABS((PCO-PCOI)/PCO).LE..0005)GOTO1
GOTO7800
C
C   INCREMENT TIME AND UPDATE CO2 GENERATION RATE
C
8100CONTINUE
NT=NT+NDT
QPRINT=MOD(NT,NPRINT).EQ.0
IF(NT.GT.TMAX(IGEN))IGEN=IGEN+1
CO2GEN=CGEN(IGEN)
C
C   WRITE THE TIME:
C
IF(.NOT.QPRINT)GOTO8200
NHRS=NT/60
NMIN=NT-NHRS*60
WRITE(IOUT;135)NHRS,NMIN
135FORMAT(1X,I2,":",I2)
C
C   UPDATE CABIN CO2 PARTIAL PRESSURE
C
8200 CONTINUE
```

continued-

Table 12 - continued

```
 XA=PCO
 SLOPEA=U5*(CO2GEN-CTRANS)
 SLOPE=SLOPEA
 PCN=PCO+SLOPE*DT
 YA=XA-PCN
 XB=PCN
 PCO=PCN
 CALL BASE(KMODE,0,0,KERROR)
 IF(KERROR.NE.0)GOTO1
 SLOPEB=U5*(CO2GEN-CTRANS)
 SLOPE=.5*(SLOPEA+SLOPEB)
 PCN=XA+SLOPE*DT
 YB=XB-PCN
 PCO=(YA*XB-YB*XA)/(YA-YB)
 KPRINT=0
 IF(QPRINT)KPRINT=1
C
C   CALL BASE TO CALC. SYSTEM PARAMETERS AT NEW CABIN PCO2
C
 CALL BASE(KMODE,KBASE,KPRINT,KERROR)
 IF(KERROR.NE.0)GOTO1
 DO 728MN=1,NDEX
 IN=INDEX(MN)
 728AVG(MN)=AVG(MN)+AO(IN)
C   CHECK ACCURACY OF INTEGRATION:
C
 SLOPEC=U5*(CO2GEN-CTRANS)
 SLOPE=.5*(SLOPEA+SLOPEC)
 PCN=XA+SLOPE*DT
 YC=PCO-PCN
C   YC IS THE INACCURACY IN PCO
 GOTO7900
 END
C
 SUBROUTINE BASE(KMODE,KBASE,KPRINT,KERROR)
C
C     *** CS-6 MATH MODEL BASE PROGRAM ***
C
 REALN,I
 COMMONIOUT,CPA,CPH,N,V3,T5,T3,T1,BK(12),
&POPSA,POOPSA,TO,VOLUME,P8PSA,T7,V7,
&DW7,P4PSA,T9,V9SL,DW9,PWPEN,HTPEN,H2OPEN,OXPEN,NFLAG,
&PCO,I,V1,HEATLD,DHC,DHA,DHH,DTREQ,DTAVA,E,
&HC,ETA,T2,V5A,T6A,DELT1,V9MSL,V7M1,V5MIN,V5,
&DUM(5),YA,YB,YC,SLOPEC,CO2GEN,
&V5INP,V10,COR34,DP34,P3,P3PSA,COR93,DP93,P9,P9PSA,
&DP78,P7,P7PSA,DP12,P1,P2,CURDEN,DELT1E,PC1,TI,
&OCON,CTRANS,HCON,WPROD,VC4,PW9,PW3,VH3,VH4,PW1,
&VW1,VW3,VWPROD,VW2,POO,PO7,PN1,VN1,VO1,VC1,
&VO2,VC2,V2,PW2,DW2,DDP1,DDP2,DPTDAV,DELT1P,T2P,
```


continued-

Table 12 - continued

```
3600&VC7,VW7,VO7,VN7,RH7,FC1,FW1,PH3,FH3,EMOD,
3610&POWER,TE,PC2,FC2,FW2,RH2,DW4,PW4,VW4,V4,
3620&V4SL,VC4SL,VH4SL,FC4,FH4,FW4,F4,CHWRTO,HCVRTO,DP56,
3630&P6,T6,PWRCTB,T11,DP1213,PWRCLB,P12,T12,V8,VW8,
3640&VC8,PC8,VN8,PN8,VO8,PW8,DW8,T8,RH8,AV1,
3650&AV2,AV3,AV4,AV5,AV6,AV6A,AV7,AV8,AV9,AV10EX,
3660&AV11,AV12,AV13,PWRTOT,HTTOT,PWRWGT,HTWGT,H2OWGT,OXWGT,EQWGT
3670 EXTERNAL PHTO,DEWT,TICOR,ROOT,TDRIFT,ERT1,ERT,BMODE
3680 DATA CPA,CPH/1.0765,1.0666/
3690&,U1,U2,U3,U4/51.7007,386.7,3.419,28.32/
3700&,C782,C562,C561,C12132/2.25E-5,1.303E-5,.0101,8.6118E-4/
3710&,C5132,C5131,QA/8.742E-4,.0101,8.517E-4/
3720&,HRDWGT,PWRPC,PWREC,PWRDAU/817.9,136.,45.,100./
3730 KERROR=0
3740 IF(KMODE+KBASE.EQ.0)GOTO 7700
3750 IF(KMODE.EQ.1)CALL BMODE
3760C
3770C   CHECK FOR SUFFICIENT H2:
3780C
3790 V9MSL=1.3*N*I*7.508E-3
3800 IF(V9SL.GE.V9MSL)GOTO1213
3810 WRITE(IOUT;213)V9MSL
3820 213 FORMAT(" INSUFFICIENT H2.",G10.4," SLPM IS REQUIRED")
3830 KERROR=1
3840 RETURN
3850 1213 CONTINUE
3860C
3870C   CHECK CATHODE AIR CAPACITY:
3880C
3890 IF(V1.LE.70)GOTO9001
3900 V1=70.
3910 WRITE(IOUT;9000)
3920 9000FORMAT(" V1 HAS BEEN CHANGED TO 70 SCFM, BLOWER CAPACITY.")
3930 9001 CONTINUE
3940C
3950C   CALC. COOLING AIR FLOW WITH COOLING BLOWERS OFF:
3960C
3970 V7M1=V7-V1
3980 QB=C5131+2.*C782*V7M1
3990 QC=C782*V7M1**2
4000 V5MIN=(-QB+SQRT(QB*QB+4.*QA*QC))/(2.*QA)
4010C
4020C   CALC. COOLING AIR HEAT LOAD, ETC. FOR INPUT MODULE TEMP:
4030C
4040 DW1=DW7
4050 T2=DW1+DELT1
4060 T2INP=T2
4070 E=.729-.22*ALOG(I)+.008*I+.005*(T2-78.)
4080 HEATLD=N*I*(1.25-E)*U3
4090 T1=T7
```

continued-

Table 12 - continued

```
T3=T9
V3=V9SL/U4
T5=T1
DHA=V1*CPA*(T2-T1)
DHH=V3*CPH*(T2-T3)
DHC=HEATLD-DHA-DHH
C
C   CHECK NEED FOR COOLING:
C
IF(DHC.GT.0)GOTO898
C
C   CALC. NEW MODULE TEMP IF COOLING BLOWERS ARE OFF:
C
888 CONTINUE
V5=V5MIN
V5A=N*V5MIN/96.
CALL TDRIFT
DROP=T2INP-T2
IF(DROP.LE.3.)GOTO766
IF(KPRINT.EQ.0)GOTO766
WRITE(IOUT;469)DROP,T2INP,T2
469 FORMAT(" COOLING BLOWERS ARE OFF."/" MODULE TEMPERATURE FALLS",
&F6.2,"F BELOW THE DESIRED",F6.2,"F TO",F6.2,"F.")
GOTO766
C
C   CHECK THAT MODULE TEMP IS HIGH ENOUGH TO TRANSFER HEAT
C   AT LEAST TO COOLING FIN ROOTS:
C
898 CONTINUE
IF(T2-T5.GE..376*DHC/N)GOTO765
C
C   CALC. NEW MODULE TEMP IF COOLING BLOWERS ARE ON FULL:
C
886 CONTINUE
V5=440.
V5A=V5*N/96.
CALL TDRIFT
RISE=T2-T2INP
IF(RISE.LE.3)GOTO766
IF(KPRINT.EQ.0)GOTO766
WRITE(IOUT;479)RISE,T2INP,T2
479 FORMAT(" COOLING BLOWERS ARE ON FULL."/" MODULE TEMPERATURE RISES",
&F6.2,"F ABOVE THE DESIRED",F6.2,"F TO",F6.2,"F.")
GOTO766
C
C   CALC. COOLING AIR FLOW FOR INPUT MODULE TEMPERATURE:
C
765 CONTINUE
VA=1.01*DHC/(CPA*N*(T2-T5))
VB=2.*VA
```

continued-

Table 12 - continued

