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DEVELOPMENT OF INTEGRATED ENVIRONMENTAL CONTROL SYSTEM DESIGNS FOR AIRCRAFT

VOLUME II-ECS COMPUTER PROGRAM

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NOTICE

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FOREWORD

This report presents results developed by the McDonnell Douglas Corporation under Air Force Contract F33615-70-C-1235 "Development of Integrated Environmental Control System Designs for Aircraft". This development program was conducted under the sponsorship of the Air Force Flight Dynamics Laboratory, Project 6146, with Mr. Eugene A. Zara, FEE as Project Engineer. This report is in four volumes:

I. ECS Design

II. ECS Computer Program

III. IECS Computer Program Users Manual

IV. Laboratory Demonstration Test

The ECS Computer Program described in this volume was developed by the McDonnell Aircraft Company (MCAIR) of the McDonnell Douglas Corporation. The program manager was R. R. Dieckmann and A. E. Whitney was the ECS Computer Program Group Leader. C. E. Whitman and K. C. Li assisted in the development of the computer program. A. C. Watson of the Douglas Aircraft Company provided assistance in evaluating the computer program. A Users Manual for the ECS Computer Program is available.

This technical report has been reviewed and is approved.

William C. Savage

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ABSTRACT

This report presents the results of a study of environmental control system (ECS) designs for aircraft. The study was performed for the Air Force Flight Dynamics Laboratory. This volume describes the computer program developed to analyze aircraft ECS and several sample problems used to evaluate and to verify the computer program. Additional sample problems are presented in Volumes III and IV. Analyses with the computer program are set up in a general manner. It is able to analyze almost any ECS. The program computes the steady state performance, the size, and aircraft penalties of an ECS. Options provide for several data input levels from rough to refined. The sample problems presented in this volume are for the rough performance and sizing of three Air Force aircraft, and the detailed performance and sizing of one Air Force aircraft. The computer program has been demonstrated on the CDC 6600 computer facility at Wright Patterson Air Force Base.

Volume I of this report presents analytical ECS design information which has been incorporated into the computer program. Volume III of this report is the users manual for the IECS Computer Program which contains information on how to use the computer program and a complete description of sample problems for rough performance and sizing analyses, and detailed performance analysis. Volume IV of this report presents the laboratory demonstration ECS, the results obtained from the tests of this ECS, and setup information and results of the computer program detailed performance and sizing analyses which were used to evaluate this ECS.

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NOMENCLATURE

Symbol	Definition
D	Net ECS Drag (inlet drag minus thrust recovery), lb
D_{ECS}	ECS Drag (Plus Thrust Reduction for ECS Fuel), lb
D_{eq}	Equivalent Drag, lb
D_r	Aircraft Flight Drag without ECS, lb
E	Error Variable
LDR_r	Aircraft Lift to Drag Ratio without ECS
n	Number of State and Error Variables
P	Influence Partial Derivatives
R_r	Aircraft Range without ECS
S	State Variable
SFC	Total Specific Fuel Consumption including ECS, lb fuel/lb thrust-hr
SFC_r	Engine Specific Fuel Consumption without ECS, lb fuel/lb thrust-hr
W_{ex}	ECS Expendable Flow Rate, lb/hr
Wt	ECS Component Weight, lb
Wt_{dev}	ECS Weight Standard Error, lb
Wt_{ECS}	Installed ECS Weight Including Power Drive, lb
Wt_{emp}	Aircraft Empty Weight, lb
Wt_{gr}	Aircraft Gross Takeoff Weight without ECS, lb
$Wt_{pl,r}$	Aircraft Payload Weight without ECS, lb
X	Ratio of Aircraft Expendable Weight to Aircraft Gross Takeoff Weight with ECS
X_r	Ratio of Aircraft Fuel Weight to the Aircraft Gross Takeoff Weight without the ECS
ΔR	Aircraft Range Decrease Due to ECS
ΔWt_{gr}	Aircraft Gross Weight Increase Due to ECS, lb
ΔWt_{pl}	Aircraft Payload Decrease Due to ECS, lb
σ	ECS Component Standard Error for Weight

Used on Computer Program Output Sheets*

Symbol	Definition
AD	Inlet Diffuser Exit Area, in^2
AI	Inlet Area, in^2
AN	Ejector Total Primary Nozzle Area, in^2
D	Diameter, in
DS	Specific Diameter
EFF	Effectiveness or Efficiency
EV	Error Variable
EWT	Expendable Weight, lb
FN	Fluid Number Code
FT	Fluid Type Code
HI	Inlet Humidity, lb water/lb dry air
HO	Outlet Humidity, lb water/lb dry air
HP	Horsepower
KT	Valve Pressure Loss Coefficient
LC	Cold Flow Length, in
LH	Hot Flow Length, in
LN	No Flow Length, in
M	Mach Number
N	Rotational Speed, rpm, or State or Error Variable Number
NS	Specific Speed
NTU	Number of Transfer Units
PI	Inlet Pressure, psi
PO	Outlet Pressure, psi
SV	State Variable
T	State or Error Variable Type
THK	Thickness, in
TI	Inlet Temperature, $^{\circ}R$
TO	Outlet Temperature, $^{\circ}R$
U	Tip Speed, ft/sec
V	Fluid Velocity, ft/sec
VOL	Volume, in^3

Symbol	Definition
W	Flow Rate, lb/min
WTC	Core Weight, lb

* Component names used in the computer program input data are defined in Sections 3 and 4.

SECTION 1

INTRODUCTION

A digital computer program to determine the steady state thermodynamic performance and estimates of various penalties of aircraft environmental control systems has been developed. This computer program was written in the Fortran IV language for the Air Force CDC 6600 computer at Wright Patterson Air Force Base, Ohio. The performance analyses obtained from this computer program assume that all components of the ECS have reached a steady state operating condition (i.e., it does not calculate the transient performance of the ECS). The ECS penalties obtained from this computer program include its size, weight, reliability, and cost based on typical present state-of-the-art designs (i.e., the computer program does not provide an optimization analysis); and penalties imposed by an ECS on an aircraft.

The computer program was developed to analyze the environmental control systems and subsystems described in Volume I, which include several potentially new concepts. Briefly these include simple and bootstrap air cycle systems, and vapor cycle systems. Several forms of input power may be included. Heat sinks may be air, water, or fuel. The performance or sizing calculations can be made with the typical (rough) analytical design information contained in Volume I, with specific detailed information desired by the computer program user, or with typical and detailed information (i.e., intermediate level of detail). The ECS to be analyzed is specified by the use of subroutines representing components of an ECS. The program user can alter the ECS being analyzed by adding or deleting component subroutines.

This volume presents a general discussion about the structure of the computer program, the inputs to the computer program, and the results obtained from it. These results provide the engineer with information to be used in evaluating the thermodynamic performance of existing and proposed ECS, and of typical sizes and penalties of these ECS. A users manual (Volume III) and the computer program are available from the Air Force Flight Dynamics Laboratory.

The capabilities of this computer program were evaluated by comparing its output with ECS component weight data (from Reference 1) for three Air Force aircraft. These aircraft were the C-5A cargo aircraft, the F-111A fighter aircraft, and the B-52H bomber aircraft. These analyses were based on the typical design characteristics presented in Volume I. An evaluation also was made of the computer program results compared to those of the C-9A Aeromedical Transport. The results of these four evaluations are presented in Section 5 of this report. The computer program also was used for evaluating the Laboratory Demonstration ECS. (See Volume IV.) Techniques for using the computer program, as a result of solving these sample problems, are included in the users manual, Volume III.

SECTION 2

PROGRAM STRUCTURE

The computer program is divided into two main sections: 1) the performance analysis section, and 2) the sizing analysis section. The performance analysis section computes the steady state performance of the ECS (e.g., flow rates in each flow branch of the system; pressures and temperatures, humidities in air flow lines, and enthalpies in refrigerant lines at points within the system). The performance section can be used independently of the remainder of the program. The sizing analysis section computes the size of the ECS (e.g., characteristic dimensions, weight, cost units, reliability index, and development risk). The sizing section can also be used to compute relative aircraft penalties of drag, takeoff gross weight, payload, and range. The sizing section is dependent on system performance, and any sizing analysis must be preceded by a performance analysis. The program also is structured to accept simple through detailed descriptions of an ECS and the components used in the ECS.

The performance or sizing analysis may consist of a full set of data, called a base case, or it may consist of a partial set of data, consisting of changes to a base case, called a change case. A sizing case must always be preceded by a performance or performance change case. A performance change case must always be preceded by a performance case. A sizing change case must always be preceded by a sizing case.

2.1 Overlay Structure

The computer program has been structured into an overlay form to reduce the amount of main computer core storage required to run the program. The structure is shown in Figure 1. At the first overlay level the performance analysis section is contained in the "Performance Segment", and the sizing analysis section is contained in the "Sizing Segment". Also shown in Figure 1 at the first overlay level are the "Dummy Performance Segment" and the "Permanent Table Segment." The Dummy Performance segment is a short section which allows the user to directly input performance data of a system without running a performance analysis. The Permanent Table Segment is to load permanent table data.

The performance and the sizing segments both are overlayed at the second level into three similar subsegments. The first subsegment, designated the M phase, preprocesses the input data cards for a case. Error messages are written if any data cases are determined to be missing, unrecognizable, or in the

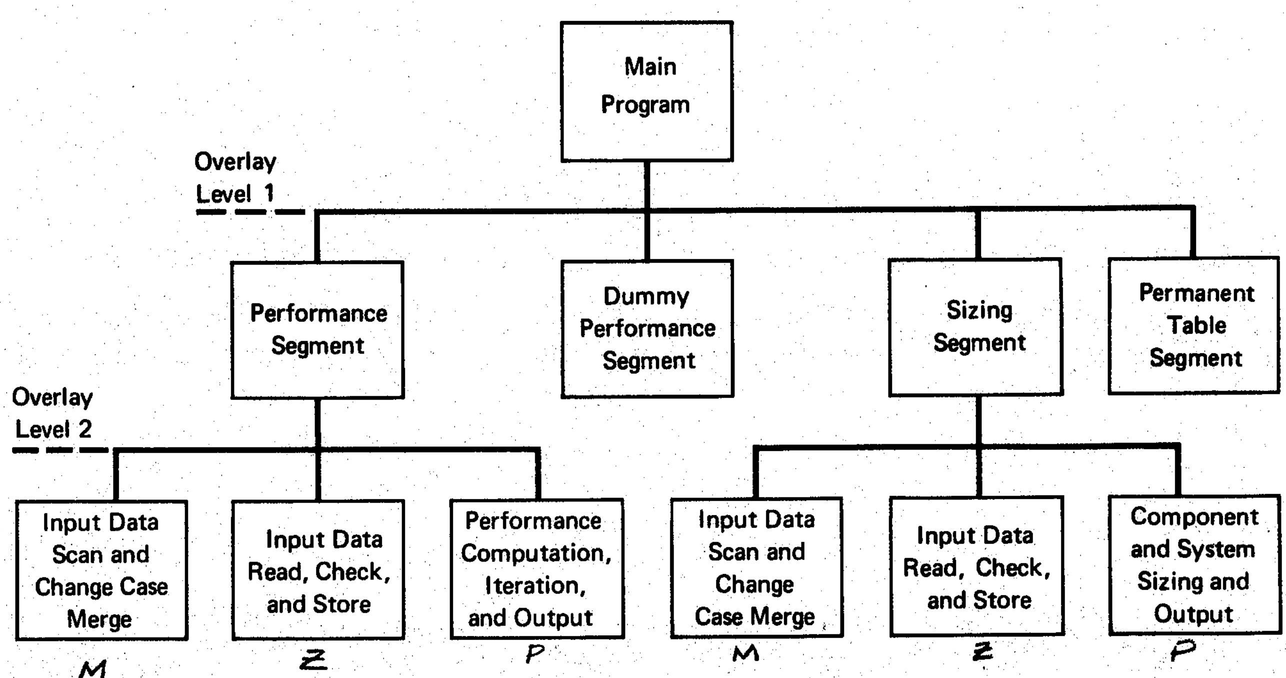

Figure 1 Computer Program Structure

wrong order. If the case being processed is a change case, the change cards will be merged into the base cards. These change cards allow for the removal or addition of components to the base case ECS, and designation of new conditions to be analyzed.

The second subsegment, designated the Z phase, reads the input data values, performs extensive error checks, and stores the data in the computer core storage for use by the third phase. Error messages are written if any data values are determined to be missing or incorrect.

The third subsegment, designated the P phase, performs the system analysis (i.e., either performance or sizing). If any errors were detected in the M or Z phases, the P phase will be bypassed. For a performance analysis the components are analyzed simultaneously to determine the system performance. For a sizing analysis the components are analyzed sequentially. The component sizing results can then be summed to give the system results, and the penalties can be determined.

2.2 Solution Method

The analysis of a flow system usually requires the simultaneous solution of a set of nonlinear equations. For a performance analysis and for the sizing of some components, the computer program uses the generalized Newton-Raphson iteration method. In a flow system there is a set of key variables, whose values, once known, allow the equations to be solved explicitly. These key variables are called "state variables." Examples of state variables are: inlet flow rate, flow split, compressor/turbine shaft speed, etc. If an initial guess is provided for each state variable, the equations can be solved. However, unless the state variables are given their correct values, certain conditions in the flow system will not be met. These conditions are called "error variables." Examples of error variables are: outlet pressure does not match the ambient pressure, the temperature at a sensor is not the correct temperature, the compressor power does not balance the turbine power, etc. The correct solution is obtained when the set of state variables yields a set of error variables whose values are acceptably small. For a unique solution the number of state variables must match the number of error variables.

