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ANALYTICAL SIMULATION OF THE LANGLEY RESEARCH CENTER INTEGRATED LIFE-SUPPORT SYSTEM

VOLUME I

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by Advance Biotechnology and Power Department
Douglas Aircraft Company
Missile and Space Systems Division
Huntington Beach, California
for
Langley Research Center
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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FOREWORD

Analytical Simulation of the Langley Research Center Integrated Life Support System was prepared by the Advance Biotechnology and Power Department of the Missile and Space Systems Division, Douglas Aircraft Company, Huntington Beach, California. The simulation is reported in two volumes: vol. I is a summary and discussion of the work performed; vol. II is an operations manual to be used as a guide in the preparation of computer program input data and interpretation of output data. The simulation was prepared for, and delivered to, the NASA Langley Research Center (LRC) under Contract NAS1-6448. The contractual effort was under the direction of O. K. Houck, Applied Materials and Physics Division, LRC. R. S. Barker was the principal investigator for Douglas. H. M. Stephens and R. L. Vaughan were responsible for the preparation of the simulation. Vol. I was prepared by B. N. Taylor and R. S. Barker and vol. II was prepared by H. M. Stephens and R. L. Vaughan.

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ANALYTICAL SIMULATION OF THE LANGLEY RESEARCH CENTER INTEGRATED LIFE SUPPORT SYSTEM

SUMMARY

An analytical simulation has been prepared for the NASA-Langley Research Center (LRC) Integrated Life Support System (ILSS). The LRC ILSS test chamber consists of a vertical cylinder with an upper floor functioning as a living module and a lower floor functioning as a laboratory. All of the environmental control and life support (EC/LS) subsystems necessary to sustain a 4-man crew for a 1 year mission with a 90-day resupply period are contained within these compartments. These subsystems are designed to control atmospheric temperature, humidity, CO_2 level and trace contaminates level; provide waste management; and to supply O_2, food, and water.

The analytical simulation was obtained through preparation of a special version of an existing computer program: the G-189 Generalized Environmental Control and Life Support Systems Fortran Program. The simulation was accomplished by preparing two separate analytical models for the computer program. The first is a simulation of the complete ILSS. The second model is a detailed simulation of the O_2 regeneration system.

Sample problems for these models were prepared and their solutions obtained. The results demonstrate the utility of the analytical models. Sample problems for the complete ILSS model include analyses of the following: design and off-design performance, improved performance with a modified subsystem component, failure mode performance, and performance of a potential servo system for control of compartment temperature. A sample problem for the O_2-regeneration system model was formulated to determine component characteristics required to achieve performance goals.

A comparison was made of computed analytical data and experimental data available at the time the models were prepared. Generally, good agreement occurred in the values obtained for cabin temperature, absolute humidity, and CO_2 partial pressure. Detailed information concerning the analytical models and the noted sample problems is presented in vol. II (ref. 1). That volume and the computer program comprise an analytical tool for use at LRC in future development efforts concerning the ILSS.

Specific recommendations are made for improvements in the simulation. These include addition of new program subroutines, extension of program capability to take advantage of increased computer storage capacity, and incorporations into the simulation of improved test data as they become available.

NASA LRC personnel were trained in the utilization of the simulation between 11 September and 22 September 1967. The satisfactory operation of the computer programs and computations for the simulation were demonstrated at that time.

INTRODUCTION

The Langley Research Center integrated life-support system (LRC ILSS) was constructed to aid in the study and simulation of future advanced manned spacecraft missions with extended mission durations. The life-support system includes subsystems which sustain life on board spacecraft by providing the crew with (1) a habitable environment, (2) life-support furnishings, and (3) required expendables. Specific functions of the life-support system include the control of atmospheric temperature, humidity, CO_2 level and trace-contaminants level; provisions for waste management; and the supply of O_2, food and water. The LRC ILSS is designed for a 1-year mission with a resupply period of 90 days.

The specific types of subsystems and included components selected for a life-support system depend on the spacecraft configuration and mission objectives. For a manned space mission of extended duration, such as that involved here, it becomes potentially feasible to reduce the combined effective launch weight of the life-support system and the required expendables through the use of regeneration systems. The term "effective weight" is used to signify actual weight plus the weight equivalent for the electrical power required. An example regeneration system is postulated as follows: rather than provide sufficient water for drinking, food preparation, and washing purposes for the resupply period, water could be recovered from humidity condensate, urine, and wash water. The weight and power requirements for the collecting and processing equipment included in the recovery system can be traded off against the weight of the stored expendable water. These tradeoff studies generally yield crossover points at time periods less than 1 month. Short duration missions and resupply periods of perhaps 60 days or less often include the use of fuel cells as the source of vehicle electrical power; and these units are often considered as an acceptable source of potable water. This scheme obviates the consideration of water recovery.

Vehicle studies for longer missions and resupply periods which utilize solar cells, or power systems other than fuel cells, clearly necessitate the consideration of water-recovery techniques. Besides the weight and power requirements, several intangible factors are involved in these analyses and influence the selections of subsystem methods and individual components. These include such items as volume requirements, development costs, development uncertainties, problem areas, reliability, maintainability, and compatibility with zero-g operation.

O_2 regeneration from CO_2 can also be employed to obtain reduced effective weights. This evaluation requires trading off stored O_2 (in the pure form, in chemical compounds, or in water) against the weight and power requirements for the regeneration system collection and processing equipment. Typical tradeoff data are presented on fig. 3.2-14, ref. 2. A crossover point of approximately 50 days is indicated. Again the intangible factors such as development costs and maintainability play strong roles in the selections of subsystem methods and individual components.

As implied above, the 90-day resupply period specified for the ILSS indicated the desirability of including both water-recovery and O_2-regeneration features in the system. The selection procedures used in determining which particular techniques and components were to be included in the system are outlined in section 3.0 of ref. 2. The resulting ILSS is briefly described as follows.

Control of cabin temperature and humidity are accomplished by circulating cabin atmosphere through heat exchangers which cool the gas and condense out a portion of the water generated by the crew and by other miscellaneous sources. Approximately 2 lb/day of carbon dioxide is generated by each crewman. This is removed by circulating some of the cabin atmosphere through a CO_2 collector or concentration unit. This system consists of pairs of silica gel and zeolite adsorption beds. The silica gel bed lowers the humidity level of the atmosphere entering the zeolite beds to that required to maintain a high CO_2 removal efficiency in the zeolite beds. This prevents water vapor being preferentially adsorbed by zeolite material, thus reducing the efficiency of CO_2 adsorption. The system operates in a cyclic fashion with one set of silica gel and zeolite beds adsorbing while the other set is desorbing.

The ILSS has the option of using either Sabatier or Bosch reactor systems for CO_2 reduction in the O_2-regeneration system. For a 90-day resupply period with no hydrogen storage, the Bosch technique has a weight advantage over the Sabatier technique. No H_2 storage implies that all of the H_2 for the reaction must come from that generated by electrolyzing water collected from humidity condensate, washing facilities, and urine. Mass balances indicate that not enough H_2 would be available to react stoichiometrically with the CO_2 generated by the crew; thus all of the CO_2 could not be converted and additional oxygen would have to be supplied. A working methane decomposition reactor which would form H_2 from methane generated in the Sabatier reaction was unavailable at the time of selection of components for the ILSS (p. 3-53, ref. 2). The Bosch system was selected as the primary system with the Sabatier as a backup system.

Several techniques were considered for water electrolysis. Some of these techniques receive water vapor directly from cabin atmosphere; others require water from such sources as the CO_2-reduction apparatus. The O_2 generated is returned to the cabin atmosphere. The H_2 generated is recycled to the CO_2-reduction unit. One of the principal problems in zero-g electrolysis is separation of the gaseous products from the liquid electrolyte. A cell design using double ion-exchange membranes with H_2SO_4 electrolyte was selected for use in the system. Membranes appear to offer the most positive gas-liquid barrier; and a gas pressure is maintained to further minimize the possibility of H_2SO_4 carryover into H_2 or O_2 streams. The cell cooling design provides liquid coolant tubes within the individual cells. Since electrolyte circulation is not required, potential leakage and corrosion problems are reduced.

The selected water management subsystem consists of two air-evaporation units; one for recovery from urine, and the other for water recovery from humidity condensate and used wash water. Stored water, in conjunction with a standby multifiltration unit for condensate recovery, is available for emergency use. Waste water collected from the waste-management urinal, personal-hygiene-sponge washing unit, cabin-dehumidifier circuit, and the Bosch reactor are transported, chemically treated, processed, tested, stored, and redistributed for use.

The air-evaporation unit employs a phase change as the primary mode of water purification. Vaporization takes place from wicks continuously saturated with waste liquids in a recirculating process gas stream. The process gas stream is heated in a heat exchanger, with the process heating circuit (described below) supplying the heat. Process gas temperatures are sufficiently high to vaporize the water content of the treated urine but are maintained low enough to prevent generation of ammonia and other objectionable gases. A centrifugal water separator downstream of a condensing heat exchanger removes water from the gas stream and pumps it to holding tanks for purity tests.

In the ILSS process heat used in CO_2 concentration, O_2 regeneration, water recovery, and heating of food water and wash water is provided by a process heating circuit supplied by a commercial heating and pumping unit. Thus, the life-support system corresponds to a spacecraft which would have a source for waste heat such as could be obtained with a radioisotope Brayton cycle power supply. For a spacecraft utilizing solar cells for power, this process heat would probably be supplied by electrical heaters or by a separate radioisotope heater. Process cooling for a spacecraft life-support system with cabin-temperature and humidity control, water management, CO_2 collection, and O_2 recovery would be supplied by a coolant which would be circulated to a space radiator for rejection of the waste heat to space. In the ILSS, this feature is provided by a commercial cooling and pumping unit.

There are several reasons for requiring an analytical simulation of the ILSS. The basic reason is that the simulation can provide a valuable tool for use in improving the efficiency of achieving the ILSS program objectives. These objectives are listed in section 1 of ref. 2. In particular, those objectives concerned with accomplishing satisfactory system performance in terms of specified equipment capabilities and in terms of realistic spacecraft requirements can be more efficiently achieved with the aid of the simulation. Some of the individual operating conditions which can be evaluated with the simulation are as follows:

(1) Anticipated test conditions can be simulated and the resulting system performance determined.

(2) Variations in potential design-point operating conditions with different cabin temperatures and atmospheric constituent compositions can be predicted.

(3) Variations in thermal conditions imposed on the system as a result of cabin heat load, number of crewmen, and activity level of the crewmen can be accounted for.

(4) The adequacy and limitations of individual system components can be assessed.

(5) Consequences of potential failures and the effectiveness of backup devices can be evaluated.

(6) The effects of integrating new components into the system can be determined.

(7) The relative abilities of various automatic control systems to control the subsystems satisfactorily can be evaluated.

Simulation of some of these conditions can be satisfactorily achieved on a steady-state basis; others require a transient simulation. For example, conditions 5 and 7 above require a transient simulation. For satisfactory evaluations of many operating conditions, it is necessary to simultaneously include analytical representations for all of the subsystems in the simulation. Determining the complete thermal balance for the system is a case in point. In other cases, it is appropriate to prepare simulations for individual subsystems and to apply known subsystem interface conditions in the evaluations. For example, detailed performance of regeneration systems can be evaluated following this procedure.

The G-189 Generalized Environmental Control and Life Support Systems Fortran Program which was used in preparing this simulation can be used to simulate arbitrary configurations of EC/LS systems.

The simulated components which are included in various subsystems can be computationally arranged, with no restrictions imposed on series and parallel interconnecting gaseous and liquid flow paths. Steady-state and transient heat transfer and mass transfer, chemical processes, energy, and mass balances are computed for individual components. Pressure drop-flow balances can be determined, when required.

The mathematical relationships involved in these computations are largely nonlinear algebraic equations, and for a sophisticated life-support system such as the ILSS, a large total number of these equations is involved. These result from the large number of system components.

An iterative steady-state solution is obtained with a computational flow path specified by the program user. Computational convergence is obtained through satisfaction of specified convergence tests. The forward difference technique used in solving transient cases is applied in the manner familiar to persons who have been involved in transient thermal analyzer programs and procedures. More specifically, thermal driving conditions prevailing at the end of a computing time increment, Δt_i, are used to obtain new component outlet temperatures at the end of the next computing time increment, Δt_{i+1}.