```
V5A=N*ROOT(VA,VB,ERT,0.,.005,.001,20)
V5=96.*V5A/N
V5INP=V5
C
C   ARE COOLING BLOWERS OUT OF RANGE:
C
IF(V5.LT.V5MIN)GOTO888
IF(V5.GT.440.)GOTO886
C
C   MODULE HEAT BALANCE IS MAINTAINED WITH COOLING BLOWERS IN RANGE:
C
766 CONTINUE
V10=V7-V1-V5
C
C   CHECK PLENUM BYPASS FLOW:
C
IF(V10.GE..05*V7)GOTO244
IF(KPRINT.EQ.0)GOTO244
WRITE(IOUT;242)
WRITE(IOUT;944)"V10",V10
242FORMAT(" INSUFFICIENT INLET PROCESS AIR TO ",
&"PREVENT BACKMIXING THROUGH PLENUM BYPASS.")
KERROR=2
RETURN
C
C   CALC. STREAM PARAMETERS REQUIRED FOR MOISTURE BALANCE CHECKS:
C
244 CONTINUE
IF(KBASE.EQ.0)GOTO7107
COR34=(14.1/P4PSA)**.8
P4=P4PSA*U1
V3SL=V9SL
DP34=.3822*COR34*V3SL
IF(V3SL.GT.22.)DP34=COR34*(8.3183+.4187*(V3SL-21.5801)**1.75)
P3=P4+DP34
P3PSA=P3/U1
COR93=(14.1/P3PSA)**.8
DP93=COR93*10.64*V3SL
IF(V3SL.GT.6.2)DP93=COR93*(35.14*V3SL-195.25+EXP(7.75-.6537*V3SL))
P9=P3+DP93
P9PSA=P9/U1
DP78=C782*V10*V10
P8=P8PSA*U1
P7=P8+DP78
P7PSA=P7/U1
DP12=V1*(.001903*V1+.04877)
P1=P7
P2=P1-DP12
7107CURDEN=I/.244
DELT1E=T2-DW1
```

continued-

Table 12 - continued

```
7700 CONTINUE
PC1=PC0*P7PSA/POPSA
TI=TICOR(PC1,V1/96.,CURDEN,DELT1E)
OCON=6.5803E-4*N*I
CTRANS=TI*OCON
IF(KBASE.LE.1)RETURN
HCON=OCON*2.016/16.
WPROD=OCON+HCON
VC4=CTRANS*U2/(44.01*60.)
PW9=PHTO(DW9)
PW3=P3*PW9/P9
VH3=V3*(1.-PW3/P3)
VH4=VH3-HCON*U2/(2.016*60.)
C TRIAL VALUE OF H2+CO2 OUTLET WATER VAPOR PRESSURE:
PW4=PHTO(T2-6.)
VW4=PW4*(VC4+VH4)/(P4-PW4)
DW1=DW7
PW1=PHTO(DW1)
VW1=V1*PW1/P1
VW3=V3-VH3
VWPROD=WPROD*U2/(18.01*60.)
VW2=VW1+VW3-VW4+VWPROD
PO0=POOPSA*U1
PO7=PO0*P7PSA/POPSA
PO1=PO7
PN1=P1-PO1-PW1-PC1
VN1=V1*PN1/P1
VO1=V1*PO1/P1
VC1=V1*PC1/P1
VN2=VN1
VO2=VO1-OCON*U2/(32.*60.)
VC2=VC1-VC4
V2=VO2+VN2+VW2+VC2
PW2=VW2*P2/V2
DW2=DEWT(PW2)
C
C   CHECK MODULE MOISTURE BALANCE:
C
DDP1=T1-DW1
DDP2=T2-DW2
IF(ABS(DDP1-11.25).LE.1.75 .AND.ABS(DDP2-11.25).LE.1.75)GOTO30
IF(DDP1.LT.4.)GOTO1210
IF(DDP1.GT.14.)GOTO1210
IF(DDP2.LT.7.)GOTO1211
IF(DDP2.GT.19.)GOTO1211
DPTDAV=.5*(DDP1+DDP2)
IF(ABS(DPTDAV-11.).LE.1.5 .AND. (DDP2.GE.13. .OR. DPTDAV.GE.10.))GOTO30
IF(KPRINT.EQ.1)WRITE(IOUT;654)
654FORMAT(" AVERAGE CATHODE AIR DEWPOINT DEPRESSION OUT OF RANGE.")
28 IF(KPRINT.EQ.1)WRITE(IOUT;543)
```

continued-

Table 12 - continued

```
543FORMAT(" ELECTROLYTE MOISTURE BALANCE IS NOT MAINTAINED.")
IF(NFLAG.EQ.0)GOTO30
KERROR=3
RETURN
1210 IF(KPRINT.EQ.1)WRITE(IOUT;432)
432FORMAT(" INLET CATHODE AIR DEWPOINT DEPRESSION OUT OF RANGE.")
GOTO28
1211 IF(KPRINT.EQ.1)WRITE(IOUT;321)
321FORMAT(" OUTLET CATHODE AIR DEWPOINT DEPRESSION OUT OF RANGE.")
GOTO28
C
C   COMPLETE ALL STREAM DEFINITIONS:
C
30 CONTINUE
IF(KBASE.EQ.2)RETURN
DELT1P=22.-T1+DW2
T2P=DW1+DELT1P
PW7=PW1
PN7=PN1
PC7=PC1
VC7=PC7*V7/P7
VW7=PW7*V7/P7
PO7=PO1
VO7=PO7*V7/P7
VN7=PN7*V7/P7
RH7=100.*PW7/PHTO(T7)
FC1=VC1*44.01*60./U2
FW1=VW1*18.01*60./U2
RH1=RH7
PH3=P3-PW3
FH3=VH3*2.016*60./U2
EMOD=16.*E
POWER=N*I*E
TE=TI/.0275
PC2=VC2*P2/V2
FC2=FC1-CTRANS
FW2=VW2*18.01*60./U2
RH2=100.*PW2/PHTO(T2)
T4=T2
V9=V3
DW4=.77*(DW1+DW2)/2. + .23*T2
PW4=PHTO(DW4)
VW4=PW4*(VH4+VC4)/(P4-PW4)
V4=VH4+VC4+VW4
V4SL=V4*U4
VC4SL=VC4*U4
VH4SL=VH4*U4
FC4=CTRANS
FH4=VH4*2.016*60./U2
FW4=VW4*18.01*60./U2
```


continued-

Table 12 - continued