The generalized Newton-Raphson iteration method provides for iterating an initial set of state variables to yield a set of error variables which are sufficiently small. Numerous texts describe the Newton-Raphson iteration method (e.g., see Reference 2). The Newton-Raphson method states that given an initial set of state variables S_j ($j = 1, n$), where n is the number of state and error variables, and a corresponding computed set of error variables E_i ($i = 1, n$), a better estimate of the state variables, that will produce a set of zero error variables, can be obtained from the equation (in matrix form):

$$[S]_{new} = [S]_{old} - [P]^{-1}\,[E]_{old} \qquad (1)$$

where S represents a column matrix of state variables, E represents a column matrix of error variables, and P represents a square matrix of influence partial derivatives $P_{ij} = \partial E_i/\partial S_j$. The partial P_{ij} is evaluated numerically by perturbing the state variable S_j and computing the change in the error variable E_i. Equation (1) can be repeatedly applied until the error variables are sufficiently small.

$$\begin{bmatrix} S_1 \\ S_2 \end{bmatrix}_{new} = \begin{bmatrix} S_1 \\ S_2 \end{bmatrix}_{old} - \left[\begin{bmatrix} \partial E_1/\partial S_1 & \partial E_1/\partial S_2 \\ \partial E_2/\partial S_1 & \partial E_2/\partial S_2 \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \end{bmatrix}_{old} \times \text{relax} \right]$$

SECTION 3

PROGRAM INPUT

The input data for a performance or sizing analysis is input on cards in a common manner. A case is a set of cards arranged in groups as shown in Figure 2. Every data card contains a name in the first card columns. A case is started with a case control card. The case control card may specify a performance base case (PERFORM), a performance change case (PCHANGE), a sizing base case (SIZE), or a sizing change case (SCHANGE). The change cases allow for the addition or removal of components to a base ECS, changes to the characteristics of components in a system, and changes in the mission conditions being evaluated. A case is ended by a case end card (ENDCASE). Any number of cases may be run in a job. The cases may be arranged in any order, except as noted in Section 2. The last case in a job is followed by a job end card (ENDJOB).

3.1 Performance Case Input

The user of the computer program defines the system or portion of the system which is to be analyzed (e.g., from a schematic of the ECS). Each flow branch is assigned a leg number. Surrounding each component in a leg the user specifies inlet station and outlet station numbers. Leg and station numbers are arbitrary and can be assigned any positive number. With the specification of the inlet flow conditions, outlet flow conditions, component parameters (e.g., diameter, length), defining component performance (e.g., pressure drop, effectiveness), the user inputs the ECS model to be analyzed as described in the following sections.

3.1.1 Performance Title Cards - The user may input a group of title cards (TITLE). These cards will be printed on the output and serve to document the case being run. The first title card will be printed on the top of every page of output for that case.

3.1.2 Performance Case Specification Cards - The case specification cards consist of four cards (CASEA, CASEB, CASEC, CASED). These cards specify the number of legs and stations in the ECS, the printout options, the altitude, Mach number (or velocity), and ambient conditions.

3.1.3 Performance Parameter Table Cards - Parameter values for an ECS analysis are input in a table. These parameter values include initial guesses of state variables, certain control variables of an ECS (e.g., desired cockpit pressure, etc.), and other constants described in later sections.

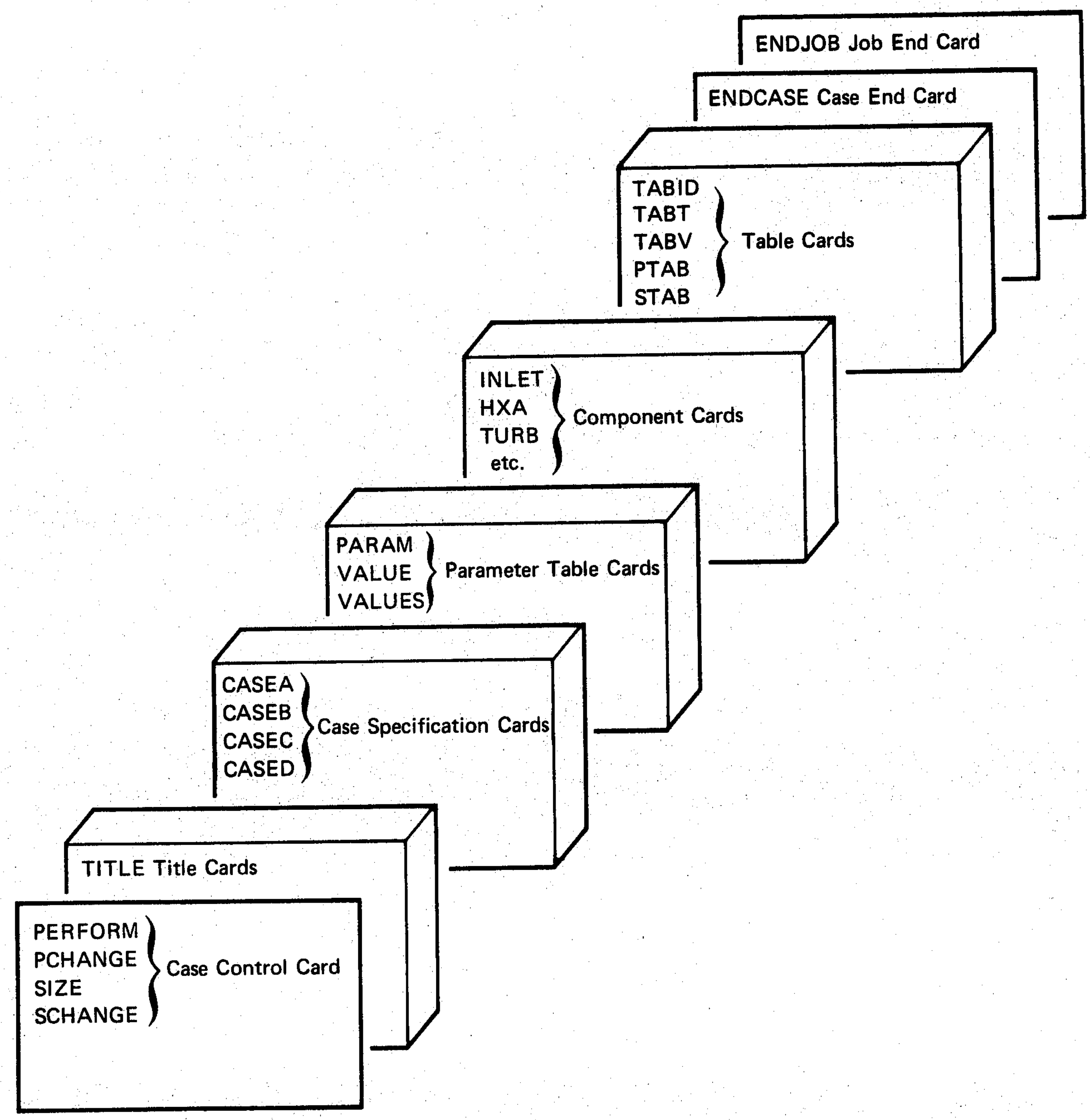

Figure 2 Program Input Data

The first card of the table (PARAM) specifies the number of values in the table. The following cards contain the parameter values, either one value per card (VALUE) or five consecutive values per card (VALUES).

3.1.4 Performance Component Cards - The component cards (e.g., INLET, HXA, TURB) specify the components in the ECS and the manner in which they are connected. In general, the component name (sometimes abbreviated) and user selected leg and station numbers are input. Change case information also is included when appropriate. The performance components cards also refer to numerical data in the parameter table or to data defined by the performance table cards. (See Section 3.1.5.) The shaft number of rotating components is identified (i.e., two or more components on the same shaft have the same shaft number). The cards also provide for user selected options to define from rough through detailed analyses that are to be considered for the component. The total set of component cards may specify rough analyses of some components and detailed analyses of other components for the same performance case. Some of the cards are used to specify data needed for a performance analysis, but do not represent actual components (e.g., INLET defines inlet conditions and is not a ram air inlet). Component names may be used to represent different components than what the component name suggests. For example, in the analysis of the F-111A ECS in Section 5.2, a temperature SENSOR was used to ensure that the ram air flow out of the F-111A heat exchanger did not exceed reasonable structural temperature limits, although no temperature sensor is used at this point in the F-111A ECS. The arrangement of the performance component cards must follow certain rules in order for them to represent the ECS desired by the user. This is discussed later in this section.

Brief discussions of the general meaning of the performance component card names are presented alphabetically, according to their component name.

APU - This component represents an Auxiliary Power Unit (APU). It may provide bleed air or shaft horsepower, or both.

BOILER - This component represents a boiler heat exchanger.

CNNCT - This does not represent a component. It allows the user to insert or delete components from subsequent analyses of a basic set of components representing any ECS.

COMP - This component represents an air compressor used in an air cycle turbomachine (including the fan in some simple air cycle systems), or an auxiliary or boost compressor. The user selects the type (i.e., axial, mixed, radial) by defining its performance map.

<u>COND</u> - This component represents a vapor cycle condenser heat exchanger.

<u>CVALVE</u> - This component represents a modulating control valve. An initial guess of the valve pressure loss coefficient (which represents valve position) and a minimum pressure loss coefficient (i.e., full opened valve) are specified. This component also can be used to limit the flow rate in a rough analysis to simulate an unknown fixed restriction (e.g., an orifice).

<u>DRAIN</u> - This component represents a water drain from another component (e.g., duct, heat exchanger, etc.).

<u>DSEP</u> - This component represents a static or self-cleaning dust separator.

<u>EJECT</u> - This component represents an ejector (i.e., jet pump).

<u>EVAP</u> - This component represents a vapor cycle evaporator heat exchanger.

<u>FAN</u> - This component represents a constant speed fan (i.e., essentially constant speed) used to circulate air in compartments or to provide ram air during static operations.

<u>HXA</u> - This component represents a heat exchanger having essentially single phase fluid flow on each side (i.e., condensation or evaporation of water in an air stream is included). It is used when the fluid conditions at both heat exchanger inlets can be determined explicitly during any calculation pass of the analysis.

<u>HXB</u> - This component represents the same type of heat exchanger as HXA. It is used when the flow rate and temperature at one heat exchanger inlet cannot be determined explicitly during any calculation pass of the analysis (e.g., a regenerative heat exchanger). The user must input initial guesses of these parameters.

<u>INJECT</u> - This component represents a water injector (e.g., to inject water collected by a water separator into the ram air side of a heat exchanger).

<u>INLET</u> - This does not represent a component. It is used to specify the initial fluid conditions of flow rate, temperature, pressure, and humidity (e.g., at an engine compressor bleed port). If any of these are unknown, initial guesses are made.

LINE - This component represents a liquid or air line (or duct). Its pressure drop can be specified in a simple manner (e.g., table) or in a detailed manner (e.g., friction factor and bend loss coefficients). Heat losses or gains can be included.

LOOP - This does not represent a component. It is used for an open or closed loop. A user starts the loop analysis at a point in the loop. At this point he specifies or guesses initial flow properties (i.e., flow rate, temperature, pressure, humidity). After specifying the components in the loop, the loop is ended, and the analysis balances the flow properties.

MERGE - This does not represent a component. It is used where two flow streams are merged.

MISC - This does not represent a component. It is used to obtain a number of miscellaneous mathematical calculations. For example, in the C-5A ECS evaluation of Section 5.1 it was used to obtain the static pressure at the throat of the ram air inlet.

NOZZLE - This component represents a choked or unchoked nozzle. One of its uses is to represent a ram air outlet.

ORIF - This component represents an orifice. One of its other uses is to represent a ram air inlet.

OUTLET - This does not represent a component. It may be used at the end of an open ECS.

PREG - This component represents a pressure regulator which controls its outlet pressure. The user specifies its pressure setting and its wide open pressure drop. (If pressure is to be controlled at a remote location a CVALVE and a pressure SENSOR are used.)

PUMP - This component represents a liquid pump.

QLOAD - This does not represent a specific component. It is used to define pressure drops and heat loads in compartments. The heat loads (positive or negative) can be specified, or determined from an overall heat transfer coefficient and source or sink temperature.

SENSOR - This component represents a sensor used for control. The user inputs the type of sensor (i.e., flow, pressure, temperature, humidity), and its control value is input into the parameter table.

SHAFT - This does not represent a component. It is used to define the shaft speed. If the shaft speed is not known an initial quess is made.

SPLIT - This does not represent a component. It is used when the flow is split into two legs.

SPOWER - This does not represent a component. It is used if the power provided and required by the components on a shaft are to be balanced.

TURB - This component represents an air turbine. The turbine may be used in an air cycle system or may be used to provide power for other appropriate components (e.g., a vapor cycle compressor - VCOMP).

VALVE - This component represents a valve having a fixed pressure drop characteristic (e.g., an open check valve).

VCOMP - This component represents a vapor cycle compressor.

VLINE - This component represents a line through which the refrigerant used in a vapor cycle flows.

WSEP - This component represents a water separator, with or without moisture in the air.

Several general rules concerning the component data card order must be followed in using them to represent an ECS. Basically the upstream leg and station numbers of a component must be defined previously as the downstream of another component. Different leg numbers must be used if the flow rate(s) from a component (i.e., performance component card) changes. Several component cards do not require upstream and downstream station numbers (e.g., INLET, OUTLET, LOOP).

A brief example of the use of these components to construct a mathematical model of an ECS is described relative to the primary heat exchanger portion of an ECS shown in Figure 3. Either INLET, representing the ram air or bleed air circuit, may be first. The ORIF in leg 1 and the SPLIT with outlet leg 5 must be used before the HXA component card; CVALVE and HXA must be used before MERGE; and VALVE and HXA must be used before EJECT. SENSOR must be used after leg 6 (or station 16) is defined if it is a flow rate (or temperature, pressure, or humidity) control point. Additional discussion on the use of these components is presented in Section 5 of the computer program evaluation.