The prepared G-189 program simulation of the ILSS consisted of steady-state and transient analytical models of the overall system and a separate detailed steady-state model of the O_2-regeneration system. A complete description of the details concerning these two analytical models, including the required input data, is given in vol. II of this report (ref. 1).

The objectives of this simulation were to prepare the above models in such a way that various system operating conditions, such as conditions of the seven types enumerated above, can be evaluated using the overall system model and so that detail performance characteristics of the O_2-regeneration system can be obtained from its model. The documentation of the simulation is intended to be complete enough to enable personnel at NASA-LRC to effectively use the simulation as an analytical tool in further ILSS development and operational efforts.

The discussion that follows includes a brief description of the simulation of the ILSS, an outline of the principal features of the G-189 computer program, and a summary of sample problems demonstrating steady-state and transient analyses of the overall ILSS and a steady-state analysis of the O_2-regeneration system. A comparison is then made of computed analytical data and experimental results obtained from the ILSS.

ANALYTICAL SIMULATION MODELS

The ILSS is installed in a test chamber that is a vertical cylinder 220 in. in diameter and 215 in. long. Two floors are provided: the lower floor is the laboratory module or compartment, and the upper floor is the living module or compartment. The life-support system equipment, with the exception of the food- and waste-management subsystems, are located on the lower floor. The system is a closed cycle to the extent that oxygen is recovered from CO_2 and water is recovered from liquid wastes.

Functionally, the ILSS is described as consisting of the following subsystems:

(1) Thermal control.

(2) Atmospheric control.

(3) Water management.

(4) Waste management.

(5) Personal hygiene.

(6) Food management.

(7) Instrumentation and controls.

For purposes of the analytical simulation, however, the overall ILSS model is considered to be comprised of the following functional groups of components:

(1) Thermal-control circuit.

(2) Process-cooling circuit.

(3) Process-heating circuit.

(4) Water-management system.

(5) O_2-regeneration system.

These groups of components include the functional subsystems noted above; however, the regrouping of components as designated here was found to aid in clarifying the simulation documentation, especially in vol. II (ref. 1).

Following are brief descriptions of the individual groups of listed components.

Thermal-Control Circuit

This circuit provides circulation of the living and laboratory compartments atmospheric gas through the "closed" loops of components which cool the gas; remove water vapor, CO_2, trace contaminants (primarily CO, hydrocarbons, and odors); and provide makeup gases. (See fig. 1.)

Process-Cooling Circuit

Circulation of cooling fluid through components which are required to reject heat is provided by this circuit. (See fig. 2.) These components provide compartment thermal control and assist in CO_2 concentration, O_2 regeneration, and water recovery. In lieu of a space-radiator system, cooling and pumping of the fluid is provided by a commercial type cooling and pumping unit. Heat additions at electronic cold plates are simulated in this circuit through an electric liquid-coolant heater.

Process-Heating Circuit

This circuit, shown in fig. 3, provides circulation of heating fluid to components which are required to add heat to gas streams or that must operate at temperatures higher than the compartment atmospheric temperature. These components assist in CO_2 concentration, O_2 regeneration, water recovery, and heating of food water and wash water. Heating of this fluid in a real space vehicle would be provided by waste heat from the vehicle power system, by a separate heat source, or by electrical power from the vehicle power system. In the ILSS, this heating is supplied by a commercial type heating and pumping unit.

Water-Management System

This system contains typical "air-evaporation" water-recovery components. Wash water, humidity condensate, and urine water are subjected to air evaporation processes in the distillation units. Urine is processed in one unit, whereas a mixture of wash water and humidity condensate is processed in a second unit. Fig. 4 shows the evaporators, condensers, and water-separator units; fans; and heaters which comprise each of these units. In addition, the requirements for heating and cooling fluids are indicated.

O_2 Regeneration System

This system uses (1) a Bosch reactor or, optionally, a Sabatier reactor to reduce CO_2 to water and (2) a water-electrolysis unit to regenerate O_2. No attempt was made to provide a detailed analysis of this system in the analysis of the overall ILSS. This procedure was appropriate because of the mild interaction between this system and the other life-support systems. It was decided that the O_2-regeneration system should be separately analyzed in