```
F4=FC4+FH4+FW4
CHWRTO=FC4/FH4
HCVRTO=VH4/VC4
P5=P7
DP56=V5*(V5*C562+C561)
P6=P5-DP56
T6=(V5A*T6A+(V5-V5A)*T5)/V5
IF(V1.LE.62.)PWRCTB=2.8*V1+153.8
IF(V1.GT.62. .AND. V1.LE.65.)PWRCTB=40.*V1-2150.
IF(V1.GT.65.)PWRCTB=-34.*V1+2660.
T11=T2+PWRCTB*U3/(V1*CPA)
V11=V2
P11=P8
PWRCLB=0.
DP1213=C12132*V5*V5
IF(V5.LT.1.01*V5MIN)GOTO14
DP1213=C12132*V5MIN*V5MIN
TR=(DP78/1.869+.05)/1.3
TR=TR**(.128+.102*DP78/1.869)
PWH=410.-.00396*(V5-368)**2
PWL=410.-.00178*(V5-306.)**2
PWRCLB=TR*PWH+(1.-TR)*PWL
14CONTINUE
P12=P8+DP1213
T12=T6+PWRCLB*U3/(V5*CPA)
T13=T12
V12=V5
P13=P8
V13=V5
V8=V10+V2+V5
VW8=VW7+VW2-VW1
VC8=VC7-VC4
PC8=VC8*P8/V8
VN8=VN7
PN8=VN8*P8/V8
VO8=VO7-.5*(VH3-VH4)
PW8=P8*VW8/V8
DW8=DEWT(PW8)
T8=(T11*V11+T13*V13+T7*V10+POWER*U3/CPA)/V8
RH8=100.*PW8/PHTO(T8)
IF(KBASE.EQ.3)RETURN
AV7=V7*(T7+460.)*1.434/P7
AV1=V1*AV7/V7
AV2=V2*(T2+460.)*1.434/P2
AV11=V11*(T11+460.)*1.434/P11
AV9=V9*(T9+460.)*1.434/P9
AV3=V3*(T3+460.)*1.434/P3
AV4=V4*(T4+460.)*1.434/P4
AV5=V5*AV7/V7
AV6=V5*(T6+460.)*1.434/P6
```


continued-

Table 12 - continued

```
6600 V6A=V5A
6610 AV6A=V6A*(T5A+460.)*1.434/P6
6620 AV12=V12*(T12+460.)*1.434/P12
6630 AV13=V13*(T13+460.)*1.434/P13
6640 AV10EX=V10*(T7+460.)*1.434/P8
6650 AV8=V8*(T8+460.)*1.434/P8
6660C
6670C   EQUIVALENT WEIGHT CALCULATIONS:
6680C
6690 PWRTOT=PWRPC+PWREC+PWRCLB+PWRCTB+PWRDAU
6700 HTTOT=HEATLD+U3*(PWRTOT+POWER)
6710 PWRWGT=PWPEN*PWRTOT
6720 HTWGT=HTPEN*HTTOT
6730 H2OWGT=H2OPEN*WPROD
6740 OXWGT=OXPEN*OCON
6750 EQWGT=PWRWGT+HTWGT+H2OWGT+OXWGT+HRDWGT
6760 IF(KBASE.EQ.4)RETURN
6770C
6780C
6790C   MAJOR OUTPUT SATEMENTS
6800C
6810 WRITE(IOUT;456)DELT1P,T2P,DW1,DELT1P
6820 456 FORMAT(" PREFERRED VALUE OF DELT1 IS",F6.2,
6830&" UNDER THESE CONDITIONS"/" SO THAT",F6.2,
6840&" = T2 = DW1 + DELT1 =",F6.2," +",F6.2,".")
6850C
6860 944FORMAT(5X,A6,G10.4,3("  !  ",A6,G10.4))
6870C
6880 WRITE(IOUT;1020)
6890 1020 FORMAT(" MODULES:")
6900 WRITE(IOUT;944)"TI ",TI,"TE ",TE,"E  ",E,"EMOD",EMOD,
6910&"CTRANS",CTRANS,"OCON",OCON,"HCON",HCON,"WPROD",WPROD,
6920&"CURDEN",CURDEN,"HEATLD",HEATLD,"POWER",POWER
6930C
6940 WRITE(IOUT;1014)
6950 1014FORMAT(" CATHODE AIR INLET:")
6960 WRITE(IOUT;944)"P1 ",P1,"PC1",PC1,
6970&"PW1",PW1,"FC1",FC1,"FW1",FW1,"VC1",VC1,"VW1",VW1,
6980&"VO1",VO1,"VN1",VN1,"T1 ",T1,"DW1",DW1,"RH1",RH1
6990C
7000 WRITE(IOUT;1024)
7010 1024FORMAT(" CATHODE AIR OUTLET:")
7020 WRITE(IOUT;944)"P2 ",P2,"DP12",DP12,"PC2",PC2,
7030&"PW2",PW2,"V2 ",V2,"VC2",VC2,"VW2",VW2,
7040&"VO2",VO2,"VN2",VN2,"FC2",FC2,"FW2",FW2,"T2 ",T2,"DW2",DW2,"RH2",RH2
7050&,"P11",P11,"V11",V11,"T11",T11
7060C
7070 WRITE(IOUT;1010)
7080 1010FORMAT(" PROCESS AIR INLET:")
7090 WRITE(IOUT;944)"P7 ",P7,"PW7",PW7,"PN7",PN7,"VC7",VC7,"VW7",VW7,"VO7",VO7,
```


continued-

Table 12 - continued

```
7100&"VW7",VW7,"DW7",DW7,"RH7",RH7
7110C
7120 WRITE(IOUT;1015)
7130 1015FORMAT(" PROCESS AIR OUTLET:")
7140 WRITE(IOUT;944)"P8 ",P8,"PC8",PC8,"V10",V10,"DP78",DP78,
7150&"V8 ",V8,"VW8",VW8,"VC8",VC8,"VO8",VO8,"PW8",PW8,"T8 ",T8,
7160&"DW8",DW8,"RH8",RH8
7170C
7180 WRITE(IOUT;1019)
7190 1019FORMAT(" H2 INLET:")
7200 WRITE(IOUT;944)"P9 ",P9,"PW9",PW9,"DP93",DP93,"P3 ",P3
7210&,"PW3",PW3,"PH3",PH3,"V3 ",V3,"VH3",VH3,"VW3",VW3,"FH3",FH3,"V9MSL",V9MSL
7220C
7230 WRITE(IOUT;1013)
7240 1013FORMAT(" H2 OUTLET:")
7250 WRITE(IOUT;944)"P4 ",P4,"DP34",DP34,"PW4",PW4,"V4 ",V4,"VC4",VC4,
7260&"VH4",VH4,"VW4",VW4,"V4SL",V4SL,"VC4SL",VC4SL,"VH4SL",VH4SL,"F4 ",F4,
7270&"FC4",FC4,"FH4",FH4,"FW4",FW4,"DW4",DW4,"CHWRTO",CHWRTO,"HCVRTO",HCVRTO
7280C
7290 WRITE(IOUT;1023)
7300 1023FORMAT(" HEAT BALANCE, MODULES:")
7310 WRITE(IOUT;944)"HEATLD",HEATLD,"DHA",DHA,"DHH",DHH,"DHC",DHC
7320C
7330 WRITE(IOUT;1012)
7340 1012FORMAT(" COOLING AIR:")
7350 WRITE(IOUT;944)"P5 ",P5,"DP56",DP56,"P6 ",P6
7360&,"V5 ",V5,"T5 ",T5,"T6 ",T6,"HC ",HC,"ETA",ETA
7370&,"V5A",V5A,"T6A",T6A
7380&,"P12",P12,"V12",V12,"T12",T12,"DP1213",DP1213,"V5MIN",V5MIN
7390C
7400 WRITE(IOUT;1041)
7410 1041FORMAT(" ACTUAL VOLUMETRIC FLOW RATES:")
7420 WRITE(IOUT;944)"AV1",AV1,"AV2",AV2,"AV3",AV3,"AV4",AV4,"AV5",AV5,
7430&"AV6",AV6,"AV6A",AV6A,"AV7",AV7,"AV8",AV8,"AV9",AV9,
7440&"AV10EX",AV10EX,"AV11",AV11,"AV12",AV12,"AV13",AV13
7450C
7460 WRITE(IOUT;1016)
7470 1016FORMAT(" EQUIVALENT WEIGHT:")
7480 WRITE(IOUT;944)"PWRCLB",PWRCLB,"PWRCTB",PWRCTB,"PWRPC",PWRPC,
7490&"PWREC",PWREC,"PWRDAU",PWRDAU,"PWRTOT",PWRTOT,"HTTOT",HTTOT,
7500&"PWRWGT",PWRWGT,"HTWGT",HTWGT,"H2OWGT",H2OWGT,"OXWGT",OXWGT,
7510&"HRDWGT",HRDWGT,"EQWGT",EQWGT
7520 RETURN
7530 END
7540C
7550 FUNCTIONPHTO(TF)
7560 DATA A,B,C,D,EE,F,G/3.2437814,.00586826,1.1702379E-8,
7570& .0021878462,5.219603,273.16,2.3025851/
7580 TC=(TF-32.)/1.8
7590 X=374.11-TC
```


continued-

Table 12 - continued