The component cards, by means of data card options, implicitly specify state and error variables. A state variable, for example, can be generated by the INLET component. The user may specify the INLET option where inlet

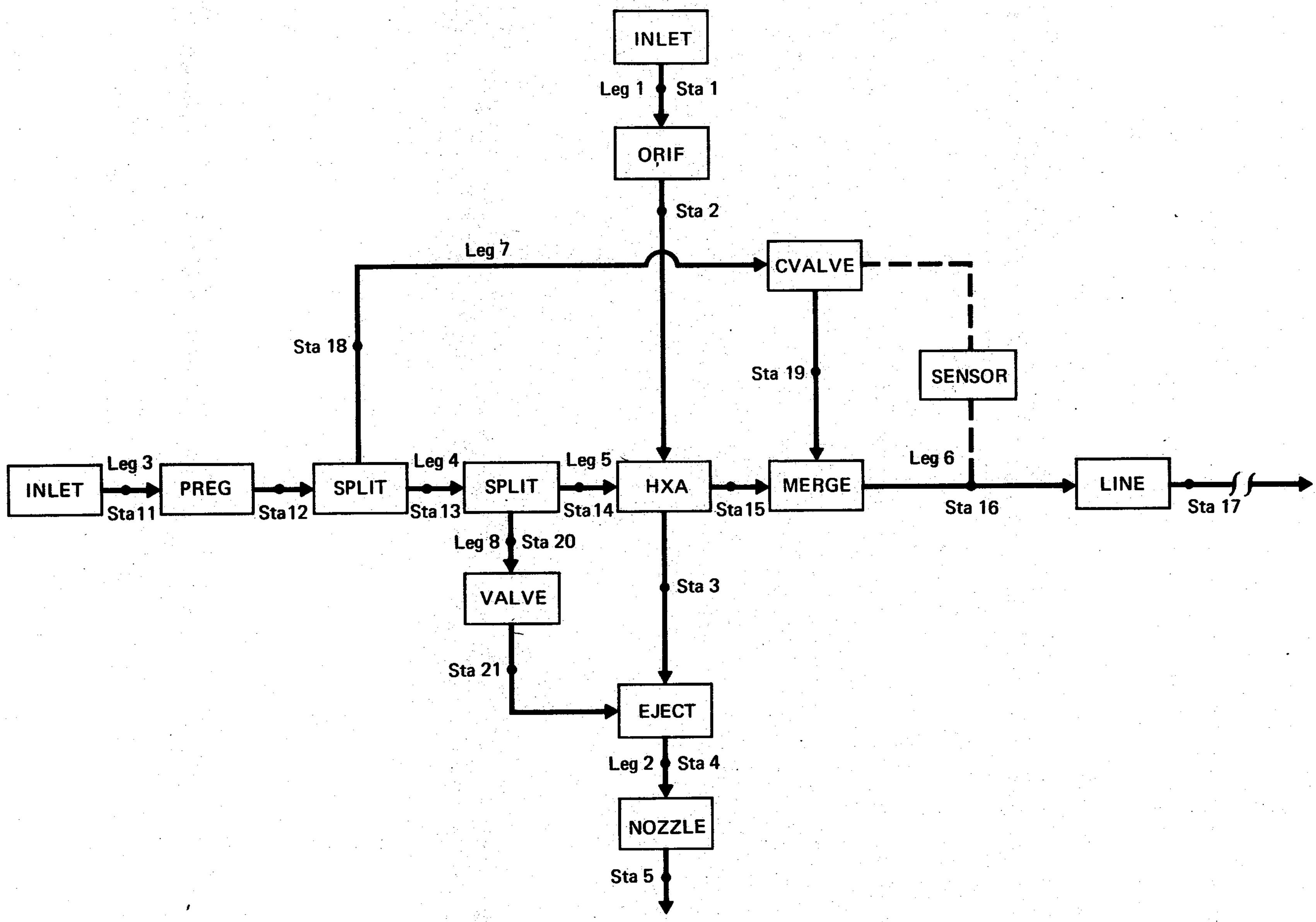

Figure 3 Computer Program Model Construction

pressure, temperature, and humidity are known, but inlet flow rate is unknown. The inlet flow rate is then specified as a state variable, and the user must provide an initial guess for its value in the parameter table. A SENSOR card will generate an error variable. If a temperature sensor were specified, a temperature error from the desired value specified by the user will be computed.

3.1.5 Performance Table Cards - The performance tables (e.g., heat exchanger effectiveness map) can be input in one of three ways. The first is directly by cards (temporary table). The first card of a temporary table (TABID) identifies the table. The second card (TABT) provides a table title. The following cards (TABV) specify the table values. The second table input method is by the permanent table tape. This tape contains tables previously loaded by the program for use in any case. The user inputs a data card (PTAB) specifying which permanent table is to be used. The third table input method is the same table option. This option specifies that tables be shared. The user inputs a data card (STAB) specifying which two tables are to share the same values.

Any table specified by the user can be one to three dimensional. The independent variables are selected by the user. Interpolation can be selected as linear or logarithmic and from zero to seventh order. The user can specify extrapolation or no extrapolation.

3.2 Sizing Case Input

The user can run a sizing case to size individual components or to size an entire system. Using the results from a performance case, the user can input the sizing data as described below.

3.2.1 Sizing Title Cards - The title cards are similar to those of a performance case described in Section 3.1.1.

3.2.2 Sizing Case Specification Cards - The case specification cards contain the printout options, system total size option, and the system penalty option. They also contain factors used to compute the system penalties. Calculation of these penalties is related to the aircraft in which the ECS is used. The user therefore specifies the aircraft weight (without an ECS), its drag, its fuel weight, the engine specific fuel consumption penalties due to bleed air and power extraction, the engine power used by other systems, the engine thrust, and its flight time.

3.2.3 Sizing Parameter Table Cards - The parameter table cards are similar to those of a performance case described in Section 3.1.3.

3.2.4 Sizing Components Cards - The component cards specify what components in the system are to be sized. The order of the cards in most cases is immaterial. The sizing component cards are discussed alphabetically, according to their component names. In general, the weight flows, pressures, temperatures, and humidities are obtained by specifying appropriate leg and station numbers. The component for controls (CNTRL) and insulation (INSLTN) are exceptions. The shaft number is specified for all rotating components. Optional weight, cost unit, and development risk factor multipliers; and reliability indices may be specified. The basic information for these four items is discussed in Volume I.

APU - This component is used to size an APU which provides shaft power or bleed air, or both. The equivalent horsepower required by other systems is input by the user.

BOIL - This component is used to size water boilers. The water density (at boiling temperature) and heat of vaporization are inputs. The boiler can be sized to include water storage provisions (i.e., separate storage tank, or tank and boiler), in which case the boiler usage time and extra (or ullage) water weight must be specified. The user also specifies heat transfer surface characteristics (i.e., material, friction factor and Colburn modulus data). Typical fin characteristics (presented in Volume I) and material properties are available on the permanent table tape, or may be specified by the user.

CNTRL - This component is used to size several types of ECS controls. For electronic temperature controls the user specifies the type of aircraft in which it is to be used, a technical weighting factor (e.g., greater than 1.0 if complex), a requirements weighting factor (e.g., greater than 1.0 if BITE is used), use of a selector, the number of sensors being used, and the number of input and output (NIAO) signals of the control. For pneumatic temperature controls the user specifies the technical and requirements weighting factors, and the diameter of the valve being controlled. For cabin pressure controllers typically used in cargo and heavy bomber aircraft, the user specifies if a thrust recovery valve is used. Cabin pressure controllers in fighter and light bomber aircraft normally do not include a thrust recovery valve. Controls for water separator anti-icing and for vapor cycles are specified in the same manner as temperature controls.

COMP - This component is used to size air compressors. This includes air compressors (or fans) in the turbomachines of simple and bootstrap air cycles, and auxiliary or boost compressors. The user selects the compressor type (i.e., centrifugal or low pressure ratio). Centrifugal compressors typically are used for bootstrap and some simple air cycle turbomachines, and auxiliary and boost compressors. Low pressure ratio compressors are used for some simple air cycle systems and as the fan of simple-bootstrap air cycle turbomachines. Specific speed versus specific diameter tables for these two compressor types are available on the permanent table tape, or may be specified by the user. The user also specifies the type of compressor drive (or no drive, if it is part of the air cycle turbomachine) to be used. Auxiliary or boost compressors for existing aircraft are driven from the jet engine shaft or by hydraulic motors.

COND - This component is used to size vapor cycle condensers. Heat transfer surface characteristics (i.e., material, friction factor and Colburn modulus data) are specified using the permanent table tape, or the characteristics can be input by the user. A typical refrigerant side fin geometry is: 16R(S) - 0.10 - 1/8(0) - 0.006.

DSEP - This component is used to size a static (filter) or self-cleaning dust separator. The separator type is defined by the user.

EHTR - This component is used to size an electric heater. The user specifies the fluid heat transfer surface characteristics (i.e., friction factor and Colburn modulus data) from the permanent table tape or provides his own. A typical air side fin geometry is: 16.96T(D) - 0.126/0.125 - (P) - 0.006.

EJECT - This component is used to size an ejector with its mixing tube. The user must specify the material to be used and the mixing tube wall thickness. A typical mixing tube wall thickness is 0.224 inch.

EVAP - This component is used to size vapor cycle evaporators. Heat transfer surface characteristics (i.e., material, friction factor and Colburn modulus data) are specified using the permanent table tape, or the characteristics may be input by the user. A typical refrigerant side fin geometry is: 16R(S) - 0.10 - 1/8(0) - 0.006.

FAN - This component is used to size fans that circulate air between compartments or to provide cooling air during static operations. The user specifies the type of fan drive (i.e., a.c. or d.c. electic motor, hydraulic motor, or axial flow (tip) air turbine) and the rotational speed. If an axial flow air turbine is specified the turbine inlet and outlet flow properties and general characteristics (i.e., specific speed versus specific diameter tables) are input. A typical set of these characteristics is available on the permanent table tape.

HX - This component is used to size single phase heat exchangers. The user specifies the heat transfer surface characteristics (i.e., material friction factor and Colburn modulus data) using the typical data on the permanent table tape or his own data. He can specify the single pass unmixed heat exchanger effectiveness versus NTU (from the permanent table tape) or his own (e.g., see Reference 3), including multiple pass designs with mixed or unmixed flow. The user also defines the complexity of the headers on the heat exchanger being sized.

INIT - This is used to input initialization data for system components not being sized (e.g., a known system to which additions or modifications are being made or known components that have been previously sized.) The weights input with these cards are installed values.

INSLTN - This component is used to size insulation for ducting and compartments. Insulation for bleed air ducting can be specified as air gap radiation shield, removable blanket (most common), or integral blanket types. Insulation for conditioned air distribution ducting can be specified as removable blanket (common) or integral blanket types. Compartment insulation types are blanket insulations (with covering) with or without an air gap on the external side. Use of the air gap is useful for higher speed aircraft. Typical blanket conductivities are available on the permanent table tape, or they can be input by the user. Ducting temperature can be specified or the fluid temperature in the duct or line may be used.

LINE - This component is used to size lines (ducting) for high pressure bleed air and pneumatic controls, low pressure lines for conditioned air and ram air, and liquid coolant lines (vapor cycle lines are part of the VCOMP subroutine). Line length must be input. Line diameter and wall thickness are optional inputs. If the line diameter is not specified, friction factor and bend loss,or an effective friction factor (for rough sizing) is input. (A diameter then is calculated.)

MISC - This is used to transfer miscellaneous data, or for modifying input data or results. For example, condenser and evaporator core volume is used in sizing the refrigerant receiver for a vapor cycle compressor.

PUMP - This component is used to size a liquid coolant pump package. The pump may be a vane, gear, or centrifugal type rotor, driven by an electrical motor. The user specifies the drive rotational speed. The pump package includes a filter, reservoir (total liquid coolant volume is input or obtained from MISC), and miscellaneous lines, relief valves, and connectors normally provided as an integral pump package.

RIN - This component is used to size a ram air inlet and diffuser. The user specifies the inlet type (i.e., flush, scoop, nose, and engine duct). Density of the material used for the inlet and an effective wall thickness are specified (e.g., a typical effective thickness is 0.36 inch). Input of the inlet area (if known) is optional. Static pressure and static temperature into the inlet and at its throat area must be input. (See example in Section 5.1.)

ROUT - This component is used to size a ram air outlet. The density of the material used for the outlet and its wall thickness (a typical thickness is 0.27 inch) are input by the user. The outlet area or the outlet discharge coefficient (for rough sizing) also must be specified.

TURB - This component is used to size a turbine. This includes turbines used as part of an air cycle turbomachine and power turbines (pneumatic drives). Centrifugal or axial type turbines may be specified (centrifugal types are most common in air cycle turbomachines). Specific speed versus specific diameter tables for these types are available on the permanent table tape, or may be input by the user.

VALVE - This component is used to size valves. Types included are pneumatic or electric operated butterfly valves, poppet valves, and check valves.

VCOMP - This component is used to size a vapor cycle compressor package. The compressor may be driven by an electric motor (most common), hydraulic motor, or air turbine. The package includes typical refrigerant lines, a throttling valve, fittings, and disconnects in the package, as well as the refrigerant charge and a receiver. The refrigerant charge and receiver weight are related to the refrigerant volume, hence the evaporator and condensor core volumes are input (if known) or obtained from MISC.

3.2.5 Sizing Table Cards - The table cards are similar to those of a performance case described in Section 3.1.5.

3.3 Dummy Performance Case

The computer program user may directly specify performance data for which he wants components and a system sized. In this case a dummy performance case is run, and the information is passed to a sizing case. A dummy performance case is input starting with a case control card (PDUMMY). Following this card are the leg cards (LEG) specifying the flow rates, and the station cards (STA) specifying the pressures, temperatures, and humidities. The input is ended by a case end card (ENDCASE).

SECTION 4

PROGRAM RESULTS

The program results printed on the output for a performance or sizing case may be separated into two classes: 1) output which is always given, and 2) output which the user may optionally select. The title cards input by the user will always be printed. The remaining input data groups may be optionally printed. Error messages will be written on the output if any errors are detected in the input processing or solution. Warning messages (e.g., a table was extrapolated past its input range) will be printed on the output. Solution results for a performance or sizing case also may be written on the output as explained below.