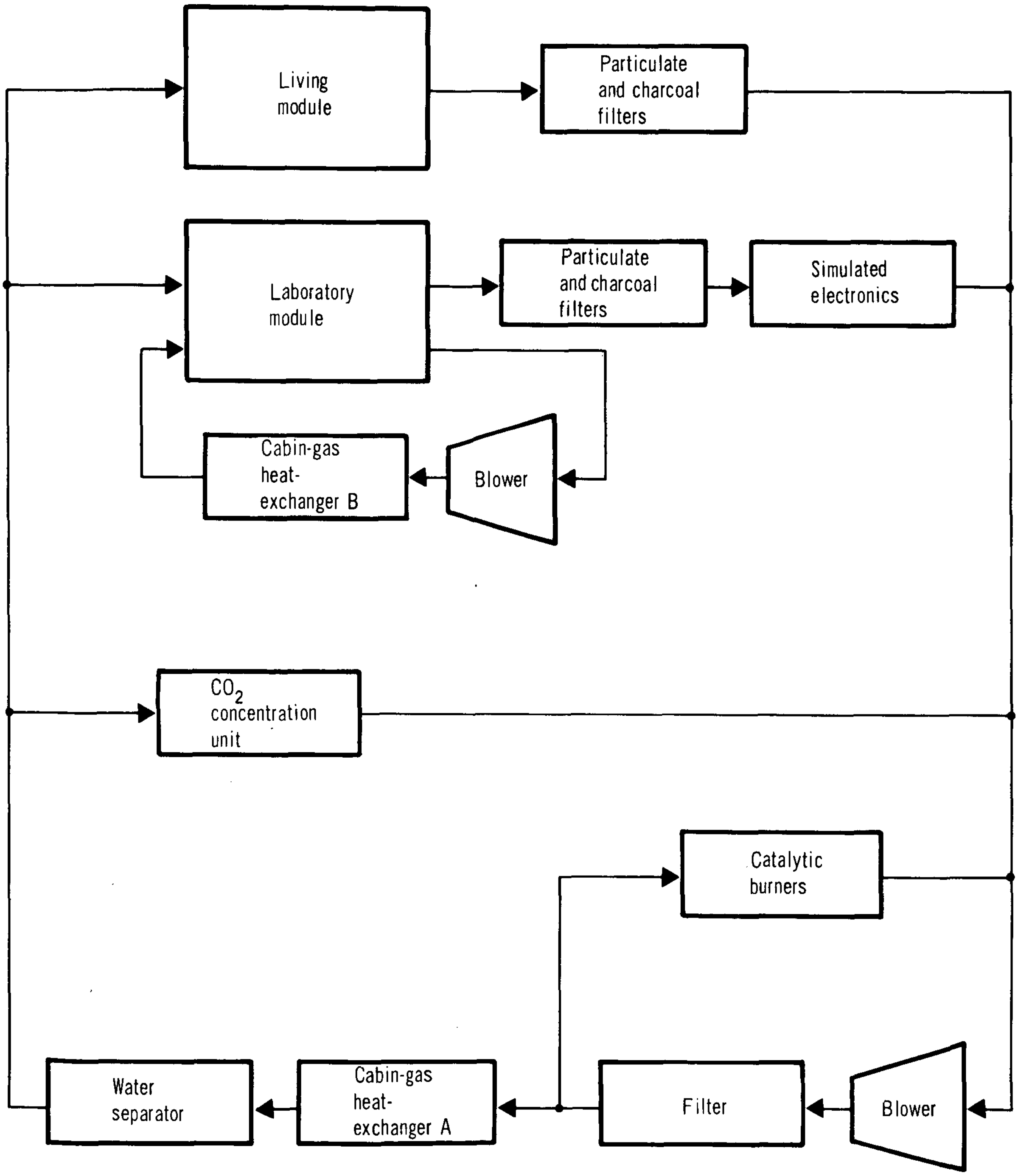


Figure 1. Thermal-Control Circuit

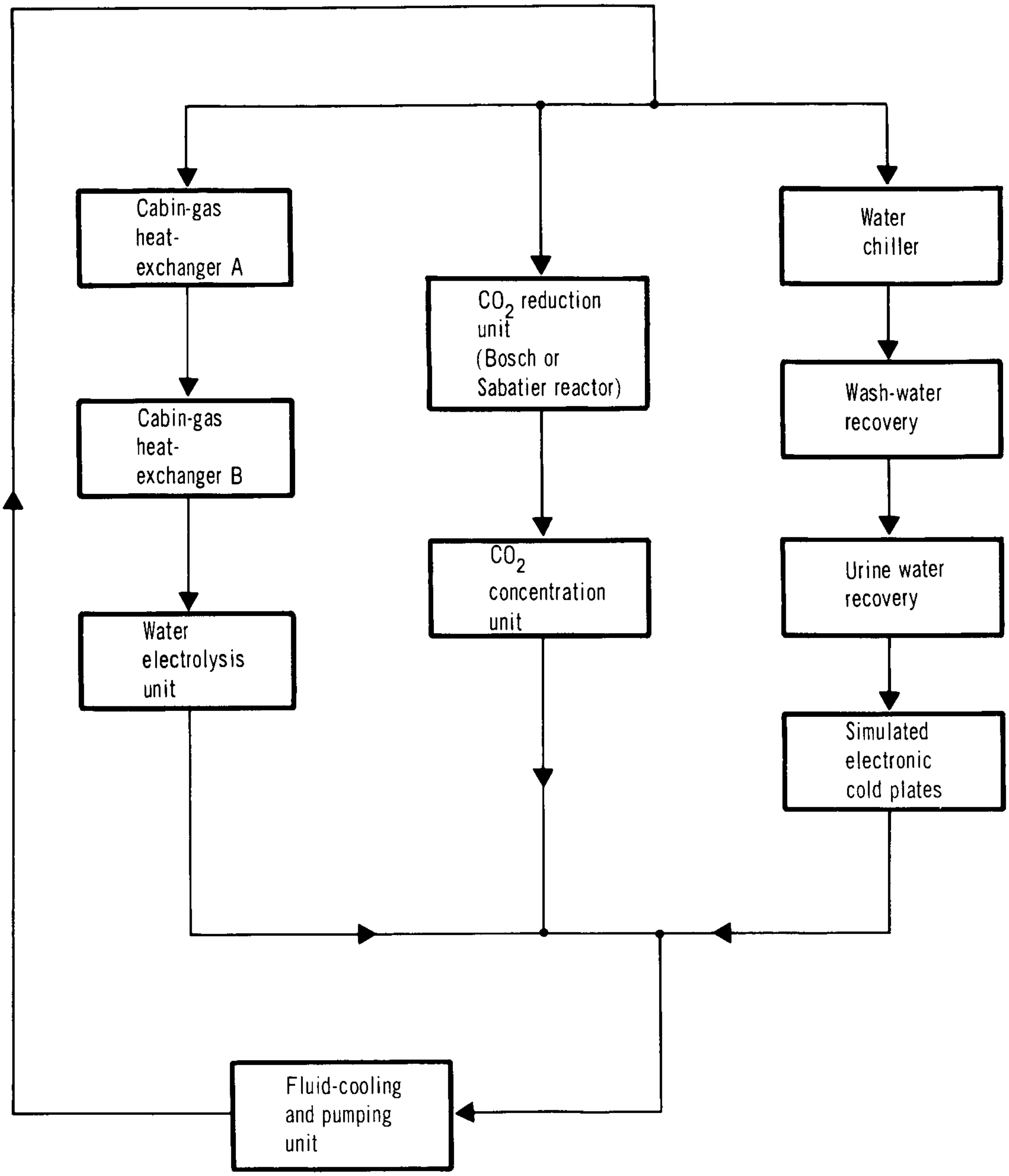


Figure 2. Process-Cooling Circuit

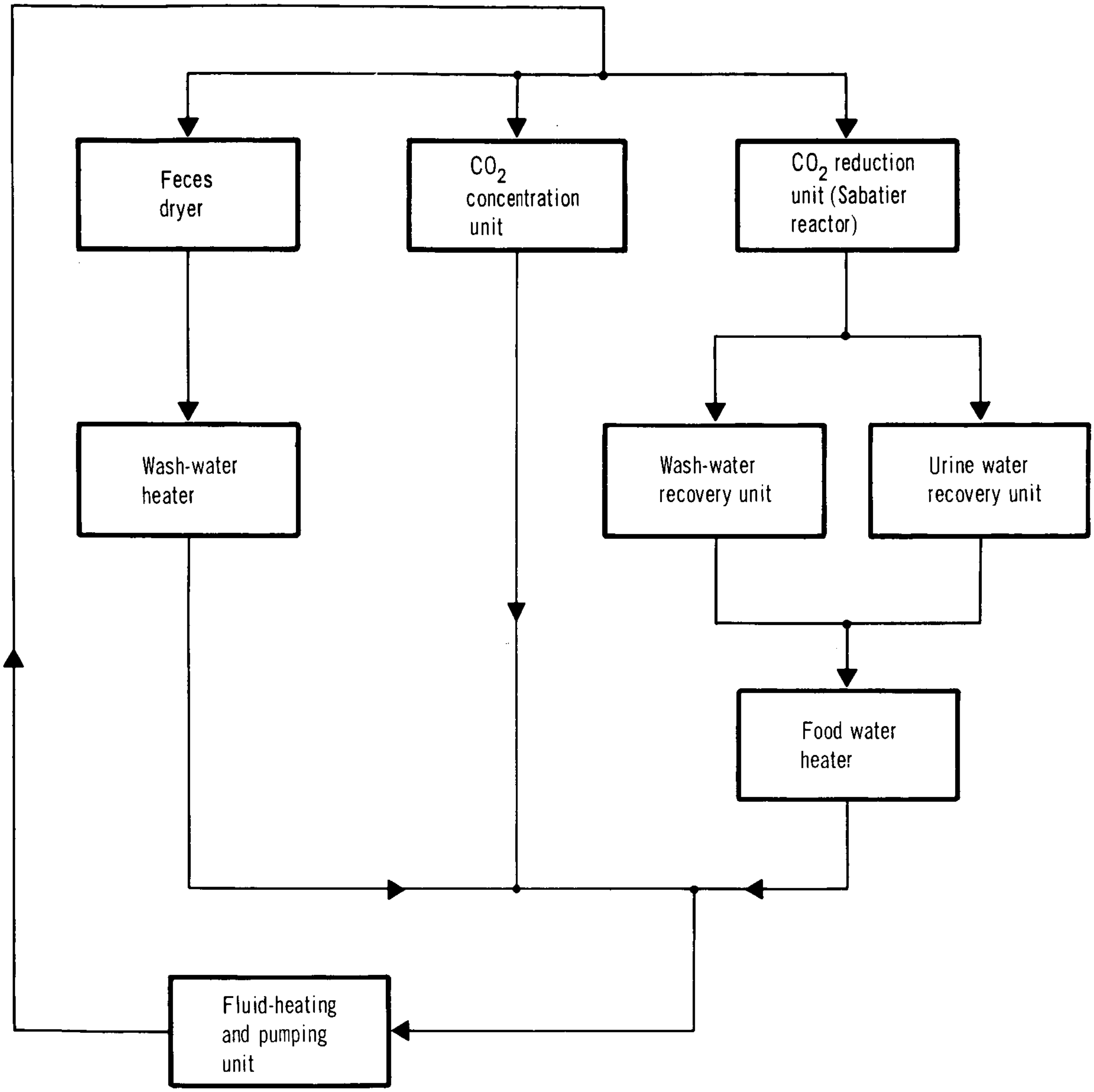


Figure 3. Process-Heating Circuit

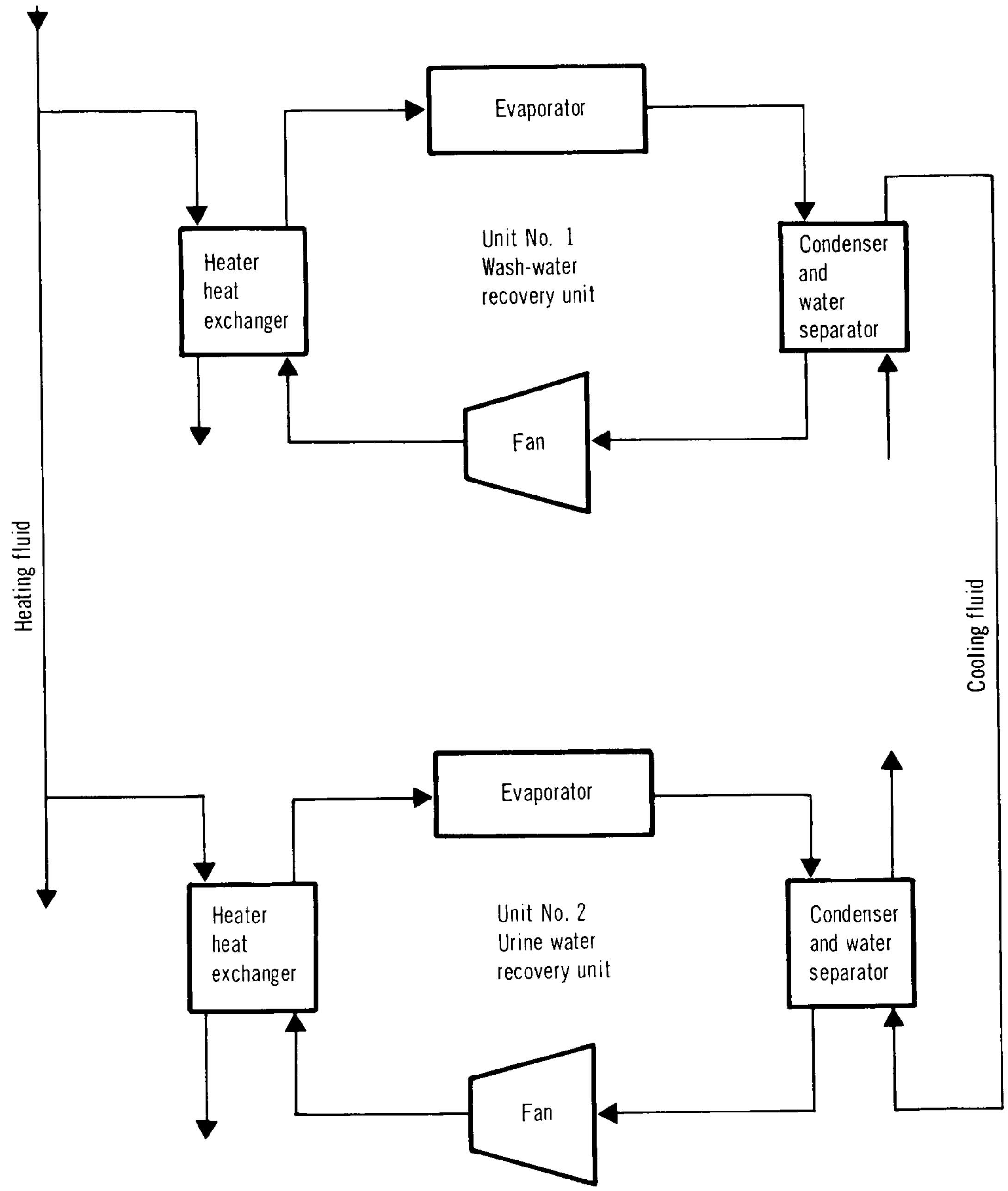


Figure 4. Air Evaporation Water Recovery Units

detail. A separate computer simulation model was prepared for this purpose. The computer analytical models were formulated such that the results from the separate, detailed simulation could be used as input data for the simplified O_2-regeneration system model incorporated in the overall ILSS simulation.

The schematic for the detailed simulation model of the O_2-regeneration system is shown in fig. 5.

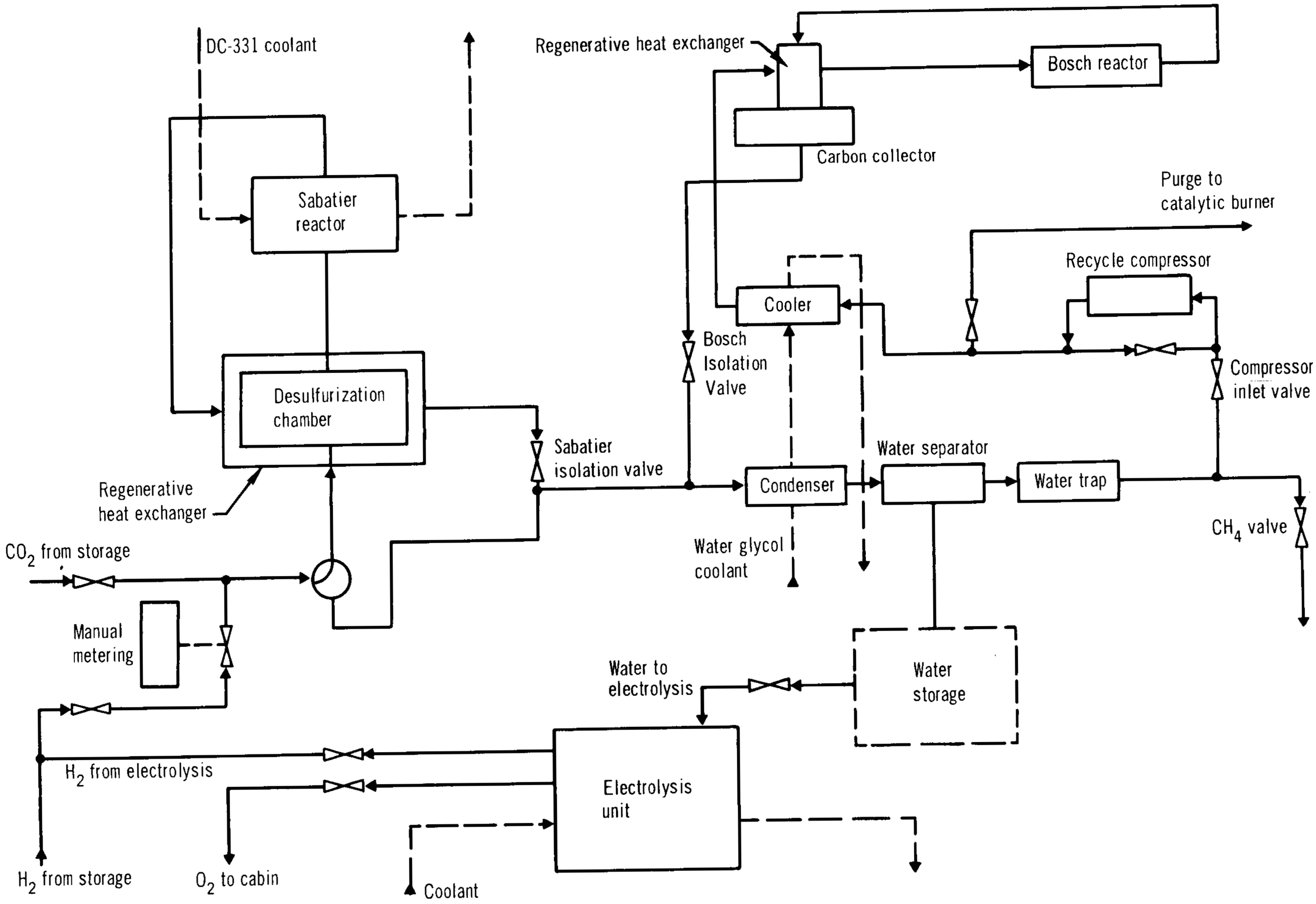
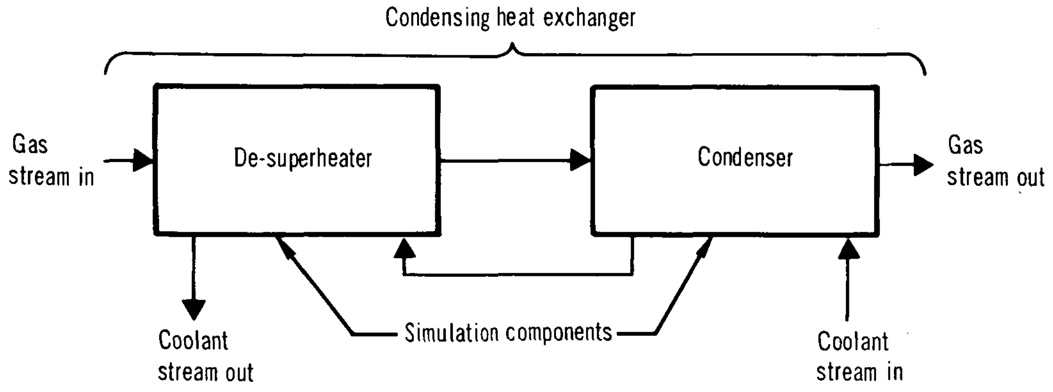


Figure 5. O_2 Regeneration System

G-189 GENERALIZED EC/LS SYSTEMS COMPUTER PROGRAM

The G-189 computer program is an analytical tool for analysis of steady-state and transient performance of EC/LS systems. The program is written in the Fortran IV computer language. The program was prepared by the Missile and Space Systems Division (MSSD) of the Douglas Aircraft Company under contract for NASA's Manned Spacecraft Center (MSC). Various versions of the program have been prepared that are compatible with the IBM 7094, Univac 1108, and CDC 6600 or 6400 computer systems.