```
7600 PHTO=EXP(G*(EE-(X/(TC+F))*(A+B*X+C*X**3)/(1.0+D*X)))
7610 RETURN
7620 END
7630C
7640 FUNCTION DEWT(P)
7650 EXTERNAL ROOT,PHTO
7660 XX=ALOG(P)
7670 TA=-2.4+20.25*XX+1.522*XX**2
7680 TB=TA+.1
7690 DEWT=ROOT(TA,TB,PHTO,P,.005,.005,5)
7700 RETURN
7710 END
7720C
7730 FUNCTION TICOR(PC,AF,CD,DEL)
7740 REAL S(5,7)
7750 DATA S/1.75187,-.511449,.0775073,-.00592584,.000179862,
7760& 1.42306,-.271935,.0210187,-.00034839,-1.8475E-5,
7770& 1.08190,-.110821,-.0081408,.00196359,-8.5832E-5,
7780&  .90258,-.105068,.0025161,.00028694,-1.3673E-5,
7790&  .71551,-.072213,.0024297,9.08E-6,-3.48E-7,
7800&  .61612,-.055237,.0003803,.00028605,-1.5623E-5,
7810&  .52087,-.035109,-.0014939,.00035115,-1.4808E-5/
7820 P=AMIN1(PC,10.)
7830 PA=P*(AF/.44)**((.84*P+1.)*EXP(-.84*P))
7840 J=CD/5.-1.
7850 IF(J.LT.1)J=1
7860 TI1=PA*(S(1,J)+PA*(S(2,J)+PA*(S(3,J)+PA*(S(4,J)+PA*S(5,J)))))
7870 IF(J.LT.7)GO TO 8
7880 TICOR=TI1
7890 GOTO9
7900 8 J=J+1
7910 TI2=PA*(S(1,J)+PA*(S(2,J)+PA*(S(3,J)+PA*(S(4,J)+PA*S(5,J)))))
7920 AII=J
7930 TERP=CD/5.-AII
7940 TICOR=TI2*TERP+TI1*(1.-TERP)
7950 9 TICOR=TICOR*(1.+.03536*(DEL-18.33))
7960 RETURN
7970 END
7980C
7990 FUNCTION ROOT(X1,X2,YFCN,W,XTOL,YTOL,K)
8000 COMMON IOUT
8010 EXTERNAL YFCN
8020 XA=X1
8030 XB=X2
8040 FA=YFCN(XA)-W
8050 FB=YFCN(XB)-W
8060 DO 91 IROOT=1,K
8070 ROOT=(FA*XB-FB*XA)/(FA-FB)
8080 FN=YFCN(ROOT)-W
8090 IF(ABS(FN).LT.YTOL .AND.
```


continued-

Table 12 - continued

```
&ABS(ROOT-XB).LT.XTOL)RETURN
 IF(IROOT.GE.K)WRITE(IOUT;200)X1,X2,W,XTOL,YTOL,IROOT,
& XA,XB,ROOT,FA,FB,FN
 200 FORMAT( " NONCONVERGENCE IN ROOT",5G11.4,I3/7G11.4)
 XA=XB
 XB=ROOT
 FA=FB
 FB=FN
 91 CONTINUE
 RETURN
 END
C
 SUBROUTINE TDRIFT
 REAL N,I
 COMMONIOUT,CPA,CPH,N,V3,T5,T3,T1,BK(12),
&BLANK(16),NBLANK,
&PCO,I,V1,HEATLD,DHC,DHA,DHH,DTREQ,DTAVA,E,
&HC,ETA,T2,V5A,T6A
 EXTERNAL ERT,ROOT,ERT1
 ENTHPR=V1*CPA*T1+V3*CPH*T3
 T2HIGH=(ENTHPR+.99*HEATLD)/(V1*CPA+V3*CPH)
 T2LOW=(ENTHPR+V5A*CPA*T5+HEATLD)/(V1*CPA+V3*CPH+V5A*CPA)
 T2=T2HIGH
 DUMMY=ERT(V5A/N)
 T2=ROOT(T2HIGH,T2LOW,ERT1,0.,.005,.005,20)
 RETURN
 END
C
 FUNCTION ERT1(T)
 REAL N,I
 COMMONIOUT,CPA,CPH,N,V3,T5,T3,T1,BK(12),
&BLANK(16),NBLANK,
&PCO,I,V1,HEATLD,DHC,DHA,DHH,DTREQ,DTAVA,E,
&HC,ETA,T2,V5A,T6A
 E=.729-.22*ALOG(I)+.008*I+.005*(T-78.)
 HEATLD=N*I*(1.25-E)*3.419
 DHA=V1*CPA*(T-T1)
 DHH=V3*CPH*(T-T3)
 DHC=HEATLD-DHA-DHH
 T6A=T5+DHC/(V5A*CPA)
 DTREQ=DHC*(.376+3.876/(HC*ETA))/N
 IF(T6A.LT.T)GOTO 1086
 ERT1=-DTREQ
 RETURN
 1086 DTAVA=(T6A-T5)/ALOG((T-T5)/(T-T6A))
 ERT1=DTAVA-DTREQ
 RETURN
 END
C
 FUNCTION ERT(V)
```


continued-

Table 12 - continued