4.1 Performance Case Output

Output from a performance case always includes the system performance (i.e., flow rates in all legs; and temperatures, pressures, and humidities at all stations). Optional output is the component performance data (flow rates, temperatures, pressures, and humidities) and other performance information pertinent to the specific component. The other performance information is presented in the following paragraphs (alphabetically according to component name). Warning messages may be output as appropriate.

APU - Output for this APU component includes the bleed air pressure ratio and polytropic efficiency, or shaft horsepower, or both, as appropriate.

BOILER - Output for this boiler component includes the boiling temperature, the boiler effectiveness, the heat removal rate, and the rate at which fluid is removed.

CNNCT - There is no output.

COMP - Output for this air compressor component includes its pressure ratio, adiabatic efficiency, and power requirement.

COND - Output for this vapor cycle condenser component includes its effectiveness and the heat transferred.

CVALVE - Output for this control valve component includes its pressure loss coefficient.

DRAIN - Output for this drain component includes the drain efficiency.

DSEP - There is no additional output for this dust separator component..

EJECT - Output for this ejector component includes the primary and secondary pressure ratios, and the weight flow ratio.

EVAP - Output for this vapor cycle evaporator component includes its effectiveness and the heat transferred.

FAN - Output for this fan component includes the volumetric flow rate (cfm), the static efficiency, and the power required to drive the fan.

HXA - Output for this heat exchanger component includes the temperature effectiveness of each side of the heat exchanger.

HXB - Output for this heat exchanger component includes the temperature effectiveness of each side of the heat exchanger.

INJECT - There is no additional output for this water injector component.

INLET - There is no output.

LINE - Output for this line component includes heat lost or gained by the line. If the diameter or cross sectional area has been specified, the output will include velocity and Mach number.

LOOP - There is no additional output.

MERGE - There is no additional output.

MISC - The output is the result of the mathematical calculations specified as input.

NOZZLE - Output for this nozzle component includes its pressure ratio.

ORIF - Output for this orifice component includes its pressure ratio.

OUTLET - There is no output.

PREG - There is no additional output for this pressure regulator component.

PUMP - Output for this liquid pump component includes the volumetric flow (gpm), the static efficiency, and the power required to drive the pump.

QLOAD - Output for heat load includes the heat load.

SENSOR - There is no output.

SHAFT - The shaft speed, if specified, is output.

SPLIT - There is no output.

SPOWER - The power balance, if not specified as zero, is output.

TURB - Output for this air turbine component includes its pressure ratio, adiabatic efficiency, and available power.

VALVE - There is no additional output for this valve component.

VCOMP - Output for this vapor cycle compressor component includes its pressure ratio, adiabatic efficiency, and power requirement.

VLINE - There is no additional output for this refrigerant (vapor cycle) line component.

WSEP - Output for this water separator component includes the efficiency.

4.2 Sizing Case Output

Output from a sizing case always includes component sizing data. The component sizing techniques are presented in Volume I. Optional outputs are system sizing, system penalties, or heat transfer equipment performance maps (as part of appropriate component output). Examples of component and system sizing outputs are presented in Section 5.

4.2.1 Component Sizing Output - All component sizing outputs contain the component weight, cost units, reliability index, and development risk factor; and component volume, and leg and station data used for the sizing analyses (if applicable). Additional output data are provided for many of the components. These are described in the following paragraphs (alphabetically according to component name). Warning messages (discussed previously) may be output when appropriate.

APU - Output for this APU component includes the shaft horsepower and fuel consumption rate due to the ECS, and the total equivalent horsepower and total weight of the APU.

BOIL - Output for this boiler component includes the dimensions of the core and its weight, the effectiveness and NTU, and the weight of water in the tank or integral boiler.

CNTRL - Output for this controller component includes the control type.

COMP - Output for this air compressor component includes the wheel diameter, the rotational speed and wheel tip speed, its specific speed and specific diameter, its adiabatic efficiency, and the fluid horsepower it requires. The reliability index of an air cycle turbomachine is output. For non-turbine drives the drive efficiency, horsepower, weight, and cost units are included in the output.

COND - Output for this vapor cycle condenser component includes the dimensions, weight, and volume of the core; the effectiveness and NTU; and the liquid volume in the heat sink side (if applicable).

DSEP - There is no additional output for the dust separator component.

EHTR - There is no additional output for this electric heater component.

EJECT - Output for this ejector component includes the total effective area of the primary nozzles.

EVAP - Output for this vapor cycle condenser component includes the dimensions, volume, and weight of the core; the effectiveness and NTU; and the liquid volume in the heat source side (if applicable).

FAN - Output for this fan component includes the tip diameter, its rotational speed, efficiency, and horsepower requirement. The drive efficiency and horsepower of the motor are included.

HX - Output for this heat exchanger component includes the dimensions, volume, and weight of the core; its effectiveness and NTU; and liquid volume on each side of the core (as applicable).

INIT - Output for initialization is the input data.

INSLTN - Output for this insulation component includes the insulation thickness.

LINE - Output for this line component includes the line diameter and wall thickness. The velocity and Mach number at the inlet of an air line, or the volume of liquid in the line are output, as applicable.

MISC - The result determined by miscellaneous is output.

PUMP - Output for this pump package component includes the pump and motor weight, reservoir weight, filter weight, rotational speed, efficiency, its horsepower requirement, and the efficiency and horsepower of the motor driving it.

RIN - Output for this ram air inlet component includes the throat and diffuser outlet areas, and the inlet drag.

ROUT - Output for this ram air outlet component includes the effective outlet area.

TURB - Output for this turbine component includes the wheel diameter, the rotational and wheel tip speed, its specific speed and specific diameter, its adiabatic efficiency, and the fluid horsepower it provides. The reliability index of an air cycle turbomachine is output under COMP.

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PENALTIES

VALVE - Output for this valve component includes diameter and pressure loss coefficient. The velocity and Mach number at the inlet of an air valve is output, as applicable.

VCOMP - Output for this vapor cycle compressor package component includes the weight of the compressor and drive, the receiver weight, the refrigerant charge weight, the line weight, the compressor rotational speed and its horsepower requirement, and the efficiency and horsepower of the motor driving it.

WSEP - There is no additional output for the water separator component.

4.2.2 System Sizing Output - System sizing output includes the system installed wet weight (including the liquid and refrigerant weight, and expendable water, as appropriate), cost units, reliability index, and development risk factor. Also output are the bleed air usage; the shaft, hydraulic, and electrical power; the drag; the equivalent engine shaft power; and fuel consumption by the APU used for the ECS. The weight error of the system weight also is output. This system weight standard error is calculated as follows:

see p. 74-77 vol IV for example

$$Wt_{dev} = \sqrt{\sum_i (\sigma_i Wt_i)^2} \qquad (2)$$

where σ_i is the standard error of each component weight (from Volume I) and Wt_i is the weight of each component.

4.2.3 System Penalty Output - System penalty outputs are the gross takeoff weight increase, payload decrease, range reduction, and equivalent drag relative to an aircraft without the ECS.

The relative gross takeoff weight increase is based on a constant range and payload (i.e., without expendables). Hence:

"XA" in fortran

$$\frac{\Delta Wt_{gr}}{Wt_{gr}} = \left(\frac{1}{1 - X_r}\right)\left(\frac{Wt_{ECS}}{Wt_{gr}}\right) + \frac{D_{ECS}}{D_r}\left[\ln\left(\frac{1}{1 - X_r}\right)\right] \qquad (3)$$

"XR"

where Wt_{ECS} is the weight of the installed wet ECS plus the weight of the power drive for the ECS, D_{ECS} is the net ECS drag plus the thrust reduction due to increased engine fuel flow required to provide bleed air and power extraction, D_r is the baseline aircraft flight drag, and X_r is the ratio of the fuel weight to the gross takeoff weight without the ECS.

The relative payload decrease is based on a constant range and gross takeoff weight (i.e., with expendables). Hence:

(IN THE FORTRAN)

"DECS" "XA" "XR" "WTT"

PSR
$$\frac{\Delta Wt_{pl}}{W_{pl,\,r}} = \frac{\frac{D_{ECS}}{D_r}\left[\ell n\left(\frac{1}{1-X_r}\right)\right](1-X_r) + \frac{Wt_{ECS}}{Wt_{gr}}}{(1-X_r) - \frac{Wt_{emp}}{Wt_{gr}}} \tag{4}$$

DRAG "XR" "WTE" "WTG"

where Wt_{emp} is the aircraft empty weight (i.e., without fuel, ECS, or payload), and Wt_{gr} is the gross takeoff weight.

The relative range reduction is based on a constant payload and gross takeoff weight (i.e., without expendables). Hence: "X" = $\ln \frac{1}{1-\frac{EWT+WTF}{WTG+WTT}}$

PSR
$$\frac{\Delta R}{R_r} = 1 - \left[\frac{SFC_r\ D_r}{SFC\ (D_r + D_{ECS}) + W_{ex}}\right]\left[\frac{\ell n\left(\frac{1}{1-X}\right)}{\ell n\left(\frac{1}{1-X_r}\right)}\right] \tag{5}$$

"XA"

where SFC_r is the specific fuel consumption without the ECS, SFC is the specific fuel consumption with the ECS, D is the net ECS drag, W_{ex} is the ECS expendable flow-rate (lbs/hr = 60 x EWT/MSNTIM), and X is the ratio of the expendable weight (including fuel) to the gross takeoff weight.

The relative equivalent drag is defined by:

PSD
$$\frac{D_{eq}}{D_r} = \frac{D_{ECS} + Wt_{ECS}/LDR_r}{D_r} \tag{6}$$

where LDR_r is the aircraft lift to drag ratio without the ECS.

SECTION 5

PROGRAM EVALUATION

The computer program was utilized to predict the performance and sizing penalties of five ECS. Rough analyses were made to predict the weights of major ECS components of one cargo, one fighter, and one bomber aircraft for comparison with data in Reference 1. These aircraft (selected by AFFDL-FEE) are the C-5A, F-111A, and B-52H. Detailed performance and sizing analyses were made for the ECS of the C-9A Aeromedical Transport and compared to actual information about the C-9A ECS. Changes were made to the interim ECS design analyses and to the computer program based on these comparisons. Detailed performance, sizing, and system penalty analyses of the laboratory demonstration test ECS are presented in Volume IV.

A rough design condition performance analysis was made for the ECS of the C-5A, F-111A, and B-52H, using References 4, 5, and 6 (respectively) to obtain additional information about these ECS. The predicted component weights were based on data obtained from these analyses and references.

Some output sheets from the IECS computer program are included in this section. The reader should refer to Volume III for a more complete understanding of these pages.

5.1 C-5A Aircraft ECS

The C-5A aircraft uses two bootstrap air cycle systems. The following brief descriptions of the operation of these systems and of some of the major components is taken from References 1 and 4.

5.1.1 C-5A ECS Operation - Bleed air is extracted from the eighth stages of the engine compressors during climb and cruise conditions, and from the final engine compressor stages during low thrust conditions. A bleed air augmenter valve provides final stage bleed air when eighth stage pressure becomes too low. The augmenter valve closes whenever final stage temperature is above 600°F. The bleed air also is used for the nacelle or wing anti-icing systems. The bleed air is ducted inboard to the two identical bootstrap air cycles systems.

A bleed air flow control and shutoff valve is located upstream of each bootstrap air cycle unit. The bleed air is cooled by a primary heat exchanger, compressed, cooled by a secondary heat exchanger, expanded and cooled by a turbine (which powers the compressor), and ducted to the loads through a water separator and mix chamber.

Temperature control is provided by mixing the water separator discharge air with hot bleed air from downstream of the flow control and shutoff valve. Hot air from the primary heat exchanger discharge is available at the water separator inlet to prevent freezing. Several hot air modulating valves are used to control the air temperature in the various heat loads. An electric motor driven fan is used to recirculate air from the cargo compartments to the mix chamber; two fans are used to circulate air over the avionics; and three fans are used to circulate air under the cargo compartment floor.

Ram air from scoops in the wing leading edges (near the wing root) is used to cool the heat exchangers. In flight this cooling air flow rate is modulated by shutters at the ram air outlet. These shutters control the bleed air exit temperature from the primary heat exchanger to 160°F or less. (See Reference 7.) At low flight speeds and on the ground a bleed air turbine driven fan provides adequate cooling air flow. When the engines are stopped on the ground, bleed air is supplied by on-board APU's.

The cabin pressure control maintains cabin altitudes not exceeding 8,000 feet up to 40,000 feet cruise altitude. In addition, it provides a selectable cabin pressure altitude range from minus 1,000 feet to plus 10,000 feet with isobaric control at the selected cabin pressure altitude up to the aircraft altitude at which cabin differential pressure of 8.2 psi is reached. Above this altitude the constant 8.2 psi differential is maintained to a limiting cabin pressure altitude of 10,000 feet.

5.1.2 C-5A ECS Components - The following descriptions of several major components are based primarily on References 1 and 4.

The primary and secondary heat exchangers are of the same plate-fin design. The primary heat exchanger is fabricated from Hastelloy X steel and the secondary heat exchanger from aluminum alloy. A single pass is used on both the bleed air and ram air sides.

The wheels of the turbine-compressor unit are radial flow designs, and each is 5.7 inches in diameter. Its maximum operating speed is approximately 55,000 rpm.

The water separator contains a perforated metal cone supporting a woven Dacron fabric coalescer bag, and an integral relief valve which allows air to bypass the coalescer bag if it becomes blocked. It has a water removal efficiency of at least 75% during sea level flight and high moisture conditions.

The cargo compartment recirculation fan operates at 11,800 rpm and circulates 90 lb/min of air. The two avionics fans operate at approximately 11,000 rpm and circulate 45 lb/min of air each. The three floor recirculation fans operate at 11,800 rpm and circulate 150 lb/min of air each.