An EC/LS system is simulated with the G-189 by describing the system in terms of individual "components" connected by flow streams. Components are simulated through individual subroutines in the program. Each component corresponds to all or part of a complete physical part, such as a heat exchanger, electronic cold plate, etc., or to a component process. For example, consider the case of a condensing heat exchanger. This single physical part could be represented by two G-189 program components. The first component could account for the de-superheating process through the heat exchanger subroutine and the second component could account for the condensing process through the condenser subroutine. This portion of a schematic flow diagram would appear as follows:



Two flows can be specified for each component. A gas-to-liquid heat exchanger is an example of a type of component requiring two flow streams. The component subroutines perform heat transfer, mass transfer, chemical reactions, and mass and energy balances for either steady-state or transient operating conditions. Pressure drop-flow balances can also be determined when required. Examples of energy balances are (1) the summation of cabin-heat rejection rates from individual sources within the cabin balanced with the total heat load imposed on the cabin heat exchanger and (2) the summation of individual system heat loads balanced with the heat rejected by the space radiator. Examples of mass balances include balancing water vapor and CO_2 generation rates from crewmen, leakage rates, and removal rates by system equipment.

Individual subroutines are available to simulate cabins or compartments, heat exchangers and condensers, electronic cold plates, space radiators, catalytic burners, and adsorption beds. Subroutines also are available to simulate the ducts and pipes connecting individual components and to perform the mixing and splitting of gaseous and liquid flow streams. Special subroutines exist for performing pressure drop analyses and for simulating miscellaneous types of enthalpy and mass altering processes.

Calculations are performed for the individual components according to a computational sequence specified by the program user. This sequence generally, though not necessarily, follows paths corresponding to the paths of the flow streams in the system.

The equations which are used to compute the above component processes can be thought of as comprising a set of linear and nonlinear algebraic equations. The processes involved here, such as heat transfer and mass transfer, are often represented with nonlinear algebraic (or differential) equations. In some cases, linear relationships suffice. The set of equations used for solving a steady-state case differs from that used for solving a transient case. In particular, thermal capacitance terms are included in the transient-case equations but not in the steady state equations. These terms lead to time lags in temperature responses of various components in a given system. Several basic methods are available for use in solving the steady-state and transient sets of equations. As a result of the occurrence of nonlinear terms in the equations, the available methods for use in solving steady-state cases all involve iterative techniques of one sort or another.

The basic technique used in the G-189 program is to solve the steady-state equations individually as opposed to solving the equations simultaneously. In each equation, latest available values for independent variables are used to obtain revised values for dependent variables. Computational flow paths through the set of steady-state equations are specified by the program user. Some computational convergence tests are built into the program; others are specified by the program user. During the course of a steady-state computer run, these tests are applied to successively computed values for a particular quantity. Failure of these tests indicate lack of convergence, and the program logic then calls for additional computational passes, often supplemented with revised estimates of system variables. These revised estimates are determined by the degree of nonconvergence and are intended to aid in achieving convergence. Similar tests and procedures for revising system variables are used in sizing system components so that design-point conditions are achieved. For example, the cabin heat exchanger can be sized so that the design-point cabin temperature is obtained in conjunction with the specified cabin-heat load.

The transient equations are also solved individually, but a basically different and noniterative technique is used. The technique used here is referred to as a forward difference or an explicit method. The equations used are referred to as finite difference equations and they are approximations to the solutions of the differential equations which describe the transient behavior of individual system components. Analytical solutions to these differential equations cannot generally be obtained because of included nonlinear terms and arbitrary system driving conditions. Briefly, these transient equations are solved by imposing thermal driving conditions prevailing at the end of computing increment, Δt_i, to obtain new component outlet temperatures at the end of the next computing time increment, Δt_{i+1}.

The G-189 program is essentially comprised of two sections: (1) a main program or master control block and (2) a set of system-component subroutines. A simplified schematic of the program is shown in fig. 6. This shows the master control block and the program subroutines. Various operations performed in the master control block are noted, and the subroutine names indicate their applicability to various system components. Complete simulation of an existing system component often requires the use of more than one subroutine and several features of the master control block. The necessary complexity of a particular component's simulation is determined from such factors as (1) the basic complexity of the analytical representation for the component, (2) extent of available performance data, and (3) sensitivity of system performance to that of the component. The functions of the master control block and the individual subroutines are described briefly in the discussion that follows.

Master Control Block

The master control block collects input data, controls the flow of program logic through the simulation of a physical system, and controls the printout of data.

Some of the important operations involved in controlling the flow of program logic are as follows:

(1) The interpolation and polynomial sections are used to compute values for system variables based on the functional relationships between these variables and other physical quantities in a given system. These computations supplement those performed by the subroutines.

(2) The tests for the master control test section tests specified system variables with design point values and for computational convergence.

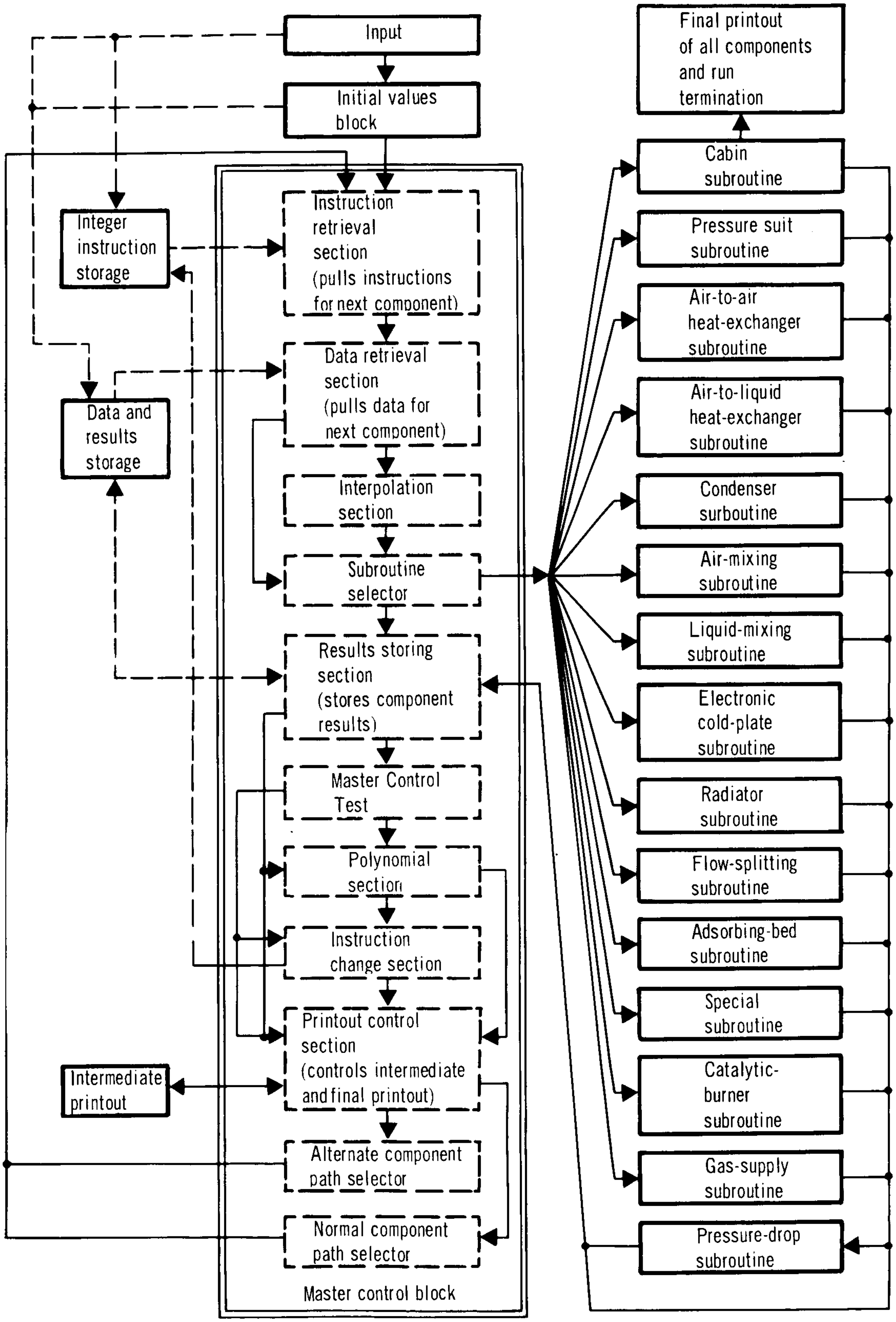


Figure 6. G-189 Program

Failures of these numerical tests are used to generate changes in system variables intended to achieve either design point values or computational convergence. The steady-state performance of the system controllers is thus simulated by the first of these actions.

Input data for the master control block provides the proper interface conditions for system components: flow-stream paths and thermal connections are specified. For example, the master control block is used to provide component interface conditions in accordance with the LRC ILSS characteristics.

Subroutines

System components and component processes are simulated by appropriate subroutines. A brief description of the subroutines follows.

Cabin and space suits.—The cabin subroutine computes cabin temperatures and flow constituent mixtures. Entering gasflows are generally from the cabin heat-exchanger system, space suits, and the atmosphere purification system. Heat inputs are from incoming gas streams, through the walls, and from internal heat sources.

Computed values for relative humidity, temperature, CO_2 concentration, and trace contaminant concentration are tested against design values. Deviations from these design values may be directed to generate changes in operating conditions in various system components, thus simulating the action of controllers.

The space-suits subroutine simulates the effects of the crew's sensible and latent heat loads, CO_2 generation rate, and O_2 consumption rate.

These subroutines can perform steady-state and transient computations.

Heat exchanger and condenser.— These subroutines calculate (1) the temperature of exit streams, (2) the total heat transferred, (3) the amount of water condensed or evaporated, and (4) the resulting water vapor content and entrained liquid water content in exit streams. Steady-state and transient computations can be performed.

Air-mixing and liquid-mixing.— These subroutines are used to mix any two streams of the appropriate fluid. The temperature and the flow rate of the mixture are computed. In the case of gas flows, the amounts of water condensed or evaporated are computed.

Electronic cold plate and space radiation.— Steady-state and transient performance of these units can be determined.

Adsorption bed.— This subroutine is used for CO_2, water, and trace contaminant removal beds. Adsorbent performance and included heat-exchanger performance are determined. Average steady-state or transient adsorption computations can be performed.

Special.—This subroutine is basically used to vary flow rates and provide heat additions (or subtractions). This subroutine is useful in simulating pumps, fans, chemical conversion processes, and other miscellaneous process involving enthalpy or mass altering.

Servo.—This subroutine is used during transient analyses to simulate the dynamic performance of closed-loop automatic controls. The common types of controller compensation may be simulated by this subroutine.

Flow-splitting, catalytic burner, gas supply, and pressure drop.—These subroutines perform simulations and computations as their titles suggest. The catalytic burner subroutine calculates trace-contaminant removal, and the gas supply subroutine calculates the amounts of O_2 and diluent gas required to make up for the use rate and leakage rate.

SAMPLE PROBLEMS

The G-189 analytical models for the overall ILSS and the oxygen regeneration system can be used to simulate a variety of different environmental conditions or equipment configurations. Several sample problems were prepared to demonstrate the utility of the analytical models. Two steady-stage and two transient sample problems were prepared for the overall ILSS simulation. Principal quantities computed for these problems include cabin temperature, cabin humidity, and water-recovery rate. A brief description of these sample problems and the computed results are summarized in table I. A more detailed discussion of these sample problems follows the table.