```
REAL N,I
COMMONIOUT,CPA,CPH,N,V3,T5,T3,T1,BK(12),
&BLANK(16),NBLANK,
&PCO,I,V1,HEATLD,DHC,DHA,DHH,DTREQ,DTAVA,E,
&HC,ETA,T2,V5A,T6A
IF(V.LE.1.)HC=1.97*V**(.3333)
IF(V.GT.1. .AND. V.LT.2.9883)HC=1.21+V*(.34+.42*V)
IF(V.GE.2.9883 .AND. V.LE.4.)HC=2.*V
IF(V.GT.4.)HC=2.639016*V**(.8)
ETA=1.
IF(V.GT..32194 .AND. V.LT.24.72)ETA=1.0644-.1135*SQRT(V)
IF(V.GE.24.72)ETA=2.486/SQRT(V)
T6A=T5+DHC/(V*CPA*N)
DTREQ=DHC*(.376+3.876/(HC*ETA))/N
IF(T6A.LT.T2)GO TO 86
ERT=-DTREQ
RETURN
86 DTAVA=(T6A-T5)/ALOG((T2-T5)/(T2-T6A))
ERT=DTAVA-DTREQ
RETURN
END
C
SUBROUTINET(VARNAM,VAR,BOT,TOP,I)
COMMON IOUT
IF(VAR.GE.BOT.AND.VAR.LE.TOP)RETURN
WRITE(IOUT;10)VARNAM,VAR,BOT,TOP
I=I+1
RETURN
10FORMAT(1X,A6,"=",G10.4," RANGE: ",2G10.4)
END
C
SUBROUTINE BMODE
REAL N,I
COMMONIOUT,CPA,CPH,N,V3,T5,T3,T1,BK(12),
&BLANK(16),NBLANK,PCO,I,V1
I=BK(1)
IF(PCO.LE.BK(2))GOTO10
I=BK(4)
IF(PCO.GE.BK(3))GOTO10
I=BK(9)*PCO+BK(10)
10 V1=BK(5)
IF(PCO.LE.BK(6))RETURN
V1=BK(8)
IF(PCO.GE.BK(7))RETURN
V1=BK(11)*PCO+BK(12)
RETURN
END
```

TABLE 13 CHECKS AND MESSAGES

1.	CONDITION:	An input variable is out of the prediction range.
	MESSAGE:	VARIABLE = XX.XX RANGE: XX.XX XX.XX
2.	CONDITION:	Less than 1.3 times stoichiometric amount of H_2 is supplied.
	MESSAGE:	INSUFFICIENT HYDROGEN. XXX.XX SLPM IS REQUIRED.
3.	CONDITION:	Cathode air blowers cannot supply the requested flow rate. Program sets the flow equal to blower capacity.
	MESSAGE:	V1 HAS BEEN CHANGED TO 70 SCFM, BLOWER CAPACITY.
4.	CONDITION:	Not enough heat is generated in the modules to attain the setpoint module temperature.
	MESSAGE:	COOLING BLOWERS ARE OFF. MODULE TEMPERATURE FALLS X.XXF BELOW THE DESIRED XX.XXF TO XX.XXF.
5.	CONDITION:	Process streams and cooling air cannot remove enough heat to maintain the setpoint module temperature.
	MESSAGE:	COOLING BLOWERS ARE ON FULL. MODULE TEMPERATURE RISES X.XXF ABOVE THE DESIRED XX.XXF TO XX.XXF.
6.	CONDITION:	Normal heat balance is attained.
	MESSAGE:	DESIRED MODULE TEMPERATURE IS MAINTAINED WITH COOLING BLOWERS AT PARTIAL CAPACITY.
7.	CONDITION:	Process air flow does not exceed cathode air plus cooling air flow by at least 5%.
	MESSAGE:	INSUFFICIENT PROCESS AIR TO PREVENT BACKMIXING THROUGH PLENUM BYPASS.
8.	CONDITION:	Inlet process air moisture conditions are out of tolerance and will not support steady state cell operation.
	MESSAGE:	INLET PROCESS AIR DEW POINT DEPRESSION OUT OF RANGE. ELECTROLYTE MOISTURE BALANCE IS NOT MAINTAINED.
9.	CONDITION:	Outlet process air moisture conditions are out of tolerance and will not support steady state cell operation.
	MESSAGE:	OUTLET PROCESS AIR DEW POINT DEPRESSION OUT OF RANGE. ELECTROLYTE MOISTURE BALANCE IS NOT MAINTAINED.

continued-

C-3

Table 13 - continued

10. CONDITION: Average of inlet and outlet process air moisture condition is out of tolerance and will not support steady state cell operation.

    MESSAGE: AVERAGE PROCESS AIR DEW POINT DEPRESSION OUT OF RANGE. ELECTROLYTE MOISTURE BALANCE IS NOT MAINTAINED.

11. CONDITION: Convergence subroutine (ROOT) did not approach a solution within the specified number of iterations.

    MESSAGE: NONCONVERGENCE IN ROOT (PRINT ROOT PARAMETERS)

TABLE 14 NOMENCLATURE AND UNITS

Composite Variable Names

First Prefix	P	(Partial) Pressure, mm Hg
	V	Volume Flow Rate, Scfm 70F, 760 mm Hg
	AV	Volume Flow Rate, Cfm
	F	Mass Flow Rate, Lb/Hr
	DP	Pressure Drop
	DW	Dew Point, F
	T	Temperature, F
	RH	Relative Humidity, %
Second Prefix	C	Carbon Dioxide (CO_2)
	O	Oxygen (O_2)
	N	Nitrogen (N_2)
	H	Hydrogen (H_2)
	W	Water (H_2O)
	(None)	Total Stream
Stream Number	Ø	Cabin Atmosphere
	1	Cathode Air Modules Inlet
	2	Cathode Air Modules Outlet
	3	H_2 Modules Inlet
	4	H_2 Modules Outlet
	5	Cooling Air Inlet
	5A	Cooling Air Inlet, Active Cells
	6	Cooling Air Outlet
	6A	Cooling Air Outlet, Active Cells
	7	Process Air Inlet
	8	Process Air Outlet
	9	H_2 System Inlet
	1Ø	Plenum Bypass
	11	Cathode Blowers Outlet
	12	Cooling Blowers Outlet
	13	Cooling Dampers Outlet
Units Suffix	(None)	Units of First Prefix
	PSA	Psia
	PSG	Psig
	SL	Slpm

Additional Variable Names

A,B,C,D,EE,F,G	Constants in pH_2O Dew Point Equation
A11,J	Indices Determine S Constants
CD	Current Density
CHWRTO	CO_2/H_2 Weight Ratio, Lb CO_2/Lb H_2

continued-

Table 14 - continued

CJKN	Coefficient in Pressure Drop Equation J = Inlet Stream Subscript K = Outlet Stream Subscript N = Degree of Term
COR34,COR93	ΔP Correction Factors for Absolute Pressure
CPA	Volumetric Specific Heat, Air, Btu/Hr-Scfm-F
CPH	Volumetric Specific Heat, H_2, Btu/Hr-Scfm-F
CTRANS	CO_2 Transferred, Lb/Hr
CURDEN	Current Density, A/Ft^2
DELT1	Input Control Variable = T2-DP1, F
DELT1P	Preferred Value Control Variable = T2-DP1, F
DELIE	Actual Control Variable = T2-DP1, F
DHA	Enthalpy Gain of Inlet Process Air, Btu/Hr
DHC	Enthalpy Gain of Cooling Air, Btu/Hr
DHH	Enthalpy Gain of Inlet H_2, Btu/Hr
DDP1,DDP2	Dew Point Depression, Streams 1 and 2
DPTDAV	Process Air Dew Point Depression, Average, F
DROP,RISE	T2-(DWI + DELT1), Absolute Value of Module Temperature Offset
DTAVA	Log Mean Available Temperature Drop, F
DTREQ	Required Module - Cooling Air Temperature Drop, F
E	Cell Voltage, Volt
EMOD	Module (16 Cells) Voltage
EQWGT	Total System Equation Weight
ERT,ERT1	Difference Between DTREQ and DTAVA
ESTACK	Stack Voltage, Volt
ETA	Cooling Fin Efficiency, Dimensionless, 0-1
FA,FB,FN	Dependent Values Corresponding to XA,XB,XN
FNAME	Variable Equal to Output File Name
HC	Cooling Fin Heat Transfer Coefficient, Btu/Hr-Ft^2-F
HCON	H_2 Consumption, Lb/Hr
HCVRTO	H_2/CO_2 Volume Ratio, Scfm H_2/Scfm CO_2
HEATLD	Net Heat Produced, Btu/Hr
HTPEN	Heat Rejection Penalty, Lb/Btu/Hr
HTTOT	Total Heat Rejection
HTWGT	Heat Rejection Penalty Weight
H2OPEN	H_2O Vapor Rejection Penalty, Lb/Lb/Hr
H2OWGT	H_2O Rejection Penalty Weight
I	Current, Amp
INP	Input Device Code: 2=File, 50=Terminal
IOUT	Output Device Code: 1=File, 66=Terminal
MATHIN	Name of Input Data File
N	Number of Cells in Circuit
NERROR	Check Violation Indicator 0 - No Violation 1 - Violation

continued-

Table 14 - continued

NFLAG,FLAG	Program Option Integer = 0 or 1
OCON	O_2 Consumption, Lb/Hr
OXPEN	O_2 Consumption Penalty, Lb/Lb/Hr
OXWGT	O_2 Consumption Penalty Weight
P	Inlet pCO_2
PA	Inlet pCO_2 Corrected for Effect of Air Flow
POWER	Electrical Power Produced, Watt
PWPEN	Power Penalty, Lb/Watt
PWRCLB	Cooling Blower Power, Watt
PWRCTB	Cathode Blower Power, Watt
PWRDAU	Data Acquisition Unit Power, Watt
PWREC	Emergency Controller Power, Watt
PWRPC	Primary Controller Power, Watt
PWRTOT	Total Power, Watt
PWRWGT	Power Penalty Weight
QA,QB,QC	Coefficients of V5 in Quadratic Formula
S	Array containing Coefficients of PA in TI Correlation
TA,TB	Trial Values of Dew Point, F
TC,TF	Dew Point, C, F, respectively
TE	Current Efficiency, %
TERP	Current Density Interpolation Variable
TI	Transfer Index, Lb CO_2/Lb O_2
T2INP	Set Point Value of T2
T2P	Preferred Value of T2
T11	TI at one of the seven current densities just below the desired current density
T12	TI at one of the seven current densities just above the desired current density
U1	Conversion Factor, mm Hg/Psi
U2	Conversion Factor, Scf/Lb Mol
U3	Conversion Factor, Btu/Hr-Watt
U4	Conversion Factor, $1/Ft^3$
V,TR	Dummy and Interpolation Variables
VA,VB	Trial Values for V5
V5INP	Cooling Flow for Set Point Module Temperature
V5MIN	Cooling Flow with Blowers Off
V7M1	Plenum Inlet Flow less Cathode Air Flow
V9MSL	Minimum Flow of H_2 Required
WPROD	Water Production, Lb/Hr
X1,X2,XA,XB,XN	Trial Values of Independent Variable in Subroutine Root

Additional Variables, Main Program Only

AØ	Output Variable Array
AVG	Array Containing Average TAB Values
BK	Mode B Parameters
CGEN	Numeric Array, CO_2 Generation Rates, Lb/Hr

continued-

Table 14 - continued

HEAD	Alphabetic Constant Array, Containing Output Variable Names
HDG	Array Containing Selected Values of HEAD
IGEN	CO_2 Generation Step Subscript
INDEX	Subscripts of Selected Output Variables
IR	Out-of-Range Input Variable Counter
KBASE	Variable Indicating Range of BASE to be Executed
KERROR	Non-Steady State Indicator
KMODE	Mode Indicator, 0=Mode A, 1=Mode B
KPRINT,NPRINT, DPRINT,QPRINT	Output Indicators
MINCYC	Length of One Cycle, Min
NDAY	Day Counter
NDT,DT	Integration Increment, Min
NDAYS,DAYS	Maximum Number of Days to be Simulated
NDEX	Number of Selected Output Variables
NSTEPS	Number of Steps in CO_2 Generation Table
NT	Time, Min
QCO2GT	New CO_2 Generation Table Indicator
QFIN	File Input Indicator
QFOUT	File Output Indicator
QPRINT	Base Program Output Table Indicator
QSUBS	New Subscript Indicator
SAME	Dummy File Name to Prevent Closing Output File
SLOPE,SLOPEA, SLOPEB,SLOPEC	pCO_2 Rate of Change, mm Hg/Min
TAB	Array Containing Selected Values of AØ
TMAX	Ending Times for CO_2 Generation Rates, Min
U5	Conversion Factor, $\frac{\text{mm Hg/Min}}{\text{Lb/Hr}}$
XA,YA,XB,YB,XC,YC	Successive Values of Cabin pCO_2 Approximation and Error

TABLE 15 KEY TO SELECTIVE OUTPUT VARIABLES

AV1	130	FC1	86	RH8	129
AV10EX	140	FC2	94	SLOPEC	29
AV11	141	FC4	104	T11	114
AV12	142	FH3	89	T12	118
AV13	143	FH4	105	T2	13
AV2	131	FW1	87	T2P	80
AV3	132	FW2	95	T6	112
AV4	133	FW4	106	T6A	15
AV5	134	H2OWGT	148	T8	128
AV6	135	HC	11	TE	92
AV6A	136	HCON	53	TI	50
AV7	137	HCVRTO	109	V1	3
AV8	138	HEATLD	4	V10	32
AV9	139	HTTOT	145	V2	73
CHWRTO	108	HTWGT	147	V4	100
CO2GEN	30	I	2	V4SL	101
COR34	33	OCON	51	V5	20
COR93	37	OXWGT	149	V5A	14
CTRANS	52	P1	45	V5INP	31
CURDEN	47	P12	117	V5MIN	19
DDP1	76	P2	46	V7M1	18
DDP2	77	P3	35	V8	119
DELT1	16	P3PSA	36	V9MSL	17
DELT1E	48	P6	111	VC1	70
DELT1P	79	P7	42	VC2	72
DHA	6	P7PSA	43	VC4	55
DHC	5	P9	39	VC4SL	102
DHH	7	P9PSA	40	VC7	81
DP12	44	PC0	1	VC8	121
DP1213	115	PC1	49	VH3	58
DP34	34	PC2	93	VH4	59
DP56	110	PC8	122	VH4SL	103
DP78	41	PH3	88	VN1	68
DP93	38	PN1	67	VN7	84
DPTDAV	78	PN8	124	VN8	123
DTAVA	9	PO0	65	VO1	69
DTREQ	8	PO7	66	VO2	71
DUM1	21	POWER	91	VO7	83
DUM2	22	PW1	60	VO8	125
DUM3	23	PW2	74	VW1	61
DUM4	24	PW3	57	VW2	64
DUM5	25	PW4	98	VW3	62
DW2	75	PW8	126	VW4	99
DW4	97	PW9	56	VW7	82
DW8	127	PWRCLB	116	VW8	120
E	10	PWRCTB	113	VWPROD	63
EMOD	90	PWRTOT	144	WPROD	54
EQWGT	150	PWRWGT	146	YA	26
ETA	12	RH2	96	YB	27
F4	107	RH7	85	YC	28

continued-

Table 15 - continued

1	PCO	51	OCON	101	V4SL
2	I	52	CTRANS	102	VC4SL
3	V1	53	HCON	103	VH4SL
4	HEATLD	54	WPROD	104	FC4
5	DHC	55	VC4	105	FH4
6	DHA	56	PW9	106	FW4
7	DHH	57	PW3	107	F4
8	DTREQ	58	VH3	108	CHWRTO
9	DTAVA	59	VH4	109	HCVRTO
10	E	60	PW1	110	DP56
11	HC	61	VW1	111	P6
12	ETA	62	VW3	112	T6
13	T2	63	VWPROD	113	PWRCTB
14	V5A	64	VW2	114	T11
15	T6A	65	P00	115	DP1213
16	DELT1	66	P07	116	PWRCLB
17	V9MSL	67	PN1	117	P12
18	V7M1	68	VN1	118	T12
19	V5MIN	69	V01	119	V8
20	V5	70	VC1	120	VW8
21	DUM1	71	V02	121	VC8
22	DUM2	72	VC2	122	PC8
23	DUM3	73	V2	123	VN8
24	DUM4	74	PW2	124	PN8
25	DUM5	75	DW2	125	V08
26	YA	76	DDP1	126	PW8
27	YB	77	DDP2	127	DW8
28	YC	78	DPTDAV	128	T8
29	SLOPEC	79	DELT1P	129	RH8
30	CO2GEN	80	T2P	130	AV1
31	V5INP	81	VC7	131	AV2
32	V10	82	VW7	132	AV3
33	COR34	83	V07	133	AV4
34	DP34	84	VN7	134	AV5
35	P3	85	RH7	135	AV6
36	P3PSA	86	FC1	136	AV6A
37	COR93	87	FW1	137	AV7
38	DP93	88	PH3	138	AV8
39	P9	89	FH3	139	AV9
40	P9PSA	90	EMOD	140	AV10EX
41	DP78	91	POWER	141	AV11
42	P7	92	TE	142	AV12
43	P7PSA	93	PC2	143	AV13
44	DP12	94	FC2	144	PWRTOT
45	P1	95	FW2	145	HTTOT
46	P2	96	RH2	146	PWRWGT
47	CURDEN	97	DW4	147	HTWGT
48	DELT1E	98	PW4	148	H2OWGT
49	PC1	99	VW4	149	OXWGT
50	TI	100	V4	150	EQWGT

APPENDIX D CS-6 CABIN pCO_2 SIMULATION PROGRAM SAMPLE OUTPUTS

TABLE 1 OUTPUT EXAMPLES