The cabin pressure control system consists of an electronic controller which controls an electric motor actuated pressure regulator and a thrust recovery valve, and two pressure relief valves. Negative pressure relief is provided by two doors. The controller includes BITE.

5.1.3 C-5A ECS Rough Performance Analysis - The rough performance analysis for the C-5A ECS was made for the bootstrap air cycle system components at sea level, hot day conditions with 0.022 lb water per lb dry air humidity at a Mach number of 0.5. A schematic of the computer program performance analysis model is shown in Figure 4, and the computer program output of the component data cards is shown in Figure 5. A description of this setup follows.

The bleed air flow was started with INLET (Card 10) having a known flow rate of 258 lb/min (half of the total airflow at sea level hot day from Reference 1), an unknown pressure, a temperature of 600°F (approximated from data of Reference 3), and a humidity of 0.022 lb water/lb dry air. The connect (CNNCT, card 20) was used to allow for a change case if a hot air bypass, via a SPLIT card, were needed (CNNCT, card 180, would be replaced with a MERGE if hot air bypass flow were needed).

INLET card 30 started the ram air flow. It had an unknown flow rate; and known pressure, temperature, and humidity consistent with the sea level, Mach 0.5, hot day conditions. The next two ORIF cards had a constant pressure ratio based on the information in Volume I for a scoop inlet and a nominal ram air diffuser. The MISC (cards 42, 44, and 46) were used to obtain the static pressure and temperature into the diffuser section (as required for the sizing segment). SPLIT (card 60) provided an assumed 50/50 specified flow split ratio of the ram air flow to each heat exchanger. (This flow split is typical for many aircraft.)

The bleed flow through the primary heat exchanger was defined by HXA card 70. The pressure drop ($\sigma\Delta P$) on each side was 0.05 P_{in} (as suggested in Volume I). The ram air outlet of the C-5A ECS contains shutters which are controlled to maintain the bleed air temperature out of the primary

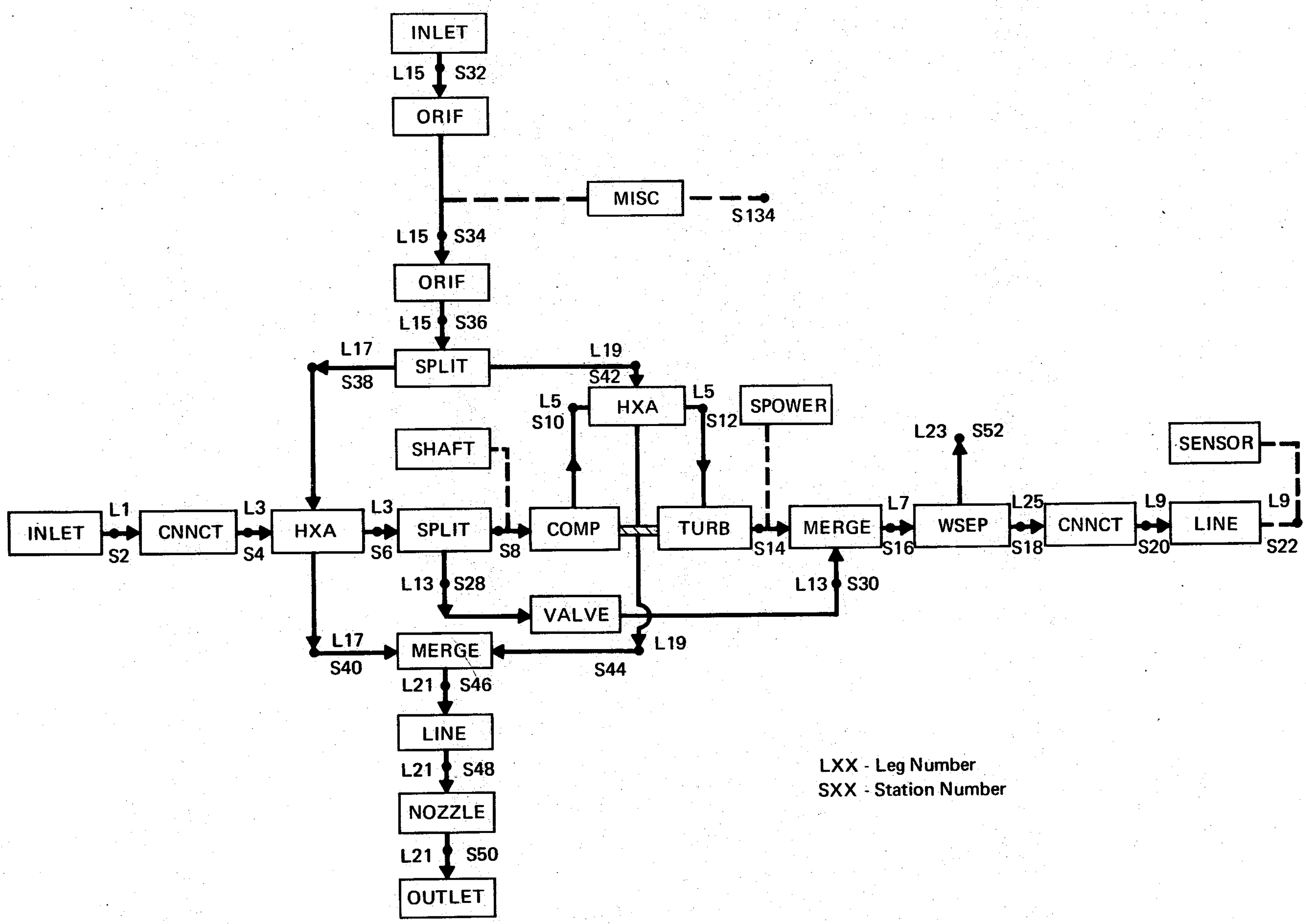

Figure 4 Schematic of C-5A ECS Performance Model

CASE C-5

COMPONENT(S)

flow known press unknown temp known humid. known

parameter tables (values for flow, temp, humid; guess for press) gas. property tables for substances types identified in col. 44

1	6	8	12	16	20	24	28	32	36	40	44	48	52	56	60	64	68	72	76	80					
INLET			10	1	2	0100	1	2	3	4	2	-1	-0	-0	-0	-0	-0	-0	-0	-0					
																					SV	N	1	T	2
CNNCT			20	1	2	3	4	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0					
INLET			30	15	32	1000	6	7	8	9	2	-1	-0	-0	-0	-0	-0	-0	-0	-0					
																					SV	N	2	T	1
ORIF			40	15	32	34	0	1	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0					
MISC			42	2	134	2	34	3	-1	27	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0					
MISC			44	3	134	3	34	3	-1	28	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0					
MISC			46	4	134	4	34	0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0					
ORIF			50	15	34	36	0	2	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0					
SPLIT			60	15	36	17	38	19	42	0	10	-0	-0	-0	-0	-0	-0	-0	-0	-0					
HXA			70	3	4	6	17	38	40	3	3	4	1	-0	-0	-0	-0	-0	-0	-0					
SPLIT			80	3	6	5	8	13	28	0	11	-0	-0	-0	-0	-0	-0	-0	-0	-0					
SHAFT			90	1	0	12	-0	-0	-0	0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0					
COMP			100	5	8	10	1	0	13	3	15	-0	-0	-0	-0	-0	-0	-0	-0	-0					
HXA			110	5	10	12	19	42	44	3	5	6	2	-0	-0	-0	-0	-0	-0	-0					
TURB			120	5	12	14	1	1	14	1	15	-0	-0	-0	-0	-0	-0	-0	-0	-0					
																					SV	N	3	T	8
SPOWER			130	1	16	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0					
																					EV	N	1	T	5
VALVE			140	13	28	30	0	0	7	-0	0	-0	-0	-0	-0	-0	-0	-0	-0	-0					
MERGE			150	5	14	13	30	7	16	0	-0	-0	0	-0	-0	-0	-0	-0	-0	-0					
WSEP			160	7	16	25	18	23	52	1	9	1	-0	-0	-0	-0	-0	-0	-0	-0					
CNNCT			180	25	16	9	20	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0					
LINE			200	9	20	22	0	0	11	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0					
SENSOR			210	2	22	18	0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0					
																					EV	N	2	T	2
MERGE			220	17	40	19	44	21	46	0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0					
LINE			230	21	46	48	0	10	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0					
NOZZLE	R		250	21	48	50	19	[illegible]	1	2	25	25	26	-0	-0	-0	-0	-0	-0	-0					
																					EV	N	3	T	1
OUTLET	R		260	21	50	0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0					
STATE/ERROR VARIABLE(S)						3																			

card leg station

1-Flow
2-press
3-temp
4-humidity
5-power
8-Press. ratio

PR table # η table # $\left[\frac{D_{throat}}{D_{line}}\right]$ D_{throat} A_{throat}

error variable = computed value - control value
set for P = 14.7

Figure 5 C-5A ECS Component Data Cards Output

heat exchanger to a maximum of 160°F. Thus, the bleed air side temperature effectiveness of the primary heat exchanger must be 0.938. The SPLIT (card 80) was available if hot anti-ice air were needed. For this case, the flow through leg 13 was specified as zero. The SHAFT (card 90) was needed to put the bootstrap cycle compressor and turbine on shaft number 1. Shaft rotational speed was not considered in this rough analysis. The compressor (COMP, card 100) had a fixed pressure ratio of 1.8, an adiabatic efficiency of 0.64, (see Volume I), and an assumed mechanical efficiency of 0.98. The secondary heat exchanger pressure drops ($\sigma\Delta P$) also were 0.05 P_{in}, and its bleed air side temperature effectiveness was assumed to be 0.9 (higher than suggested in Volume I since the primary heat exchanger effectiveness is large). The turbine (TURB, card 120) had an unspecified pressure ratio and an adiabatic efficiency of 0.76 (from Volume I). SPOWER (card 130) balanced the power between the compressor and turbine.

The anti-ice control VALVE (card 140) was not used in this case, hence its pressure drop was set equal to its inlet pressure. Its outlet was merged to the turbine outlet with card 150. The water separator (WSEP, card 160) had a pressure drop ($\sigma\Delta P$) of 1.83 psi (from Volume I) and a water removal efficiency of 0.75 (from Reference 4). A LINE (card 200) having a length of 50 feet and a Mach number of 0.05 was provided between the water separator and load. SENSOR (card 210) was set at sea level pressure (14.7 psia) to simulate cabin pressure.

The ram air flow from the two heat exchangers was merged (card 220). The LINE (card 230) to the ram outlet had a length of 3 feet with a Mach number of 0.15 (hence the $\Delta P/P_{in}$ is obtained as described in Volume I). The NOZZLE (card 250) represented the ram air outlet. It discharged to sea level pressure (14.7 psia), had a discharge coefficient of 0.8, and an adiabatic efficiency of 1.0 (not necessary for this case, hence set at 1.0). The throat diameter and diameter ratio were not used for this case, hence 0.0 was used. The outlet area can vary between 60 and 270 square inches, hence it was set equal to 270 (i.e., parameter value number 26) because a large ram air flow should be required to obtain the high heat exchanger effectivenesses. The OUTLET (card 260) was used, but was not necessary.

This C-5A ECS performance analysis had three state and error variables (SV and EV, in the right side of Figure 5). The state variables were the bleed air pressure into the primary heat exchanger (SVN1), the ram air flow rate (SVN2), and the turbine pressure ratio (SVN3). The error variables were the power balance between the compressor and turbine (EVN1), the cabin pressure (EVN2), and the nozzle flow rate (EVN3).

The system performance output of this case is shown in Figure 6. The bleed air pressure into the primary heat exchanger is seen to be 56.46 psia. The turbine pressure ratio may be calculated as 5.99 (amazingly close to the nominal 6.0 suggested in Volume I). The ram air flow rate is 2445.88 lb/min. This system performance output was used to size the components, as discussed in the next section.

5.1.4 Sizing of Major Components of the C-5A ECS - Rough sizes of the following components of the C-5A ECS were computed with the computer program sizing segment: primary heat exchanger, secondary heat exchanger, turbine-compressor unit, water separator, ram air scoop, cabin pressure control system, and fans for circulation of air in the cargo compartment, the avionics, and to the floor. The computer program calculated weights are compared to the proposed specification weights given in Reference 1.