TABLE I.—OVERALL ILSS ANALYTICAL MODEL SAMPLE PROBLEMS AND COMPUTED RESULTS

Steady state problems			
	Conditions	Computed results	
		Living module	Laboratory module
(1a)	Design performance--maximum design heat loads.	73.5°F dB (dry bulb) 0.0105 SPHW*	73.9°F dB 0.0107 SPHW
(1a)	Off-design performance--flow rate of coolant to heat exchanger A reduced from 910 lb/hr to 91 lb/hr.	102.9°F dB 0.0194 SPHW	77.5°F dB 0.0110 SPHW
		Existing unit	Improved unit
(2)	New and revised components--replace fan in wash water recovery unit with fan which provides more flow; and increase operating time.	Design water recovery rate: 3.56 lb/hr Computed water recovery rate: 1.57 lb/hr	 2.37 lb/hr 2.31 lb/hr

*Specific humidity, lb water/lb gas.

Sample problems were also prepared to demonstrate the detailed simulation of the O_2-regeneration system. A considerable number of component characteristic data are necessary to provide an adequate simulation with this model. Available test data generally were inadequate for direct calculation of these individual component characteristics. For this reason, a different approach was used in preparing the sample problems for this system. The

TABLE I.-OVERALL ILSS ANALYTICAL MODEL SAMPLE PROBLEMS AND COMPUTED RESULTS - (Continued)

Transient problems		
	Computed results	
Conditions	Living module	Laboratory module
(1) Failure mode--step change in coolant flow rate to heat exchanger A from 910 lb/hr to 91 lb/hr. Results noted are for a relatively short time period and do not reflect the final steady-state conditions which are the same as for the off-design condition studied in the first steady-state sample problem.	(See fig. 8 for time histories.) Temperature increases from 73.5° to 83.5°F in approximately 30 min. Specific humidity increases from 0.0105 to 0.0136 in same time period.	Slight reduction in temperature from 73.9° to 73.3°F. Slight decrease in specific humidity from 0.0107 to 0.0096.
	Basic controller	Compensated controller
(2) Automatic control system--laboratory module temperature controller modulating coolant flow to heat exchanger B. Initially cabin temperature is 10°F below the setpoint temperature. Two controllers are investigated: Basic controller has only a temperature sensor; compensated controller has additional sensor for measuring rate of change of laboratory temperature.	Cabin temperature reaches setpoint in about 9 min, but there is a 1°F overshoot and a continued oscillation of about 3°F around the setpoint.	A compensated controller is found which brings the cabin temperature to the setpoint in about 10-1/2 min, with almost no overshoot. Subsequent oscillations are less than 1°F.

problems were formulated to force the simulation to match the experimental values obtained for the water-generation rates for the Bosch and Sabatier reactors and O_2-generation rates from the electrolysis units. That is, estimated component characteristics were varied by the program in order to match the experimental values for the water- and O_2-regeneration rates. The computed values for these characteristics represent the principal output data for these sample problems. The results obtained for these sample problems follow the discussion presented for the steady-state and transient sample problems for the overall ILSS simulation.

Steady-State Sample Problems

Two sample problems illustrating the use of the steady-state simulation of the ILSS are presented. The first sample problem involves design and off-design system operation. The second problem investigates the effect of new and revised components.

Design/off-design. — This first steady-state sample problem shows how the analytical simulation can be used to study design and off-design performance of the ILSS. The design case uses the maximum design heat-load conditions and normal fluid-flow distributions. The off-design case is basically the same, but with a significant change in the flow distribution of the process cooling circuit; the flow rate of coolant in cabin heat-exchanger A is reduced from its design value of 910 lb/hr to only 91 lb/hr.

Table II compares the results of the design and off-design cases. Only a small part of the computed output is shown in this table. These selected results consist of the system parameters most strongly influenced by the reduction of coolant flow to cabin heat-exchanger A.

The results for this problem are about as one would expect; the reduction in coolant flow through cabin heat-exchanger A results in the much higher gas outlet temperature of 84.4°F, compared with 32.7°F for the design case, and a much lower heat-transfer rate (8,469 versus 17,640 Btu/hr).

Consequently, no water is condensed in this heat exchanger and the humidity control function is transferred from the A-system to the B-system for the off-design case. A humidity condensation rate of 2.29 lb/hr is computed for cabin heat-exchanger B. This value of condensation (and water removal) is greater than the net water-generation rate of 1.5 lb/hr, which indicates that the iterative solution has not yet converged to the highly accurate values of specific humidity and temperature in the laboratory module necessary to obtain the correct condensing rate. This inaccuracy could most easily be corrected by increasing the number of iterative passes in the computer solution. It is anticipated that, except for a more realistic condensing rate, the more accurate solution would not differ significantly from the results listed in table II.

New and revised components. — This sample problem illustrates the use of the ILSS analytical model to predict changes in system performance resulting from the addition of new components and changes in operating characteristics of existing components. This example concerns a theoretical improvement in the performance of the wash-water-recovery unit. (See fig. 4)

Computed results from the first sample problem show that Water-Recovery Unit No. 1 is unable to process, on a daily basis, as much as is collected in the forms of humidity condensate, used wash water, and Bosch reactor water. This deficiency is emphasized by the following conditions:

(1) The relatively high latent heat loads that exist for the maximum design condition studied result in a time-average collection rate of humidity condensate of 1.51 lb/hr. When nominal collection rates of Bosch reactor water (0.32 lb/hr) and used wash water

Table II.—DESIGN/OFF-DESIGN SAMPLE PROBLEM COMPUTED RESULTS

Quantity	Design value	Off-design value
Cabin heat-exchanger A		
Coolant flow rate, lb/hr	910.0	91.0
Coolant inlet temperature, °F	32.0	32.0
Coolant outlet temperature, °F	51.8	127.4
Gas inlet temperature, °F	101.1	127.0
Gas outlet temperature, °F	32.72	84.4
Heat transfer rate, Btu/hr	17,640	8,469
Humidity-control water separator		
Water separation rate, lb/hr	1.51	0
Flow rate of entrained water past separator, lb/hr	2.26	0
Cabin heat-exchanger B		
Coolant flow rate, lb/hr	910.0	910.0
Coolant inlet temperature, °F	51.8	41.5
Coolant outlet temperature, °F	68.1	67.8
Gas inlet temperature, °F	79.5	83.2
Gas outlet temperature, °F	55.0	48.2
Heat-transfer rate, Btu/hr	14,560	23,360
Condensing rate, lb/hr	0	2.29
Living-module conditions		
Dry bulb temperature, °F	73.5	102.9
Specific humidity	0.0105	0.0194
Relative humidity, %	41.4	29.6
Laboratory module conditions		
Dry bulb temperature, °F	73.9	77.5
Specific humidity	0.0107	0.0110
Relative humidity	41.8	38.1
Dew-point temperature, °F	49.1	49.9

(0.44 lb/hr) are added, the required time-average processing rate in Water-Recovery Unit No. 1 becomes 2.37 lb/hr.

(2) The normal water-recovery unit operating time of 16 hr/day increases the required processing rate to 3.56 lb/hr.

(3) The simulated wash-water-recovery unit attained a processing rate of only 1.57 lb/hr, far short of the 3.56 lb/hr required.

To make the actual processing rate equal to, or greater than, the required rate, the following two changes are proposed:

(1) Increase the unit operating time to 24 hr/day on the assumption that downtime for equipment maintenance can be postponed until the maximum-design latent heat-load condition subsides.

(2) Increase the atmospheric flow rate of gas in the wash-water-recovery unit to about 160 lb/hr. Allowing for reduced effectivenesses of the wick, condenser, and heater, this larger gas flow rate should increase the water-processing rate by about 50%.

Fig. 7 shows the performance curve of the presently used fan (Joy, Unit No. X-702-83B, Model No. AVR42-35D794) and the old system operating point at the 33-ft^3/min flow rate. The system pressure-drop curve, constructed through this old operating point shows that for a new flow rate of 53 ft^3/min or 160 lb/hr, a fan with a static pressure rise of 14.2 in. H_2O is required. A search of blower manufacturers' catalogs uncovered one fan whose performance curve (fig. 7) passes through the system pressure drop curve at the desired flow rate. This fan is a Joy "mixed flow" fan (Unit No. 500702-5040, Model No. AVRM 55-41D1490) with about the same overall dimensions as the presently used fan.

Selected results for this sample problem are shown in table III. The performance figures for the existing wash-water-recovery unit were computed using the same computer program input data that were used for design point operation in the first sample problem.

The computed processing rate of the improved unit is 2.31 lb/hr, compared with a required rate of 2.37 lb/hr. The discrepancy between these values (2-1/2%) is less than the estimated inaccuracy of the input data for wick effectiveness, water separator efficiency, and thermal conductances of the heat exchangers. Therefore it is concluded that the performance of the improved wash-water-recovery unit is satisfactory.

Transient Sample Problems

Two sample problems are used to demonstrate the transient simulation of the ILSS. The first problem is a hypothetical failure-mode condition. The second problem investigates the automatic control of the laboratory-module atmospheric-gas temperature.

Failure mode conditions. — This sample problem consists of a transient solution for the same conditions studied in the first steady-state sample problem.

The steady-state problem considers an extremely low flow rate of coolant through cabin heat-exchanger A as an off-design condition; and in table II computed steady-state results for this condition are compared with results for the design-condition coolant flow rate.