```
 ****  MODE B   ZERO TO STEADY STATE   PCO2 LIMITS 1 & 2 MMHG   ****
**********INPUT DATA**********
CABIN ATMOSPHERE:
    POPSA       14.70  !  PCO    0.1000E-02  !  POOPSA      3.100  !  TO         70.00
    VOLUME      8000.  !
PROCESS AIR OUTLET/INLET:
    P8PSA       14.75  !  T7          55.00  !  V7          265.0  !  DW7        50.00
H2 OUTLET/INLET:
    P4PSA       20.00  !  T9          72.00  !  V9SL        10.00  !  DW9        69.00
MODULES:
    N           96.00  !  I           2.586  !  DELT1       22.00  !  V1         20.00
PENALTY WEIGHT FACTORS:
    PWPEN      0.5910  !  HTPEN      0.1280  !  H2OPEN      134.0  !  OXPEN      1536.
CONTROL:
    KMODE       1.000  !  NFLAG       1.000  !  IMIN        2.586  !  PCIMIN     1.000
    PCIMAX      2.000  !  IMAX        6.600  !  VMIN        20.00  !  PCVMIN     1.000
    PCVMAX      2.000  !  VMAX        60.00  !  DAYS        10.00  !  DT         15.00
    DPRINT      60.00  !