The sizing of the primary and secondary heat exchangers was based on fin geometries suggested in Figure 42 of Volume I. For the bleed air sides this was: 24.12 R(S) - 0.075/0.075 - 1/9 (0) - 0.004, and for the ram air sides: 15.61 R(S) - 0.251/0.250 - 1/8 (0) - 0.004. The inlet and outlet air properties from Figure 6 were used. The turbine and compressor sizing were based on the output in Figure 6 and radial flow designs. At the maximum speed of 55,000 rpm a turbine efficiency of 0.76 is not on the design map (Figure 59 of Volume I). Thus a reduced speed of 40,000 rpm was used for sizing the turbine unit. The ram air scoop was assumed to be aluminum with an effective material thickness of 0.35 inch for the inlet and an effective diffuser wall thickness of 0.25 inch. The water separator was sized with the data of Figure 6. The cabin pressure control system was sized for the total airflow (for both bootstrap air cycle packages) of 615 lb/min at sea level cruise on a cold day (Reference 1). It includes Built-In-Test-Equipment (BITE). The fans were sized for the operating conditions of Section 5.1.2 at sea level.

```
CASE    C-5

FLOW RATE(S)

(   1)  258.00 (   3)  258.00 (   5)  258.00 (   7)  258.00 (   9)  254.82 (  13)    0.00
(  15) 2445.88 (  17) 1222.94 (  19) 1222.94 (  21) 2445.88 (  23)    3.18 (  25)  254.82

PRESSURE(S)

(   2)   56.46 (   4)   56.46 (   6)   55.27 (   8)   55.27 (  10)   99.48 (  12)   98.49
(  14)   16.44 (  16)   16.44 (  18)   14.86 (  20)   14.86 (  22)   14.70 (  28)   55.27
(  30)     .00 (  32)   17.43 (  34)   17.26 (  36)   17.01 (  38)   17.01 (  40)   16.11
(  42)   17.01 (  44)   16.15 (  46)   16.13 (  48)   16.03 (  50)   14.70 (  52)   14.86
( 134)   16.11

TEMPERATURE(S)

(   2) 1060.00 (   4) 1060.00 (   6)  620.06 (   8)  620.08 (  10)  796.31 (  12)  611.53
(  14)  501.37 (  16)  501.37 (  18)  500.23 (  20)  500.23 (  22)  500.10 (  28)  620.08
(  30)  620.08 (  32)  591.00 (  34)  591.00 (  36)  591.00 (  38)  591.00 (  40)  687.68
(  42)  591.00 (  44)  530.55 (  46)  659.17 (  48)  659.17 (  50)  643.14 (  52)  501.37
( 134)  579.40

HUMIDITY(S)/ENTHALPY(S)

(   2)   .0220 (   4)   .0220 (   6)   .0220 (   8)   .0220 (  10)   .0220 (  12)   .0220
(  14)   .0220 (  16)   .0220 (  18)   .0094 (  20)   .0094 (  22)   .0094 (  28)   .0220
(  30)   .0220 (  32)   .0220 (  34)   .0220 (  36)   .0220 (  38)   .0220 (  40)   .0220
(  42)   .0220 (  44)   .0220 (  46)   .0220 (  48)   .0220 (  50)   .0220 (  52)  1.0000
( 134)   .0220

STATE VARIABLE TYPE(S)
(   1)      2 (   2)      1 (   3)      8

STATE VARIABLE(S)
(   1) 5.64579E+01 (   2) 2.44538E+03 (   3) 5.98922E+00

ERROR VARIABLE TYPE(S)
(   1)      5 (   2)      2 (   3)      1

ERROR VARIABLE(S)
(   1)-5.46934E-08 (   2)-3.26057E-08 (   3)-2.64673E-05

SOLUTION CONVERGED IN      8 TRY(S)

     0 ERROR(S) DETECTED
```

Figure 6 C-5A ECS Performance Output

The computer program output for these components is shown in Figure 7. Table I compares the computer program weight calculations to weight data from Reference 1 and other sources. All C-5A data in Reference 1 are from the proposed specifications. The computer program predicted heat exchangers' total weight are less than Reference 1. Because of the high effectiveness for the primary heat exchanger it is quite heavy compared to the secondary heat exchanger. The 160°F maximum bleed air temperature from the primary heat exchanger may be relaxed in the actual system at the performance condition considered, the ram air flow split to each heat exchanger may not be 50/50 as was assumed, and a more efficient heat exchanger core fin geometry probably is used compared to the nominal suggested by Volume I. The predicted weight of the turbine (unit) is seen to be slightly heavier than the weight in Reference 1. The ram air inlet and diffuser weight is much heavier than Reference 1 scoops. (See Table I footnote.) The predicted water separator weights are lighter than the allowed weight in the proposed specifications. The cabin pressure control system weight is compared to "Reg." from Reference 1. The total weight of the fans agree well with the Reference 1 weight data.

5.2 F-111A Aircraft ECS

The F-111A aircraft uses a simple air cycle system augmented by a water boiler at high speeds, to cool the cockpit and avionics. The following brief descriptions of the operation of this system and some of the major components is taken from References 1 and 5.

5.2.1 F-111A ECS Operation - Bleed air from the sixteenth stage flows through a bleed air check and shutoff valve for each turbofan engine into a common manifold. The bleed air then flows through a pressure regulating and shutoff valve to the ram air cooled heat exchanger. From this heat exchanger the bleed air flows through a modulating valve to the water boiler, the cooling turbine, and water separator. Air for the tail equipment is taken upstream of the water separator, and air from the water separator is used to cool the cockpit and remaining equipment.

Hot air for temperature control is obtained from upstream of the pressure regulating and shutoff valve. This bleed air is mixed with bleed air from the heat exchanger. The mixed air temperature is limited to 400°F by a modulating valve in the high pressure line. This temperature controlled hot air may be added upstream of the water separator (to limit

```
COMPONENT PHX

    WEIGHT   185.35      COST UNITS   386.56     RELIABILITY INDEX 0.00256     DEVELOPMENT RISK   1.00

    W    253.00   PI    55.49   PO    55.30   TI  1060.00   TO   620.08   HI  0.0220   HO  0.0220   FT      2   FN     -1
    W   1222.92   PI    17.01   PO    16.11   TI   591.00   TO   687.69   HI  0.0220   HO  0.0220   FT      2   FN     -1
    LF     9.47   LC     6.77   LN    60.69   VOL   3905.   WTC   152.6   EFF 0.9380   NTU   3.920

COMPONENT SHX

    WEIGHT    26.59      COST UNITS    76.95     RELIABILITY INDEX 0.00256     DEVELOPMENT RISK   1.00

    W    258.00   PI    59.55   PO    58.55   TI   796.31   TO   611.53   HI  0.0220   HO  0.0220   FT      2   FN     -1
    W   1222.92   PI    17.01   PO    16.15   TI   591.00   TO   630.55   HI  0.0220   HO  0.0220   FT      2   FN     -1
    LH     5.97   LC     3.85   LN    63.70   VOL   1708.   WTC    27.6   EFF 0.9000   NTU   3.051

COMPONENT TURB

    WEIGHT    26.31      COST UNITS   144.73     RELIABILITY INDEX 0.0         DEVELOPMENT RISK   1.00

    W    255.00   PI    58.49   PO    16.44   TI   611.53   TO   501.37   HI  0.0220   HO  0.0220   FT      2   FN     -1
    D      8.11   VOL   2285.   N    40000.   EFF 0.7628    HP   271.52   U    1416.   NS   89.41   DS    1.42

COMPONENT COMP

    WEIGHT    13.24      COST UNITS    73.35     RELIABILITY INDEX 0.06793     DEVELOPMENT RISK   1.22

    W    258.00   PI    55.27   PO    59.48   TI   620.08   TO   796.31   HI  0.0220   HO  0.0220   FT      2   FN     -1
    D      5.76   VOL    742.   N    40000.   EFF 0.6359    HP  -259.79   U    1008.   NS   95.99   DS    1.38
    DRIVE     1

COMPONENT RIN

    WEIGHT   103.46      COST UNITS   326.35     RELIABILITY INDEX 0.00010     DEVELOPMENT RISK   1.00

    W   2445.84   PI    14.70   PO    16.11   TI   563.00   TO   579.47   HI  0.0220   HO  0.0220   FT      2   FN     -1
    AI    179.2   AC    461.4   VOL  17976.   DRAG  735.5

COMPONENT WSEP

    WEIGHT    24.15      COST UNITS    69.35     RELIABILITY INDEX 0.00285     DEVELOPMENT RISK   1.00

    W    258.00   PI    16.44   PO    14.86   TI   501.37   TO   500.23   HI  0.0220   HO  0.0094   FT      2   FN     -1
    VOL   2744.
```

Figure 7 C-5A ECS Component Sizing Output

```
COMPONENT CNTRL
     WEIGHT  112.03     COST UNITS 1935.20     RELIABILITY INDEX 0.24448     DEVELOPMENT RISK  1.00
     TYPE     5   VOL  10631.

COMPONENT FAN
     WEIGHT    15.92      COST UNITS    21.61      RELIABILITY INDEX 0.00546     DEVELOPMENT RISK  1.00
     W    90.00   PI    14.82   PO    15.12   TI   530.00   TO   535.07   HI  0.0100   HO  0.0100   FT      2   FN     -1
     C     7.83   VOL    623.   N   11800.   EFF 0.5999   HP     2.58
     DRIVE    2   EFF 0.7763   HP     3.33
COMPONENT FAN
     WEIGHT    11.04      COST UNITS    19.37      RELIABILITY INDEX 0.00546     DEVELOPMENT RISK  1.00
     W    45.00   PI    14.32   PO    14.82   TI   551.00   TO   560.05   HI  0.0100   HO  0.0100   FT      2   FN     -1
     C     6.52   VOL    359.   N   11000.   EFF 0.5990   HP     2.31
     DRIVE    2   EFF 0.7692   HP     3.00
COMPONENT FAN
     WEIGHT    22.38      COST UNITS    24.59      RELIABILITY INDEX 0.00546     DEVELOPMENT RISK  1.00
     W   150.00   PI    14.82   PO    15.12   TI   530.00   TO   535.07   HI  0.0100   HO  0.0100   FT      2   FN     -1
     C     9.28   VOL   1038.   N   11800.   EFF 0.5999   HP     4.30
     DRIVE    2   EFF 0.7965   HP     5.40
```

Figure 7 C-5A ECS Component Sizing Output (Continued)

TABLE I
C-5A ECS WEIGHT SUMMARY

Component	Weight - Lb	
	Reference 1	Computer Program*
Primary Heat Exchanger		185.85**
Secondary Heat Exchanger		36.99
Heat Exchangers (4)	551	(445.68 ± 53.48)
Turbine		26.31
Compressor		13.34
Turbine (Unit)	72****	(79.30 ± 9.67 for 2)
Ram Air Inlet and Diffuser		103.46
Scoops	40****	***
Water Separator	60****	24.15
		(48.30 ± 8.36 for 2)
Cabin Pressure Control		112.03 (± 26.89)
Reg.	172	
Fan, Cargo Recirculation		15.92
Fan, Avionics (2)		22.08
Fan, Floor (3)		67.14
Fans	100	(98.14 ± 24.54 for 6)

*Tolerances based on standard errors in Volume I.

**High weight to obtain effectiveness of 0.938.

***Reference 1 apparently does not include diffuser, whereas the computer program includes a diffuser.

****It is assumed that the Reference 1 weight is for two items.

the temperature downstream of the water separator to a minimum of -65°F, this was later changed to +35°F) and to the cockpit distribution ducting. The hot air for the cockpit temperature control is added downstream of the minimum upstream pressure regulating valve. A cooling demand for cockpit temperature control first closes a modulating valve in the hot air line, and then opens a modulating valve in the cold air flow line to the water boiler. A heating demand closes the modulating valve upstream of the water boiler to a minimum flow rate, then the modulating valve in the hot air line is opened. The minimum upstream pressure regulating valve controls its upstream pressure to 12.0 psia or 1.10 psi above cockpit pressure (whichever is the greater absolute value) whenever cockpit pressure falls below 4.5 psig. The cockpit pressure approximately follows aircraft altitude to 8000 feet, and is held constant above this altitude. During combat (switch by pilot) a 5 psi differential is maintained above 23,000 feet.

Ram air to cool the bleed air in the heat exchanger is taken from the boundary layer on both sides of the aircraft. Part of the cooling air leaving the heat exchanger is compressed by the compressor, thus loading the cooling turbine. The compressed cooling air is routed out the ram air ejector located downstream of the heat exchanger in the cooling air circuit. This ejector thus loads the compressor and also induces some flow through the heat exchanger. Air flow to the compressor also can be taken directly from the boundary layer to achieve a higher (more efficient) turbine speed. A bleed air ejector is located downstream of the ram air ejector. It uses bleed air from upstream of the pressure regulator, and operates only when the rain removal or windshield wash systems are operating. The ram air exit contains a door (on later models) to control the flow under certain conditions.

5.2.2 F-111A ECS Components - The following descriptions of several components are based primarily on References 1 and 5.

The bleed air check and shutoff valve is designed for the maximum temperature and pressure from the sixteenth stage of the engine compressor. It is a 2 1/2 inch diameter pneumatically operated poppet valve.

The heat exchanger is a steel plate fin design. The bleed air is routed through two sections - one for air used to cool the cockpit and equipment, and the other for auxiliary air (e.g., fuel tank pressurization, pressure suit, etc.). The ram air makes one pass through the heat exchanger. The compressor and bleed air ejectors are installed in the cooling air outlet headers of this unit.

The water boiler consists of stainless steel dimpled tubular passages immersed in a water tank. The hot air makes one pass through the boiler. The tank holds 22 1/2 gallons of water. Auxiliary air also passes through dimpled tubular passages in the tank.

The wheels of the turbine-compressor unit are radial flow designs. Bearings are lubricated by oil. The unit includes a butterfly valve (diameter about 4.5 inches) to select ram air from the boundary layer or from the heat exchanger for the compressor.

The water separator contains a removable coalescer assembly and a bypass valve (which opens at 6.4 psi). It removes approximately 80% of the inlet entrained moisture.

Cockpit air temperature is selectable and controlled electronically. The controller receives inputs from seven sensors, and provides signals to three electric motor controlled valves. It includes BITE.

The hot air temperature control valve in the high pressure bleed air line is 3 inches in diameter. It is an electric or pneumatic actuated butterfly valve. The bleed air ejector shutoff valve, which is 1 1/2 inches diameter, is an electro-pneumatic poppet design.

5.2.3 F-111A ECS Rough Performance Analysis - The rough performance analysis for the F-111A ECS was made for the simple air cycle system (with water boiler) at 60,000 feet altitude, Mach number 2.5 for standard day ambient conditions (i.e., no humidity). A short analysis which included humidity was made for the water separator at sea level. A schematic of the computer program performance analysis model is shown in Figure 8, and the computer program output of the component data cards is shown in Figure 9. A description of this setup follows.