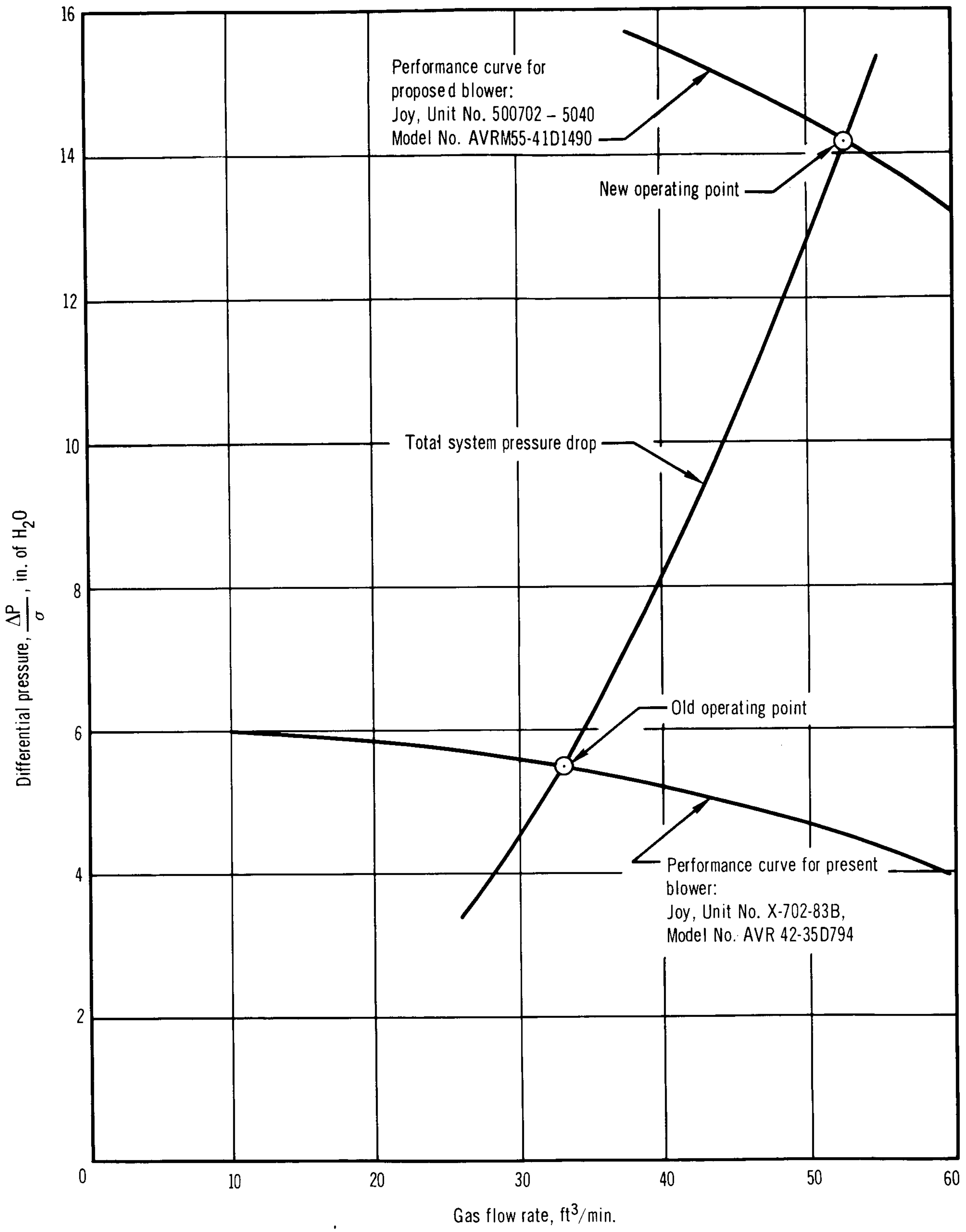


Figure 7. Proposed Modification to Wash-Water Recovery Unit

TABLE III. – COMPARISON OF EXISTING AND IMPROVED WASH-WATER RECOVERY UNITS

Description	Existing unit	Improved unit
Input data		
Fan		
Gas flow rate, lb/hr	100.0	160.0
Oxygen	23.2	36.9
Nitrogen	76.8	123.1
Ducted heat load, Btu/hr	260.0	1,000.0
Wick effectiveness	0.85	0.80
Condenser AU, Btu/hr °F	250.0	350.0
Heater AU, Btu/hr °F	20.0	30.0
Daily operation time, hr	16.0	24.0
Selected computed results		
Design processing rate, lb/hr	3.56	2.37
Processing rate attained, lb/hr	1.57	2.31
Heating fluid flow rate, lb/hr	70.0	70.0
Heat-tranfer rate in heater, Btu/hr	3,716.0	4,842.0
Wick inlet temperature, °F	167.0	164.0
Condenser outlet temperature, °F	37.6	44.8

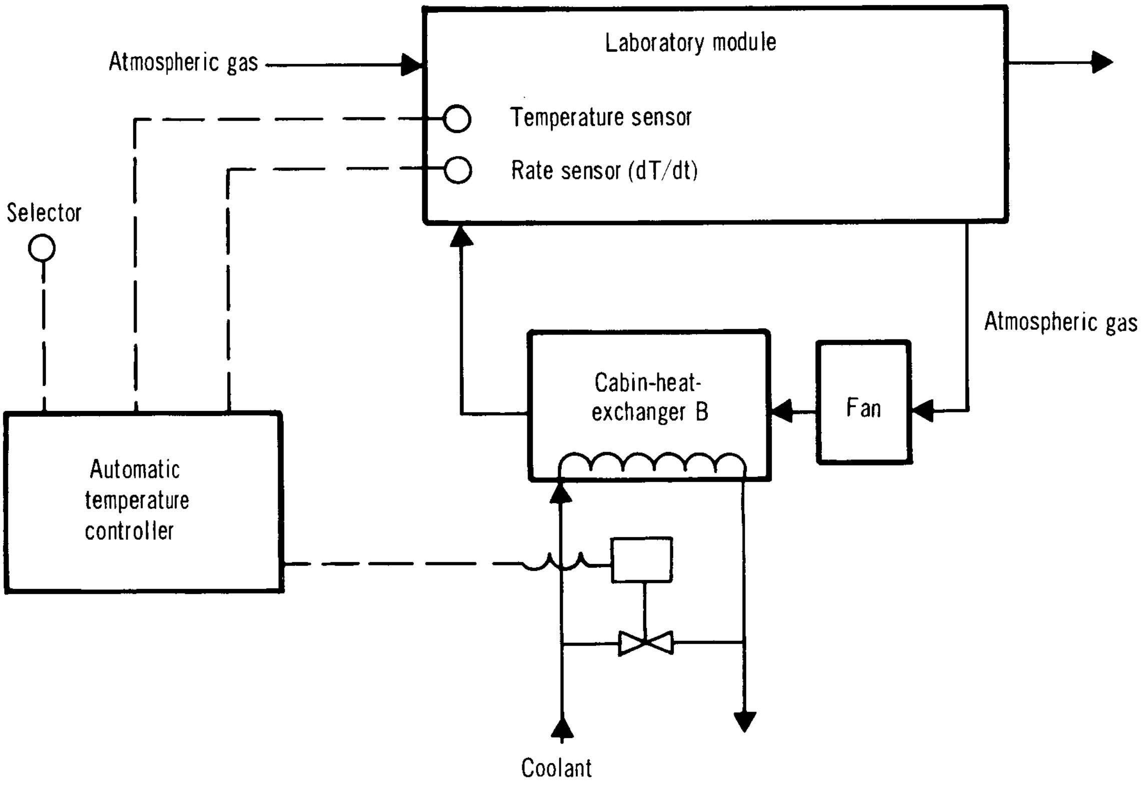
The same low coolant flow rate is considered to be a failure-mode condition in this sample problem. An extremely low coolant flow rate in cabin heat-exchanger A could be the result of a valve malfunction or some other undesirable restriction in the cooling fluid line. It is assumed that there is a step change in this coolant flow rate; at the beginning of the transient case, the heat-exchanger cooling fluid flow suddenly drops from 910 lb/hr to 91 lb/hr. The object of the transient simulation is to obtain time histories for the system parameters most influenced by the sudden change in coolant flow rate. These curves can be used to determine the time period available for corrective action by the crew before limits of tolerance (for example, cabin temperature) are exceeded.

Fig. 8 shows the actual time variation of some of these parameters as they vary between initial and the final steady-state values listed in table II. These time histories show the time available for repairs or other corrective action before the living-module temperature or some other parameter exceeds its specified tolerance limit. Similar time histories for relative humidity or CO_2 concentration could be computed for other failure mode conditions of interest.

Automatic control system. — This sample problem illustrates the application of the G-189 automatic control system subroutine to the transient simulation of the ILSS.

Several processes in the ILSS are now manually controlled, but could be automated. Probably the most obvious of these is the control of the cabin atmosphere dry bulb temperature.

The sketch below shows the simulated life-support components that control the temperature in the laboratory module. A system component representing an automatic temperature controller has been added to the simulated system for this sample problem. This hypothetical controller considers a motor-operated valve in the liquid-coolant bypass branch to modulate the flow of coolant through cabin heat-exchanger B.



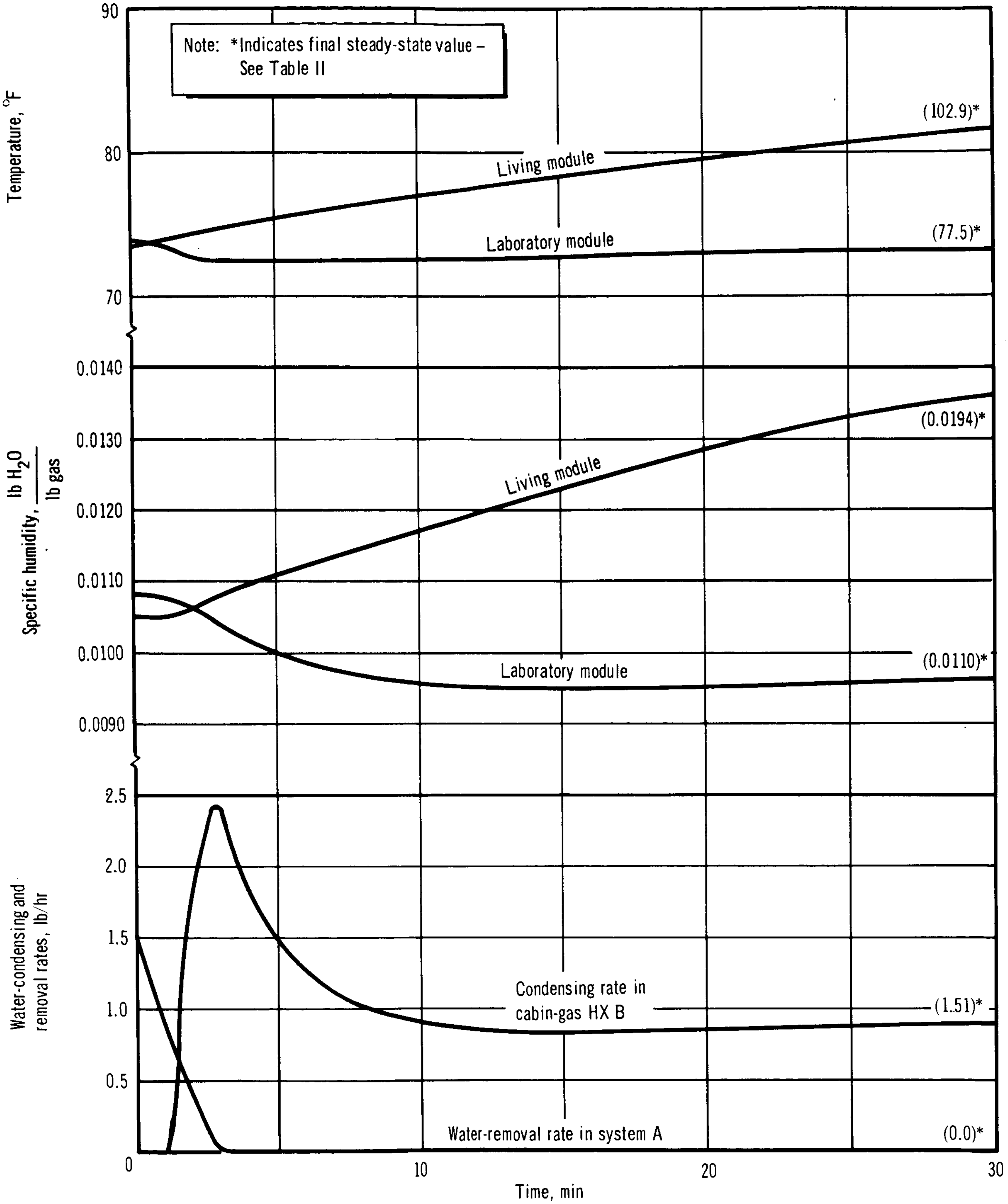


Figure 8. Failure Mode Condition

This control system has been simulated in two steps. First, the input data for the basic controller (without the rate sensor) were formulated. Then additional input data for the rate sensor were added. The performance of both the basic and compensated (with rate sensor) controllers were evaluated by imposing step changes on the controller input signal (set-point temperature) and computing the resulting response of the laboratory-module temperature. Typical values of control-system parameters (sensor time constant, gain, valve positioner speed, etceteria) were used in these simulations. Computed results for this sample problem are shown in Figs. 9 and 10.

The curves in fig. 9 show the response of laboratory-module temperature for the basic control system, without the rate sensor. These results show that, when a +10°F step change in the set-point temperature is applied, the basic controller requires about 9 min to bring the laboratory module to the required temperature. There is approximately 1°F initial "overshoot," followed by a sustained 3°F oscillation about the set-point temperature. It is possible that the performance of this basic controller could be improved by using different values of sensor time constant, gain, or maximum speed of the valve positioner. However, regardless of the values given these controller parameters, the rate of change of the cabin temperature is limited by the thermal capacitance of the cabin atmospheric gas and the equipment included in the cabin. Also, the thermal capacitance of cabin heat-exchanger B slows down the initial response of the cabin temperature, then eventually causes significant overshoot in cabin temperature.

Fig. 10 shows the improved cabin-temperature response obtained by adding a rate sensor. This additional sensor (or anticipator) has the effect of reducing the overshoot caused by the thermal capacitance of the heat exchanger. As shown in the figure, different values of rate signal gain change the temperature response.

These results indicate that an automatic control system with a rate sensor could be used to satisfactorily control the laboratory-module temperature. However, ultimate selection of control system hardware should be based on a more complete analysis. For example, this sample problem could be extended to simulate system responses to step changes in cabin heat loads and to step changes in the temperature of the coolant supplied to the heat exchanger.