***********RESULTS***********
PREFERRED VALUE OF DELT1 IS 23.58 UNDER THESE CONDITIONS
SO THAT 73.58 = T2 = DW1 + DELT1 = 50.00 + 23.58.
MODULES:
    TI    0.8810E-03  !  TE    0.3204E-01  !  E            0.5038  !  EMOD       8.061
    CTRANS0.1439E-03  !  OCON        0.1634  !  HCON  0.2058E-01  !  WPROD      0.1839
    CURDEN      10.60  !  HEATLD      633.3  !  POWER       125.1  !
CATHODE AIR INLET:
    P1          763.6  !  PC1    0.1004E-02  !  PW1         9.212  !  FC1   0.1797E-03
    FW1        0.6742  !  VC1    0.2632E-04  !  VW1        0.2413  !  VO1        4.218
    VN1         15.54  !  T1          55.00  !  DW1         50.00  !  RH1        83.20
CATHODE AIR OUTLET:
    P2          761.9  !  DP12        1.737  !  PC2   0.1992E-03  !  PW2        11.73
    V2          20.03  !  VC2    0.5239E-05  !  VW2        0.3083  !  VO2        4.185
    VN2         15.54  !  FC2    0.3577E-04  !  FW2        0.8616  !  T2         70.64
    DW2         56.58  !  RH2         61.11  !  P11         762.6  !  V11        20.03
    T11         104.0  !
PROCESS AIR INLET:
    P7          763.6  !  PW7         9.212  !  PN7         593.4  !  VC7   0.3487E-03
    VW7         3.197  !  VO7         55.88  !  VN7         205.9  !  DW7        50.00
    RH7         83.20  !
PROCESS AIR OUTLET:
    P8          762.6  !  PC8    0.9426E-03  !  V10         215.7  !  DP78       1.047
    V8          265.0  !  VW8         3.264  !  VC8   0.3276E-03  !  VO8        55.85
    PW8         9.391  !  T8          61.24  !  DW8         50.52  !  RH8        67.80
```

continued-

Table 1 continued

H2 INLET:

P9	1157. !	PW9	18.15 !	DP93	120.3 !	P3	1037.
PW3	16.26 !	PH3	1021. !	V3	0.3531 !	VH3	0.3476
VW3	0.5537E-02 !	FH3	0.1087 !	V9MSL	2.423 !		

H2 OUTLET:

P4	1034. !	DP34	2.890 !	PW4	12.02 !	V4	0.2851
VC4	0.2108E-04 !	VH4	0.2818 !	VW4	0.3315E-02 !	V4SL	8.074
VC4SL	0.5969E-03 !	VH4SL	7.980 !	F4	0.9755E-01 !	FC4	0.1439E-03
FH4	0.8814E-01 !	FW4	0.9264E-02 !	DW4	57.28 !	CHWRT0	0.1633E-02
HCVRT0	0.1337E+05 !						

HEAT BALANCE, MODULES:

HEATLD	633.3 !	DHA	336.6 !	DHH	-.5140 !	DHC	297.2

COOLING AIR:

P5	763.6 !	DP56	0.3072 !	P6	763.3 !	V5	29.31
T5	55.00 !	T6	64.42 !	HC	1.327 !	ETA	1.000
V5A	29.31 !	T6A	64.42 !	P12	763.3 !	V12	29.31
T12	64.42 !	DP1213	0.7396 !	V5MIN	29.31 !		

ACTUAL VOLUMETRIC FLOW RATES:

AV1	19.34 !	AV2	20.01 !	AV3	0.2598 !	AV4	0.2098
AV5	28.34 !	AV6	28.87 !	AV6A	28.87 !	AV7	256.3
AV8	259.8 !	AV9	0.2328 !	AV10EX	208.9 !	AV11	21.25
AV12	28.87 !	AV13	28.90 !				

EQUIVALENT WEIGHT:

PWRCLB	0.0000 !	PWRCTB	209.8 !	PWRPC	136.0 !	PWREC	45.00
PWRDAU	100.0 !	PWRTOT	490.8 !	HTTOT	2739. !	PWRWGT	290.1
HTWGT	350.6 !	H2OWGT	24.65 !	OXWGT	250.9 !	HRDWGT	817.9
EQWGT	1734. !						

***********DAY 1 ***********

TIME	PCO	I	V1	TI	OCON	CTRANS	EQWGT
0: 0	0.1000E-02	2.586	20.00	0.8810E-03	0.1634	0.1439E-03	1734.
1: 0	0.2788	2.586	20.00	0.2408	0.1634	0.3933E-01	1734.
2: 0	0.5259	2.586	20.00	0.4545	0.1634	0.7425E-01	1734.
3: 0	0.7451	2.586	20.00	0.6490	0.1634	0.1060	1734.
4: 0	0.9391	2.586	20.00	0.8246	0.1634	0.1347	1734.

****

continued -

Table 1 continued

5: 0							
	1.098	2.979	23.92	1.079	0.1882	0.2031	1808.
6: 0							
	1.196	3.373	27.84	1.236	0.2131	0.2633	1903.
7: 0							
	1.265	3.652	30.62	1.337	0.2307	0.3084	1980.
8: 0							
	1.444	4.367	37.75	1.513	0.2759	0.4174	2197.
9: 0							
	1.659	5.232	46.36	1.650	0.3305	0.5452	2458.
10: 0							
	1.794	5.775	51.78	1.684	0.3648	0.6145	2605.
11: 0							
	1.886	6.141	55.43	1.687	0.3879	0.6546	2700.
12: 0							
	1.922	6.286	56.87	1.688	0.3971	0.6703	2736.
13: 0							
	1.823	5.890	52.92	1.687	0.3721	0.6275	2635.
14: 0							
	1.782	5.726	51.29	1.683	0.3617	0.6087	2592.
15: 0							
	1.822	5.887	52.89	1.687	0.3719	0.6272	2634.
16: 0							
	1.905	6.219	56.20	1.688	0.3928	0.6631	2719.
17: 0							
	1.963	6.451	58.51	1.686	0.4075	0.6872	2777.
18: 0							
	1.948	6.392	57.93	1.687	0.4038	0.6813	2763.
19: 0							
	1.842	5.964	53.66	1.687	0.3768	0.6357	2654.
20: 0							
	1.795	5.777	51.79	1.684	0.3649	0.6146	2605.
21: 0							
	1.817	5.867	52.69	1.686	0.3706	0.6250	2629.
22: 0							
	1.818	5.869	52.71	1.686	0.3707	0.6252	2630.
23: 0							
	1.740	5.556	49.60	1.675	0.3510	0.5880	2547.
24: 0							
	1.590	4.955	43.60	1.616	0.3130	0.5057	2380.
AVERAGES:							
	1.501	4.910	43.16	1.400	0.3102	0.4724	2361.

continued -

Table 1 - continued

************DAY 2 ***********

TIME	PCO	I	V1	TI	OCON	CTRANS	EOWGT
0: 0	1.590	4.955	43.60	1.616	0.3130	0.5057	2380.
1: 0	1.490	4.552	39.59	1.549	0.2875	0.4453	2259.
2: 0	1.429	4.309	37.17	1.501	0.2722	0.4086	2178.
3: 0	1.393	4.163	35.71	1.469	0.2630	0.3863	2132.
4: 0	1.371	4.075	34.84	1.449	0.2574	0.3730	2104.
5: 0	1.358	4.023	34.32	1.436	0.2541	0.3650	2088.
6: 0	1.350	3.991	34.00	1.429	0.2521	0.3602	2079.
7: 0	1.357	4.019	34.28	1.435	0.2539	0.3644	2087.
8: 0	1.499	4.587	39.94	1.555	0.2898	0.4507	2271.
9: 0	1.693	5.367	47.71	1.662	0.3390	0.5635	2495.
10: 0	1.817	5.864	52.66	1.686	0.3704	0.6246	2628.
11: 0	1.901	6.203	56.04	1.688	0.3918	0.6614	2715.
12: 0	1.933	6.329	57.30	1.688	0.3998	0.6748	2747.
13: 0	1.831	5.920	53.22	1.687	0.3740	0.6309	2643.
14: 0	1.787	5.746	51.49	1.683	0.3630	0.6111	2597.
15: 0	1.826	5.901	53.03	1.687	0.3728	0.6288	2638.
16: 0	1.907	6.229	56.30	1.688	0.3935	0.6642	2722.
17: 0	1.965	6.458	58.58	1.686	0.4079	0.6879	2779.
18: 0	1.949	6.397	57.98	1.687	0.4041	0.6818	2764.
19: 0	1.842	5.967	53.70	1.687	0.3770	0.6361	2655.
20: 0	1.795	5.779	51.82	1.684	0.3651	0.6149	2606.

continued -

Table 1 continued