The bleed air flow was started with INLET (card 10) having a known flow rate of 78.1 lb/min, an unknown pressure, a temperature of 1067°F (from Reference 5), and no humidity. The bleed air flow rate was based on the maximum heat loads of Reference 1, plus 5 lb/min allowed for pressurization of auxiliary subsystems (e.g., suits, fuel tank, etc.). A temperature rise of approximately 120°F was allowed for the electronic equipment

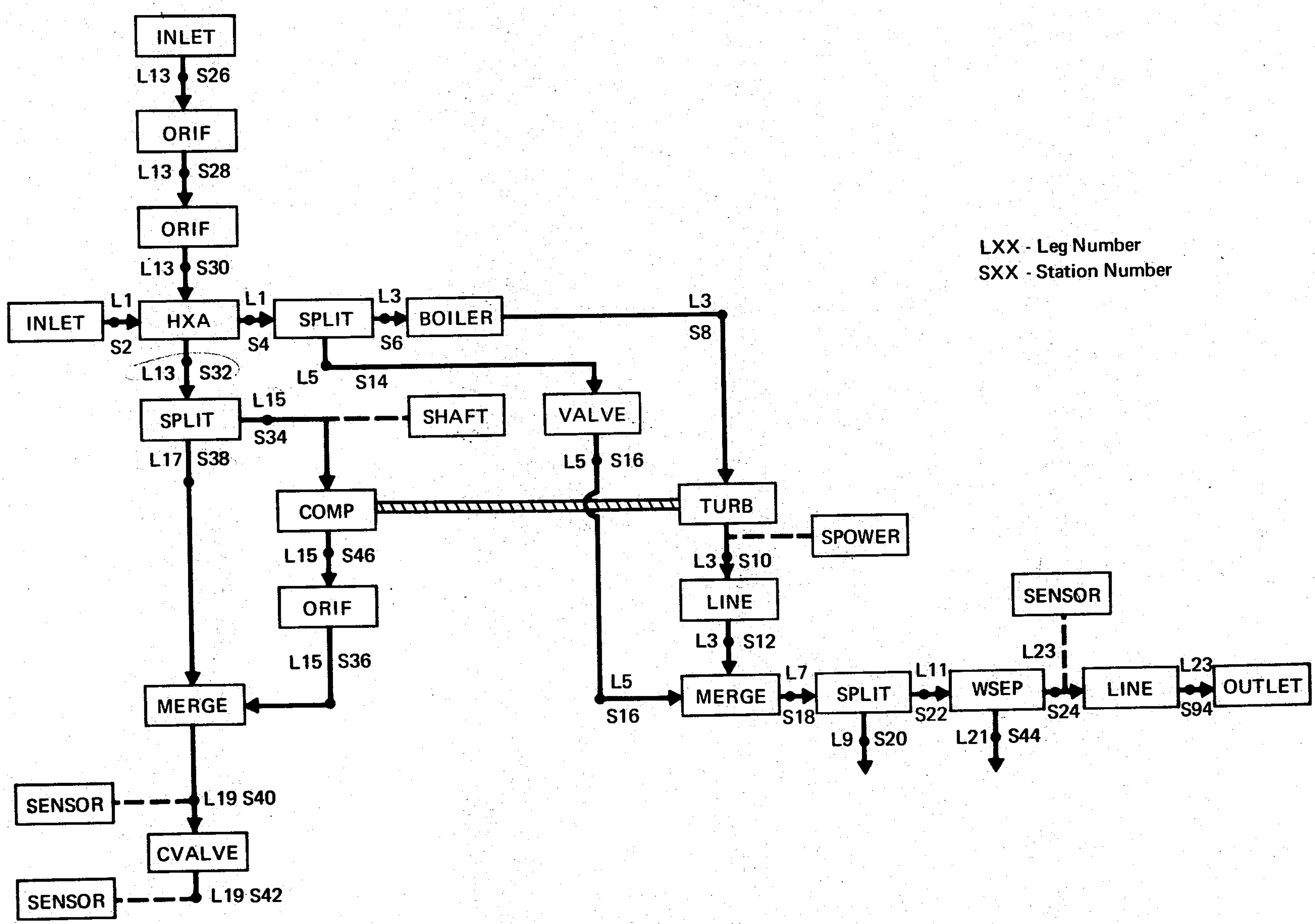

Figure 8 Schematic of F-111A ECS Performance Model

CASE F111A

COMPONENT(S)

1 6 8	12	16	20	24	28	32	36	40	44	48	52	56	60	64	68	72	76	80		
INLET	10	1	2	100	1	2	3	4	2	-1	0	0	0	0	0	0	0	0	SV N 1 T 2	PRESS INLET
INLET	20	13	26	1000	5	6	7	4	2	-1	0	0	0	0	0	0	0	0	SV N 2 T 1	FLOW INLET
CRIF	30	13	26	28	0	1	0	0	0	0	0	0	0	0	0	0	0	0		
CRIF	40	13	28	30	0	2	0	0	0	0	0	0	0	0	0	0	0	0		
HXA	50	1	2	4	13	30	32	3	3	4	1	0	0	0	0	0	0	0		
SPLIT	60	13	32	15	34	17	38	1	8	0	0	0	0	0	0	0	0	0	SV N 3 T 5	FLOW SPLIT TO COMP
SHAFT	70	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
COMP	80	15	34	46	1	0	9	3	10	0	0	0	0	0	0	0	0	0		
CRIF	85	15	46	36	0	10	0	0	0	0	0	0	0	0	0	0	0	0		
MERGE	90	15	36	17	38	19	40	0	0	0	0	0	0	0	0	0	0	0		
SENSOR	91	3	40	29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	EV N 1 T 3	RAM OUTLET TEMP
CVALVE	95	19	40	42	0	27	28	0	0	0	0	0	0	0	0	0	0	0	SV N 4 T 6	PRES LOSS COEF
SENSOR	96	2	42	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	EV N 2 T 2	AMB PRESS
SPLIT	110	1	4	3	6	5	14	0	12	0	0	0	0	0	0	0	0	0		
BOILER	120	3	6	8	1	5	13	2	14	0	0	0	0	0	0	0	0	0		
TURB	130	3	8	10	1	0	15	1	10	0	0	0	0	0	0	0	0	0		
SPOWER	140	1	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	EV N 3 T 5	POWER BALANCE COMP + TURB
LINE	150	3	10	12	0	0	6	0	0	0	0	0	0	0	0	0	0	0		
VALVE	160	5	14	16	0	0	7	0	0	0	0	0	0	0	0	0	0	0		
MERGE	170	3	12	5	16	7	18	0	0	0	0	0	0	0	0	0	0	0		
SPLIT	180	7	18	9	20	11	22	0	17	0	0	0	0	0	0	0	0	0		
WSEP	200	11	22	23	24	21	44	1	8	2	0	0	0	0	0	0	0	0		
SENSOR	210	2	24	19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	EV N 4 T 2	PRESS AFTER WATER SEP

STATE/ERROR VARIABLE(S) 4

Figure 9 F-111A ECS Component Data Cards Output

and weapons bay, and approximately 80°F rise for the cabin and cabin electronic equipment to obtain the flow rate.

The ram air INLET (card 20) used an unknown flow rate, and known total pressure and temperature consistent with the Mach 2.5 speed at 60,000 feet. The ORIF component (card 30) was used for a typical flush ram air inlet pressure ratio (actually boundary layer bleed) and ram diffuser (card 40), as described in Volume I. The heat exchanger pressure drop ($\sigma\Delta P$) was 0.05 P_{in} and its bleed air side temperature effectiveness was 0.8. (See Volume I.) From the heat exchanger part of the ram air circuit, flow was SPLIT (card 60) for an unspecified flow through the compressor. After the SHAFT (card 70), the compressor (COMP, card 80) was inserted. It had a pressure ratio of 1.8 and an adiabatic efficiency of 0.64 (from Volume I). The ORIF (card 85) pressure ratio was 1/1.8, thus insuring a pressure balance at MERGE (card 90). The SENSOR (card 91) was set at a temperature of 800°F which is typical of a ram air exit temperature for a supersonic fighter aircraft. The control valve (CVALVE, card 95) simulated the pressure drop across the ram air outlet to the ambient pressure of 1.05 psia as determined by SENSOR (card 96).

SPLIT (card 110) provided for flow of hot air to the MERGE (card 170) for temperature control. A full cold case was analyzed, hence the flow in leg 5 was zero, and the pressure drop across VALVE (card 160) was set equal to its inlet pressure. The BOILER (card 120) air pressure drop ($\sigma\Delta P$) was 0.05 P_{in}, its water boiling temperature was set at 110°F (i.e., slightly above that of the ambient pressure of 1.05 psia) with an evaporation enthalpy of 1030 Btu/lb, and its temperature effectiveness was assumed to be 0.95 (as discussed in Volume I). The turbine (TURB, card 130) had a fixed pressure ratio of 6.0, an adiabatic efficiency of 0.76, and an assumed mechanical efficiency of 0.98. Following SPOWER (card 140), a LINE (card 150) having a $\Delta P/P$ of 0.004 was used. The SPLIT (card 180) would provide for cooling air to equipment before the water separator, but in this case leg 9 had no flow. The water separator (WSEP, card 200) had a typical low, dry pressure drop ($\sigma\Delta P$) of 0.825 psi (from Volume I) and its efficiency was not needed (although an efficiency table is needed and is indicated). The SENSOR was set at 12.0 psia, which is the maximum pressure downstream of the water separator, as regulated by the minimum upstream pressure regulating valve, when cabin pressure is less than 4.5 psia (Reference 5). The line and outlet shown in leg 23 of Figure 8 were used for the short wet analysis discussed in a later paragraph.

This F-111A ECS performance analysis had four state and error variables. The state variables were the bleed air pressure into the heat exchanger (SVN1), and the ram air flow rate (SVN2), the flow split to the compressor (SVN3), and the control valve pressure loss coefficient (SVN4). The error variables were the ram air outlet temperature (EVN1), ambient pressure (EVN2), power balance between the compressor and turbine (EVN3), and pressure downstream of the water separator (EVN4).

The system performance output of this case is shown in Figure 10. The bleed air pressure into the heat exchanger is seen to be 79.86 psia. The ram air flow rate is 148.15 lb/min, with 39.59 lb/min air flow through the compressor. This system performance is used in the sizing section as described in the next section.

A short analysis with humidity included was made for the water separator. (See Figure 11.) An INLET (card 5) was used to start the component data card list. It had an unknown pressure and temperature upstream of the water separator, and an assumed humidity of 0.022 lb water/lb dry air and flow rate of 78.1 lb/min. The water separator (WSEP, card 10) efficiency for removing entrained water was 0.80 (Reference 5) and its pressure drop ($\sigma\Delta P$) was 1.83 psia (low pressure drop for wet separators as discussed in Volume I). The SENSOR (card 25) was defined as 36°F (i.e., 1°F above the 35°F sensor located downstream of the suit heat exchanger shown in Reference 5). The LINE pressure drop was approximately 10% of the water separator outlet pressure to allow for losses in the ducting and valves between the water separator and cabin. The OUTLET (card 20) had a specified pressure of 14.70 to represent cabin pressure at a sea level flight condition.

The upper portion of Figure 11 shows two state variables - the inlet pressure and temperature. These were balanced by the SENSOR temperature and OUTLET pressure error variables. Note the warning message regarding the incorrect component data card sequence, which did not affect this case. The results (lower half of Figure 11) show the pressure into the water separator was 17.80 psia and the temperature was 496.83°R. The water separator removes 1.00 lb water/min. These data were used in sizing the F-111A water separator.

5.2.4 Sizing of Major Components of the F-111A ECS - Rough sizes of the following components of the F-111A ECS were computed with the computer program sizing segment: air cycle machine with compressor diverter valve,

USED FOR SIZING

```
CASE  F111A

FLOW RATE(S)
(  1)   78.10 (  3)   78.10 (  5)    0.0  (  7)   78.10 (  9)    0.0  ( 11)   78.10
( 13)  148.15 ( 15)   39.59 ( 17)  108.56 ( 19)  148.15 ( 21)    0.0  ( 23)   78.10
PRESSURE(S)

(  2)   79.88 (  4)   78.07 (  6)   78.07 (  8)   76.84 ( 10)   12.81 ( 12)   12.76
( 14)   78.07 ( 16)    0.00 ( 18)   12.76 ( 20)   12.76 ( 22)   12.76 ( 24)   12.00
( 26)   17.90 ( 28)    6.18 ( 30)    5.98 ( 32)    4.53 ( 34)    4.53 ( 36)    4.53
( 38)    4.53 ( 40)    4.53 ( 42)    1.05 ( 44)   12.00 ( 46)    8.15

TEMPERATURE(S)

(  2) 1527.00 (  4) 1009.40 (  6) 1009.40 (  8)  591.97 ( 10)  412.19 ( 12)  412.19
( 14) 1009.40 ( 16) 1009.40 ( 18)  412.19 ( 20)  412.19 ( 22)  412.19 ( 24)  412.19
( 26)  880.00 ( 28)  880.00 ( 30)  880.00 ( 32) 1173.26 ( 34) 1173.26 ( 36) 1489.06
( 38) 1173.26 ( 40) 1260.00 ( 42) 1260.00 ( 44)  412.19 ( 46) 1489.06

HUMIDITY(S)

(  2) 0.0     (  4) 0.0     (  6) 0.0     (  8) 0.0     ( 10) 0.0     ( 12) 0.0
( 14) 0.0     ( 16) 0.0     ( 18) 0.0     ( 20) 0.0     ( 22) 0.0     ( 24) 0.0
( 26) 0.0     ( 28) 0.0     ( 30) 0.0     ( 32) 0.0     ( 34) 0.0     ( 36) 0.0
( 38) 0.0     ( 40) 0.0     ( 42) 0.0     ( 44) 1.00000 ( 46) 0.0

STATE VARIABLE TYPE(S)
(  1)    2 (  2)    1 (  3)    5 (  4)    6

STATE VARIABLE(S)
(  1) 7.98623E 01 (  2) 1.48150E 02 (  3) 2.67218E-01 (  4) 1.58579E-04

ERROR VARIABLE TYPE(S)
(  1)    3 (  2)    2 (  3)    5 (  4)    2

ERROR VARIABLE(S)
(  1)-7.32422E-04 (  2)-5.21660E-04 (  3)-2.74658E-03 (  4) 6.25610E-04

SOLUTION CONVERGED IN     9 TRY(S)

     0 ERROR(S) DETECTED
```

MIX; WS; RAM IN; COMP; RAM OUT; BLEED PRES; RAM FLOW; SPLIT FLOW TO COMP; PRES LOSS COEF CHANGE; RAM OUTLET TEMP; HX 2 PRESS; POWER BAL COMP + TURB; PRES OUT WS