Oxygen-Regeneration System Sample Problems

The sample problems formulated to achieve the experimentally measured water and oxygen-generation rates from the Bosch or Sabatier reactor and the electrolysis unit, respectively yielded the following component characteristics:

(1) Assuming a 17-Btu/hr heat loss from the Sabatier reactor to cabin atmospheric gas, a cooling load of 311 Btu/hr was found to be necessary to maintain a 500°F outlet temperature. This cooling capability is provided by the process cooling circuit. The effectiveness of the coolant heat exchanger was found to be 0.94 with an

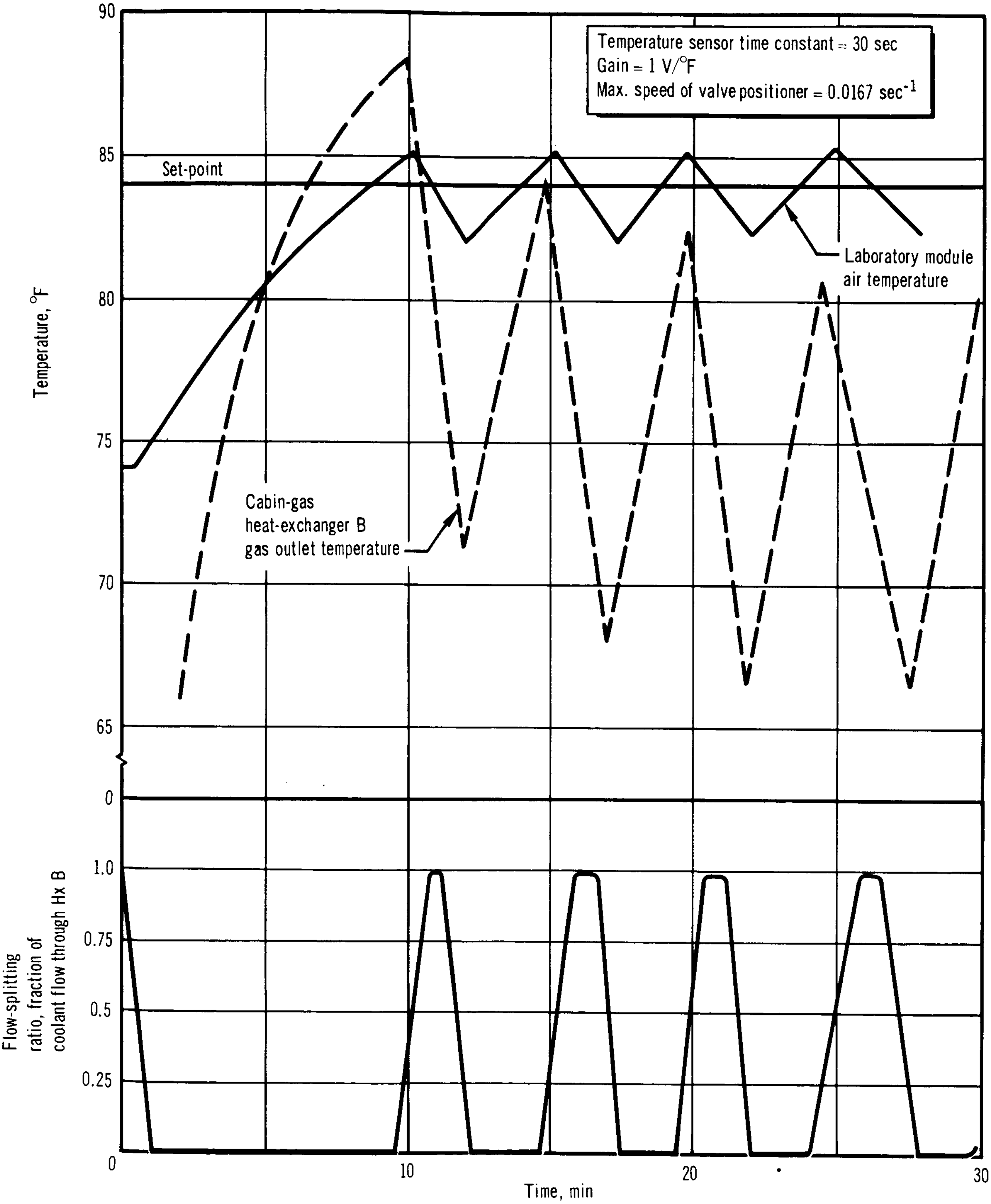


Figure 9. Transient Results – Basic Temperature Controller

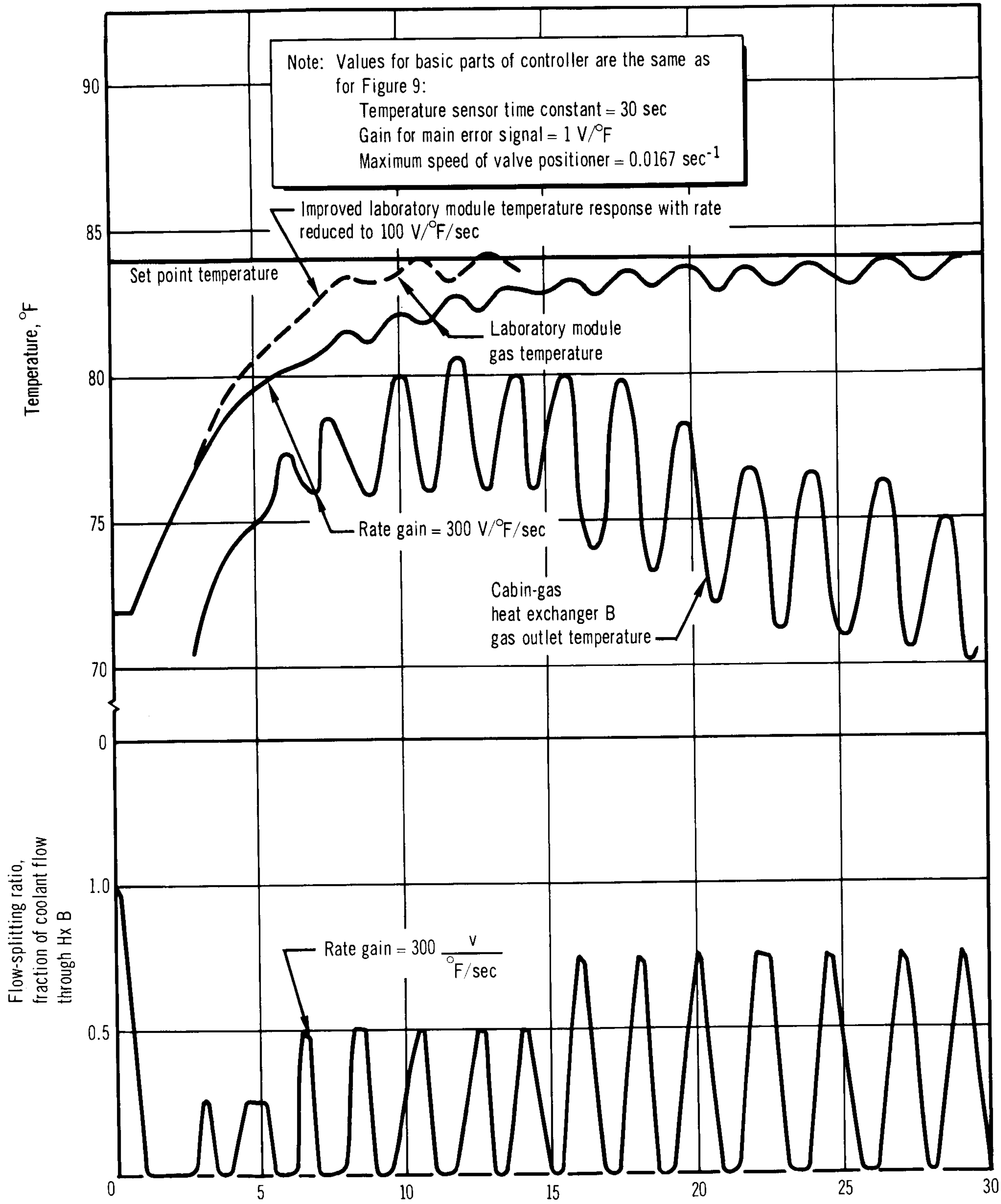


Figure 10. Transient Results – Controller with Rate Sensor

overall conductance of 0.4 Btu/hr°F. This effectiveness appears high and should be experimentally re-evaluated together with determination of the heat loss to the cabin.

(2) The regenerative heat exchanger in the Sabatier desulfurization chamber was found to have an effectiveness of 0.99 and an overall conductance of 2.5 Btu/hr°F. These computed values were highly dependent upon assumed values for the high flow inlet and outlet temperatures. This computed effectiveness also seems too high. Possibly, a large heat loss occurs in the duct connecting this component and the system condenser. This heat loss would reduce the high flow inlet temperature. All other temperatures remaining constant, a reduced effectiveness would result.

(3) The cooler in the recycle compressor branch of the Bosch reactor was found to have an effectiveness of 0.98 with an overall conductance of 12 Btu/hr°F. This effectiveness appears high, but is required to match the assumed gas inlet and outlet temperatures of 150 and 60°F, respectively, and the specified coolant inlet temperature.

(4) The oxygen system condenser was found to have an effectiveness of 0.77 with an overall conductance of 20 Btu/hr°F. These were calculated using assumed gas inlet and outlet temperatures of 90 and 46.7°F, respectively.

COMPARISON OF ANALYTICAL AND EXPERIMENTAL RESULTS

The experimental test results from the final ILSS demonstration test of 15 July 1965 (ref. 2) were used to evaluate the accuracy of the analytical simulation. A complete evaluation of the accuracy was not possible because of lack of complete experimental data. The following brief comparisons demonstrate some aspects of the accuracy of the simulation. This evaluation can be extended in the future as new experimental data become available.

A very general examination of the simulation's accuracy can be made by considering the steady-state conditions of temperature, humidity, and CO_2 concentration in the living and laboratory modules.

Compartment Temperatures

The final demonstration test of 15 July 1965 (ref. 2) was run under conditions fairly close to the maximum design heat-load conditions simulated by the basic case data prepared for the steady-state analytical model of the overall ILSS. These case data are discussed in detail in vol. II of this report (ref. 1). The main differences between the demonstration test and the basic case data for the computer program were that during the test, the CO_2 reduction unit was in the Sabatier mode rather that the Bosch mode; and the water-recovery units, water heaters, catalytic burners, and electrolysis modules were not operating. The differences in compartment head loads between the demonstration test and the basic case data were reported in ref. 3.

The analytical model basic case data were modified to account for the differences noted above. The computed results for the compartment temperatures agreed within $1^{\circ}F$ with the test temperature of 64° to $65^{\circ}F$. In general, there will be a temperature gradient from point to point within the compartment. Because the analytical model predicts only an average compartment temperature, this temperature should be compared with the average experimental temperature measured in the compartment.

Compartment Humidity

Specific humidity (in both the living and laboratory modules) for the maximum design heat-load condition was computed in the first steady-state sample problem. For the design case, the computed specific humidity values are 0.0105 lb H_2O/lb gas in the living module, and 0.0107 lb H_2O/lb gas in the laboratory module. Also, the specific humidity of the atmospheric gas entering cabin heat-exchanger A was found to be 0.0105 lb H_2O/lb gas.

No experimental values of compartment specific humidity can be found. However, the cabin gas-water separator test data of 15 July 1965 (table 8.1-I, ref. 2) include a measurement of specific humidity in the duct upstream of cabin heat-exchanger A. A discrepancy of about 4% exists between this experimental value of 0.0109 lb H_2O/lb gas and the analytical result.

The above discrepancy, although not considered large, could be eliminated entirely by adjusting input values of water separator efficiency or the AU value of cabin heat-exchanger A — that are used in the simulation. However, it is believed that more test data should be gathered for comparison with the analytical results before any such changes can be justified.

CO_2 Concentration in Laboratory Module

A rather large discrepancy exists between the computer laboratory-module CO_2 concentration and the values measured during the final demonstration tests of July 1965. The steady-state sample problems show a CO_2 weight concentration of 1.89% which converts to 1.25% by volume, or 6.6 mm Hg CO_2 pressure. This is about 32% higher than the 0.95% volume CO_2 concentration measured at the end of the Final Thermal Desorption Test (ref. 2).

The following analysis shows that the 0.95% experimental CO_2 concentration was far from the steady-state value that would have been measured if a longer demonstration test had been run.

An equation describing the time-variation of CO_2 concentration in the laboratory module can be derived by stating a few assumptions, writing the appropriate differential equation, and solving this equation for CO_2 concentration as a function of time.