```
21: 0
     1.818     5.868     52.71     1.686     0.3707     0.6251     2629.
22: 0
     1.818     5.870     52.72     1.686     0.3708     0.6253     2630.
23: 0
     1.740     5.557     49.61     1.675     0.3510     0.5881     2547.
24: 0
     1.590     4.955     43.61     1.616     0.3130     0.5058     2380.
AVERAGES:
     1.686     5.339     47.43     1.613     0.3372     0.5491     2474.

**********INPUT DATA***********
CABIN ATMOSPHERE:
    POPSA      14.70  !  PCO      10.00  !  POOPSA    3.100  !  TO       70.00
    VOLUME     8000.  !
PROCESS AIR OUTLET/INLET:
    P8PSA      14.75  !  T7       55.00  !  V7        265.0  !  DW7      50.00
H2 OUTLET/INLET:
    P4PSA      20.00  !  T9       72.00  !  V9SL      10.00  !  DW9      69.00
MODULES:
    N          96.00  !  I        6.600  !  DELT1     22.00  !  V1       60.00
PENALTY WEIGHT FACTORS:
    PWPEN     0.5910  !  HTPEN   0.1280  !  H2OPEN    134.0  !  OXPEN    1536.
CONTROL:
    KMODE      1.000  !  NFLAG    1.000  !  IMIN      2.586  !  PCIMIN   2.500
    PCIMAX     2.800  !  IMAX     6.600  !  VMIN      20.00  !  PCVMIN   2.500
    PCVMAX     2.800  !  VMAX     60.00  !  DAYS      10.00  !  DT       15.00
    DPRINT     60.00  !


***********RESULTS************
```

continued -

Table 1 continued

************DAY 1 ***********

TIME	PCO	I	V1
0: 0	10.00	6.600	60.00
1: 0	9.318	6.600	60.00
2: 0	8.641	6.600	60.00
3: 0	7.967	6.600	60.00
4: 0	7.300	6.600	60.00
5: 0	6.642	6.600	60.00
6: 0	5.999	6.600	60.00
7: 0	5.388	6.600	60.00
8: 0	4.968	6.600	60.00
9: 0	4.712	6.600	60.00
10: 0	4.471	6.600	60.00
11: 0	4.246	6.600	60.00
12: 0	4.008	6.600	60.00
13: 0	3.645	6.600	60.00
14: 0	3.344	6.600	60.00
15: 0	3.149	6.600	60.00
16: 0	3.037	6.600	60.00
17: 0	2.936	6.600	60.00
18: 0	2.786	6.415	58.16
19: 0	2.623	4.232	36.41

continued -

Table 1 - continued

20: 0			
	2.599	3.912	33.21
21: 0			
	2.628	4.292	37.00
22: 0			
	2.622	4.219	36.27
23: 0			
	2.573	3.556	29.67
24: 0			
	2.513	2.764	21.78
AVERAGES:			
	4.620	5.953	53.55

************DAY 2 ***********

TIME			
	PCO	I	V1

****

0: 0			
	2.513	2.764	21.78
1: 0			
	2.505	2.660	20.73
2: 0			
	2.505	2.649	20.63
3: 0			
	2.505	2.648	20.62
4: 0			
	2.505	2.648	20.62
5: 0			
	2.505	2.648	20.62
6: 0			
	2.505	2.648	20.62
7: 0			
	2.514	2.776	21.89
8: 0			
	2.599	3.909	33.18
9: 0			
	2.670	4.861	42.67
10: 0			
	2.688	5.104	45.09
11: 0			
	2.694	5.188	45.93
12: 0			
	2.672	4.882	42.88
13: 0			
	2.593	3.825	32.35

continued -

Table 1 - continued

14: 0			
	2.593	3.829	32.38
15: 0			
	2.635	4.388	37.95
16: 0			
	2.678	4.972	43.77
17: 0			
	2.691	5.141	45.46
18: 0			
	2.657	4.682	40.89
19: 0			
	2.589	3.783	31.93
20: 0			
	2.592	3.820	32.30
21: 0			
	2.626	4.273	36.81
22: 0			
	2.622	4.215	36.23
23: 0			
	2.572	3.556	29.66
24: 0			
	2.513	2.764	21.78
AVERAGES:			
	2.593	3.827	32.37