The assumptions for computing the CO_2 concentration in the laboratory module are as follows:

(1) The system has a single lumped capacity for CO_2 in the cabin atmospheric gas; this capacity is the combined volume of the living and laboratory modules.

(2) The flow of process gas through the CO_2 concentrator is constant with time, as is the removal efficiency, η_R.

(3) The generation rates of CO_2 in the system are lumped together and introduced within the lumped capacitance.

The symbols used in the equation for determining the CO_2 concentration in the laboratory module are as follows:

V = lumped volume or capacitance, ft^3

ρ = gas density, lb/ft^3

W = weight flow rate of gas through CO_2 concentrator, lb/hr

η_R = removal efficiency of CO_2 concentrator

C = CO_2 concentration in cabin, lb CO_2/lb gas

A single equation can be written to relate the time rate of change of CO_2 concentration to the difference between CO_2 generation and removal rates:

$$\rho V \frac{d}{dt} C = \underbrace{W_G}_{\text{generation rate}} - \underbrace{\eta_R W C}_{\text{removal rate}} \qquad (1)$$

The time solution for CO_2 concentration is

$$C(t) = e^{-\frac{\eta_R W}{\rho V} t} C(o) + \left(1 - e^{-\frac{\eta_R W}{\rho V} t}\right) \frac{W_G}{\eta_R W} \qquad (2)$$

where C(o) is the initial value of concentration, that is, at $t = o$.

Eq. (2) indicates that there is an exponential response in C, from its initial value at $t = o$, to its final steady-state value ($C(\infty) = W_G/\eta_R W$) at infinite time. The time constant for this response (the time required for the concentration to attain 63.2% of its final value) is given by:

$$\tau = \frac{\rho V}{\eta_R W} \qquad (3)$$

Substitution of appropriate values into eq. (3) gives the time constant for the operating conditions of the 10 psia final thermal desorption test, as follows:

$$\tau = \frac{0.051 \times (2240 + 1910)}{0.63 \times 61.4} = 6.5 \text{ hr}$$

Apparently, the length (3.7 hr) of the final thermal desorption test of 13 July 1965 was little more than one-half the time constant for the transient CO_2 balance. Therefore, the laboratory module CO_2 concentration did not reach steady-state, but progressed only about 44% of the way from its initial value toward the final steady-state value.

The projected steady-state experimental value (using the initial and final values of fig. 8.2-29, ref. 2) is about 1.29% by volume, compared with the analytical value of 1.25%. One might predict a slightly lower, final steady-state experimental value by considering the slight increase in removal efficiency that is likely to be observed for higher laboratory CO_2 concentrations.

The analytical simulation seems to give accurate results for the CO_2 balance in the thermal control gas circuit.

CONCLUSIONS AND RECOMMENDATIONS

The study tasks have been successfully completed. The analytical models of the ILSS and the oxygen recovery system can be used as tools for accomplishing the following:

(1) Computing design and off-design performance of the life-support system.

(2) Investigating the effects on system performance of revisions to the system.

(3) Analyzing system performance during failure-mode conditions.

(4) Computing transient performance of the system, including the effects of automatic control systems.

Having successfully simulated the Langley ILSS with the G-189 computer program, the utility of the program in analyzing rather complex EC/LS systems has been demonstrated.

This section criticizes the analytical simulation and indicates areas of possible improvement. The two levels of improvement discussed are (1) long-range improvements, corresponding to advances in the state-of-the-art of simulation methods and (2) short-range improvements consisting of minor changes of input data or the use of various options of the present G-189 program to upgrade the existing ILSS analytical models.

Long-Range Improvements

The capabilities of the program will improve in two ways: through new and revised subroutines and through greater computer storage capacity.

New and revised subroutines.—In FY 1968, it is planned that new subroutines will be developed by the contractor for simulating the following processes:

(1) Chemical reactions.

(2) Compression and expansion of gases.

(3) Change of state (evaporation, condensation, and so forth.)

(4) Mass transfer through membranes (electrodialysis, and so forth).

The existing G-189 subroutines are continually being upgraded so that the various processes can be represented with greater accuracy, faster interative convergence, and less computing machine time. Even while this contract was in progress, improvements were made in the heat-exchanger and "special" subroutines.

Greater computer storage capacity.—The simulation has been somewhat restricted by the maximum of 89 simulated components that is allowable with the version of the G-189 program used for the ILSS simulation. This maximum was dictated by the LRC program specification of a maximum of 20,480 decimal memory-cell locations. A modified version of the program that allows a maximum of 250 components has been prepared by the contractor for use with computer systems with approximately 64,000 memory cells. If and when the LRC computer system is modified to allow a relaxation of the program specification, thus permitting a program utilizing approximately 50,000 cells, the capability of the simulation could be greatly enhanced. Such an increase in the program capacity would permit the inclusion of the detailed model of the oxygen-recovery system as an integral part of the model of the ILSS. In addition, other subsystems could be simulated in greater detail, all within a single, integrated, analytical model.

Until these long-range improvements are realized, the recommendations given below can be followed to upgrade the present analytical simulations.

Recommended Short-Range Improvements

Simple changes in values of input data, or the use of various options of the G-189 program can be used to improve the analytical models. Some of these possible changes are recommended below. In some cases, the recommendations depend on the availability of sufficient experimental data to be used as a guide for upgrading the analytical simulations.

Steady-state simulation of the ILSS.—A few areas of possible improvement have been observed and these are discussed below. Other likely areas for improvement will probably be uncovered as the simulation is used at LRC.

Sensible and latent heat loads of crew: Presently, these heat loads are entered as fixed values for the components simulating the crew in the living and laboratory modules. Because the division of metabolic heat into sensible and latent components is a function of both activity level and ambient gas dry bulb temperature, the present arrangement requires previous knowledge of the compartment temperatures for any case that is being studied.

This difficulty can be overcome by using the polynominal and/or the interpolation features of the G-189 program to compute the correct sensible and latent heat loads corresponding to the computed compartment temperatures. Table 3.2-1 of ref. 3 could be used as the basis for these programming relationships.

Heat exchanger conductances: Thermal conductances (AU) are now imput as fixed values for the simulated heat-exchangers. The computed effectiveness values are quite accurate when heat-exchanger flow rates are near their design values. However, off-design flow rates introduce secondary effects that are not accounted for. A more accurate representation would account for changing values of conductance, ηhA, on either side of the heat exchanger. Experimental or theoretical relationships for ηhA versus flow rate could be incorporated via the polynominal or interpolation features of the program. Then, a polynominal could be used to compute AU as a function of the ηhA values for primary and secondary sides, as follows:

$$AU = \frac{1}{\frac{1}{(\eta hA)_{pri}} + \frac{1}{(\eta hA)_{sec}}} \tag{4}$$

h = heat transfer coefficient, $\frac{Btu}{hr\text{-}ft^2\ {}^oF}$

A = effective areas, ft^2

η = fin effectiveness, dimensionless

pri, sec = primary and secondary; designations for opposite sides of the heat exchanger.

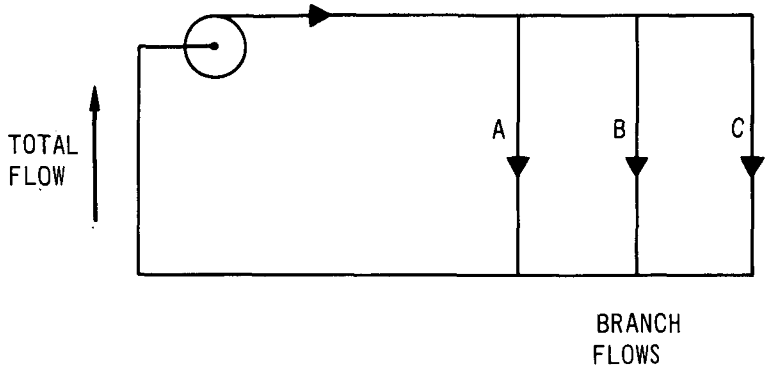
Then, the heat exchanger subroutine could use this more accurate off-design value for AU in calculating the heat-exchanger effectiveness.

Gas/water separator efficiencies: Fixed values of efficiency are now imput for the gas/water separators in the simulated system. These values should be reviewed and replaced, as necessary, with any recently determined experimental values. The additional refinement could be added of using any experimentally observed relationships for water-separator efficiency as a function of flow rate of gas and flow rate of entrained water.

Flow distribution for off-design conditions: At present, fixed values are input for the various fluid flow rates in the process cooling, process heating, and thermal control gas circuits. No attempt is made in the simulation to automatically compute changes in flow distribution caused by changes in valve positions or other changes in pressure drop characteristics of these circuits.

If these computations are desirable, the pressure drop subroutine of the G-189 program could be used to perform the necessary additional analysis. However, the requirement for additional input data would be formidable for a system this large. Experimental or theoretical values of "pressure loss coefficients" for all the major pressure drop elements of the system would have to be obtained and entered in the program. Performance curves for fans, blowers, and pumps also would be used by the program.

A simpler approach might be used to compute off-design flow distributions. This would use experimentally observed relationships between arbitrary forced changes in certain branch flow rates, and the resulting changes in other branch flow rates of the same circuit. For example, consider the simple circuit of three parallel branches shown in the sketch:



Starting with design values of flow rates in branches A, B, and C, assume that a valve in branch A is adjusted until flow A is forced to some lower off-design value. Then, it can be visualized that flow B and C will increase in magnitude and, depending on the pump performance curve, the total flow will decrease somewhat.

These kinds of relationships could be experimentally observed for the various flowing fluid circuits of the ILSS. Then, the polynominal or interpolation features of the G-189 program could be used to compute the overall changes in circuit flows that result when an arbitrary off-design flow rate is imposed in a single branch.

CO_2 concentrator: The simplified thermal model described in Section 2.5 of Volume II of this report (ref. 1) simulates heat transfer from the electrical and adsorption heat sources and the heating fluid to the cooling fluid, process gas, and surrounding laboratory module gas. The computed heat-transfer rates are believed to be of sufficient accuracy, but no attempt has been made to simulate the influence of heat transfer or mass transfer in the adsorption beds. Instead, a fixed input value of CO_2 removal efficiency is used by the program.

The simulation of the CO_2 concentrator could be extended to compute CO_2 removal efficiency as a function of inlet temperatures and flow rates of the three flowing fluids involved. This would require a series of tests on the CO_2 concentrator to determine a "map" of its performance, that is, CO_2 removal efficiency versus supply temperature and flow rate of the process gas, heating fluid, and cooling fluid.

This performance map also could be determined analytically by performing a separate, detailed simulation of the CO_2 concentration unit. The G-189 adsorption bed subroutine could be used to simulate transient heat and mass transfer in the silica gel and zeolite beds, and the heat-exchanger subroutine could be used to simulate the separate heat exchangers within the unit. Other subroutines such as flow splitting, flow mixing, and "special" also could be used. This detailed transient simulation of the CO_2 concentrator would be similar to the detailed simulation of the oxygen-recovery system that has already been prepared.

Transient simulation of the ILSS.—The recommendations previously discussed for the steady-state simulation also apply to the transient analytical model of the ILSS. A few additional comments can be made regarding the use of the transient simulation, specifically, with regard to the selection of the computing time increment.

The value used for the computing time increment is rather arbitrary and its selection represents a tradeoff between accuracy and computing machine time. Smaller time increments generally give more accurate results, but require more machine time to simulate a given length of real time.

The 15-sec increment that has been tentatively selected for this simulation is believed to be sufficiently small to give accurate results. However it may not be optimum, it might be increased to reduce computing machine time, with little sacrifice in accuracy.

The best value of computing time increment can be found by starting with relatively large value and running the same transient case with sucessively smaller values of time increment, and then comparing the results. A sufficiently small time increment will have been found when further decreases in the size of the time increment produce no substantial changes in the results.

Simulation of the oxygen recovery system.—It is recommended that the Bosch and Sabatier reactors be tested at several operating conditions to provide more accurate data on reaction rates. Variation of reaction rate for changing gas compositions should be measured. The analytical simulation of steady-state operation would be improved and analytical simulation of transient operation could be set up if these data were available.

Adjustment of overall conductance values in the components that simulate heat transfer can easily be made where test data indicate that the simulation is inadequate.

References

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3. North, B. F., and Armstrong, R. C., Reanalysis of LSS Thermal Control System. General Dynamics/Convair Report No. 64-26241, December 1965.