Figure 10 F-111A ECS Performance Output

```
      CASE F111WSEP

COMPONENT(S)

  1    6  8   12   16   20   24   28   32   36   40   44   48   52   56   60   64   68   72   76   80
_________________________________________________________________________________________________________
    INLET          5   11   22  110    1    2    3    4    2   -1   -0   -0   -0   -0   -0   -0   -0   -0
                                                                                                       SV N   1  T   2  PRES
                                                                                                       SV N   2  T   3  TEMP
    WSEP          10   11   22   23   24   21   44    1    1    2   -0   -0   -0   -0   -0   -0   -0   -0
    SENSOR        25    3   24    6   -0   -0   -0   -0   -0   -0   -0   -0   -0   -0   -0   -0   -0   -0
_________________________________________________________________________________________________________
                                                                                                       EV N   1  T   3  TEMP
    LINE          15   23   24   94    0    0    3   -0   -0   -0   -0   -0   -0   -0   -0   -0   -0   -0
    OUTLET        20   23   94  100   -0    5   -0   -0   -0   -0   -0   -0   -0   -0   -0   -0   -0   -0
                                                                                                       EV N   2  T   2  PRESS

* NOTE - CARD NUMBERS NOT IN ASCENDING ORDER
         MAY PRODUCE INVALID CHANGE CASE

    STATE/ERROR VARIABLE(S)      2

FLOW RATE(S)

(  11)   78.10 (  21)    1.10 (  23)   77.00

PRESSURE(S)

(  22)   17.80 (  24)   16.35 (  44)   16.35 (  94)   14.70

TEMPERATURE(S)

(  22)  496.83 (  24)  496.00 (  44)  496.53 (  94)  494.92

HUMIDITY(S)/ENTHALPY(S)

(  22)   .0220 (  24)   .0076 (  44)  1.0000 (  94)   .0076

STATE VARIABLE TYPE(S)
(   1)     2 (   2)    3

STATE VARIABLE(S) PESS
(   1) 1.77971E+01 (   2) 4.96827E+02   TEMP   INITIAL INPUT

ERROR VARIABLE TYPE(S)
(   1)     3 (   2)    2

ERROR VARIABLE(S) TEMP
(   1) 1.34681E-03 (   2) 1.81231E-04   PRESS   Converge Tolerance (.01)
        .0013                   .00018
SOLUTION CONVERGED IN        7 TRY(S)

     0 ERROR(S) DETECTED
```

Figure 11 F-111A ECS Water Separator Performance Output

air to air heat exchanger with ejectors, air to water heat exchanger, water separator, air temperature control, hot air temperature control valve, bleed air check and shutoff valve, and bleed air ejector shutoff valve. The computer program calculated weights are compared to available weight data (component weights are not given in Reference 1).

The sizing of the air cycle machine was based on the data of Figure 10. The diverter valve (estimated 4.5 inches diameter) was considered closed at Mach 2.5 at 60,000 feet altitude. The calculated air to air heat exchanger weight considered one bleed air core, although the actual heat exchanger has two cores. (See Section 5.2.2.) The fin geometries (selected from the typical geometries of Volume I) for the bleed air side were: 24.12 R(S) - 0.075/0.075 - 1/9 (0) - 0.004, and for the ram air side: 15.76 R(D) - 0.153/0.149 - 1/7 (0.0) - 0.004. The bleed air ejector was based on conditions downstream of a bleed air ejector shutoff valve having an inlet pressure and temperature of 195 psig and 940°F, with a 1.8 psi pressure drop at 60 lb/min flow, and exhausting to air downstream of the heat exchanger at static conditions. The air side fin geometry of the water boiler was: 12.18 R(D) - 0.178/0.174 - 0.178 (0) - 0.004 (from Volume I). It was sized as an integral boiler and tank which holds 250 lb water. The water separator sizing was based on the data of Figure 11.

The air temperature control had 15 inputs and outputs, based on the data of Reference 5. These NIAO were: the rate of change anticipator (2), the overtemperature switch, the selector (2), the cabin sensor, the minimum flow pressure switch, the suit overtemperature switch and sensor, the hot air modulating valve (2), the service air modulating valve (2), and the cold air modulating valve (2). Six sensors and switches were used, and a selector weight of 0.6 lb was used. The controller included a Built-In-Test-Equipment (BITE) feature.

The other two valves were sized for the following conditions. The bleed air check valve had a 2.5 psi pressure drop at 300 psia and 750°F, and a flow rate of 109.5 lb/min (flow from Reference 1). The hot air temperature control valve was estimated to be designed for 25 lb/min at 100 psia and 400°F, with a pressure drop of 1 psi.

The computer program output for these components is shown in Figure 12. Table II compares the computer program weight calculations to available

```
COMPONENT TURB
    WEIGHT   11.95     COST UNITS   65.75     RELIABILITY INDEX 0.0          DEVELOPMENT RISK  1.00
    W    78.10   PI   76.84   PO   12.81   TI  591.97   TC  412.19   HI  0.0      HO  0.0      FT     2  FN    -1
    C     5.47   VOL  555.    N   60000.   EFF 0.7601   HP   79.34   U   1431.    NS   77.62   DS   1.68
COMPONENT COMP
    WEIGHT   19.24     COST UNITS  105.83     RELIABILITY INDEX 0.06793      DEVELOPMENT RISK  1.20
    W    39.59   PI    4.53   PO    8.15   TI 1173.26   TC 1489.06   HI  0.0      HO  0.0      FT     2  FN    -1
    C     6.94   VOL 1543.    N   60000.   EFF 0.6354   HP  -76.21   U   1816.    NS  166.79   DS   1.03
    TIP SPEED EXCEEDS LIMITING VALUE
    DRIVE    1
COMPONENT VALVE
    WEIGHT    4.62     COST UNITS   32.90     RELIABILITY INDEX 0.04610      DEVELOPMENT RISK  1.00
    W     0.0    PI    6.18   PO    4.53   TI  880.00   TO 1173.26   HI  0.0      HO  0.0      FT     2  FN    -1
DIA D     4.50   KT    0.43   V     0.0    W    0.0

COMPONENT HX
    WEIGHT   47.03     COST UNITS   97.82     RELIABILITY INDEX 0.00256      DEVELOPMENT RISK  1.00
    W    78.10   PI   79.56   PO   78.07   TI 1527.00   TO 1009.40   HI  0.0      HO  0.0      FT     2  FN    -1
    W   148.15   PI    5.98   PO    4.53   TI  880.00   TO 1173.26   HI  0.0      HO  0.0      FT     2  FN    -1
    LH    7.01   LC    5.77   LN   18.01   VOL  728.    WTC   31.7   EFF 0.8000   NTU  2.898
COMPONENT EJECT
    WEIGHT   23.18     COST UNITS   82.90     RELIABILITY INDEX 0.00177      DEVELOPMENT RISK  1.00
    W    60.00   PI  207.90   PO   13.82   TI 1400.00   TO 1300.00   HI  0.0      HO  0.0      FT     2  FN    -1
    AN    0.34   VOL  366.

COMPONENT BOIL
    WEIGHT   32.63     COST UNITS  118.45     RELIABILITY INDEX 0.02165      DEVELOPMENT RISK  1.15
    W    78.10   PI   78.07   PO   76.84   TI 1009.40   TO  591.97   HI  0.0      HO  0.0      FT     2  FN    -1
    LH    3.89   LC    8.46   LN    8.46   VOL  278.    WTC   10.3   FWT  245.2   EFF 0.9500   NTU  2.996
```

Figure 12 F-111A ECS Component Sizing Output

```
COMPONENT WSEP
     WEIGHT    7.31     COST UNITS   34.03     RELIABILITY INDEX 0.00285     DEVELOPMENT RISK  1.00
     W    78.10   FI   17.8C   PO   16.35   TI  496.83   TO  496.00   HI  0.C220   HO  0.0076   FT       2   FN      -1
     VCL  1456.

COMPCNENT CNTRL
     WEIGHT    7.48     COST UNITS  187.39     RELIABILITY INDEX 0.27314     CEVELCPMENT RISK  1.00
     TYPE    1   VCL   217.

COMPONENT VALVE
     WEIGHT    7.04     COST UNITS   33.38     RELIABILITY INDEX 0.04610     CEVELOPMENT RISK  1.CO
     W    25.00   PI  1CC.0C   PO   59.00   TI  860.00   TO  86C.00   HI  0.C      HO  0.0      FT       2   FN      -1
     D     3.00   KT    C.43   V    27.C5   M   0.0189
COMPONENT VALVE
     WEIGHT    3.2E     COST UNITS   11.41     RELIABILITY INCEX 0.05291     CEVELOPMENT RISK  1.00
     W    60.00   PI  2C9.7C   PO  2C7.50   TI 1400.00   TO 1400.00   HI  0.0      HO  0.0      FT       2   FN      -1
     D     1.50   KT    2.74   V   2C1.56   M   C.1116

COMPONENT VALVE
     WEIGHT    5.32     CCST UNITS   13.81     RELIABILITY INDEX 0.05291     DEVELOPMENT RISK  1.0C
     W   109.50   PI  3CC.CC   PO  257.5C   TI 1210.00   TO 121C.00   HI  0.0      HO  0.0      FT       2   FN      -1
     D     2.50   KT    2.74   V    EC.CC   M   C.0475
```

Figure 12 F-111A ECS Component Sizing Output (Continued)

TABLE II
F-111A ECS WEIGHT SUMMARY

Component	Weight - Lb	
	Data	Computer Program*
Turbine		11.94
Compressor		19.25
Diverter Valve		4.62
Air Cycle Machine	36	(35.81 ± 5.38)
Heat Exchanger		47.03
Ejectors (2)		23.18**
Air to Air Heat Exchanger	87.4	(70.21 ± 11.44)
Integral Water Boiler		32.63
Air to Water Heat Exchanger	20	
Water Separator	7.5	7.31 (± 1.26)
Air Temperature Control	7.5	7.48 (± 3.06)
Hot Air Temperature Control Valve	5.96	7.04 (± 2.50)
Bleed Air Ejector Shutoff Valve	2.90	3.28 (± 1.14)
Bleed Air Check and Shutoff Valve	5.72	5.32 (± 1.85)

*Tolerances based on standard errors in Volume I
**See discussion in text

component weight data. Most of the predicted weights are close to the actual data. One exception is the integral water boiler. This core is installed in a tank which also serves as aircraft structure. Since the outlet header of the air to air heat exchanger includes the nozzles for the compressor ejector and the bleed air ejector, the total weight of the ejectors was estimated as 20% greater than for the bleed air ejector weight. (This was obtained by use of the weight multiplier in the computer program input.)

5.3 B-52H Aircraft ECS

The B-52H aircraft are equipped with a simple air cycle system to control the temperature of the forward crew and equipment compartments. The following brief descriptions of the operation of this system and some of the major components is taken from References 1 and 6.

5.3.1 B-52H ECS Operation - Sixteenth stage compressor bleed air is cooled by a pylon-mounted heat exchanger (precooler) to 450°F by ram air. The bleed air to cool the crew and equipment is ducted inboard through the wing and a catalytic filter to the simple air cycle package. The air flows through a pressure limiter valve and venturi, a ram air heat exchanger, the cooling turbine, and water separator. Water collected by the water separator is injected into the ram air side of the heat exchanger.

Hot bleed air for temperature control is obtained upstream of the heat exchanger. It flows through a modulating valve and muffler to the cabin. The cabin temperature controller is used to position the modulating valve "manually" (i.e., via electrical circuits) or to automatically control the cabin temperature selected by the crew and sensed by the cabin temperature sensing element. Cooled air from the simple air cycle package is maintained above freezing (38°F) at low altitudes by the anti-icing control. Hot air for anti-icing is taken from a heat exchanger bleed air header.

Ram air to cool the heat exchanger is taken from scoop inlets at the wing root leading edge. After passing through the heat exchanger, the ram air is ducted to the fan of the simple air cycle turbomachine and discharged overboard.

The cabin pressurization system maintains atmospheric pressure up to approximately 8000 feet, then maintains cabin pressure equivalent to 8000 feet until the aircraft reaches an altitude where a preselected pressure differential (7.45 or 4.50 psid) exists. Above this altitude the preselected pressure differential is maintained. When the cabin is at either of the preselected differential pressures, a water separator bypass control valve opens the integral bypass valve in the water separator, allowing the turbine discharge air to bypass the water separator condenser screen.

5.3.2 B-52H ECS Components - The following descriptions of several components are based on References 1 and 6.

The pressure limiter consists of a pneumatically actuated butterfly valve and control head, and a venturi section. The valve is positioned to regulate the system flow to approximately 130 pounds per minute by maintaining a constant pressure differential across the venturi. The valve diameter is 3.0 inches.

The system heat exchanger provides the multiple bleed air passes (counter-flow passes) and one ram air pass. Water from the water separator is injected into the ram air stream upstream of the heat exchanger.

The anti-ice valve is an electrically actuated 1 1/2 inches diameter butterfly valve. It is closed at altitude, as determined by the anti-ice controller.

The turbomachine contains a turbine (for cooling the bleed air) and a fan (in the ram air circuit after the heat exchanger) to load the turbine.

A four inches diameter, motor operated shutoff valve can be opened to ventilate the cabin with ram air during periods of unpressurized operation.

The water separator contains a fiberglass fabric condenser screen mounted on a cone-shaped grid with louvered openings. It contains an integral bypass valve which is actuated if the separator becomes clogged, or at a fixed altitude by a solenoid actuated pneumatic control valve.

5.3.3 B-52H ECS Rough Performance Analysis - The rough performance analysis for the F-111A ECS was made for the simple air cycle system at sea level, hot day conditions with 0.022 lb water/lb dry air humidity at a Mach number of 0.6. A schematic of the computer program performance analysis model is shown in Figure 13, and the computer program output of the component data cards is shown in Figure 14. A description of this setup follows.

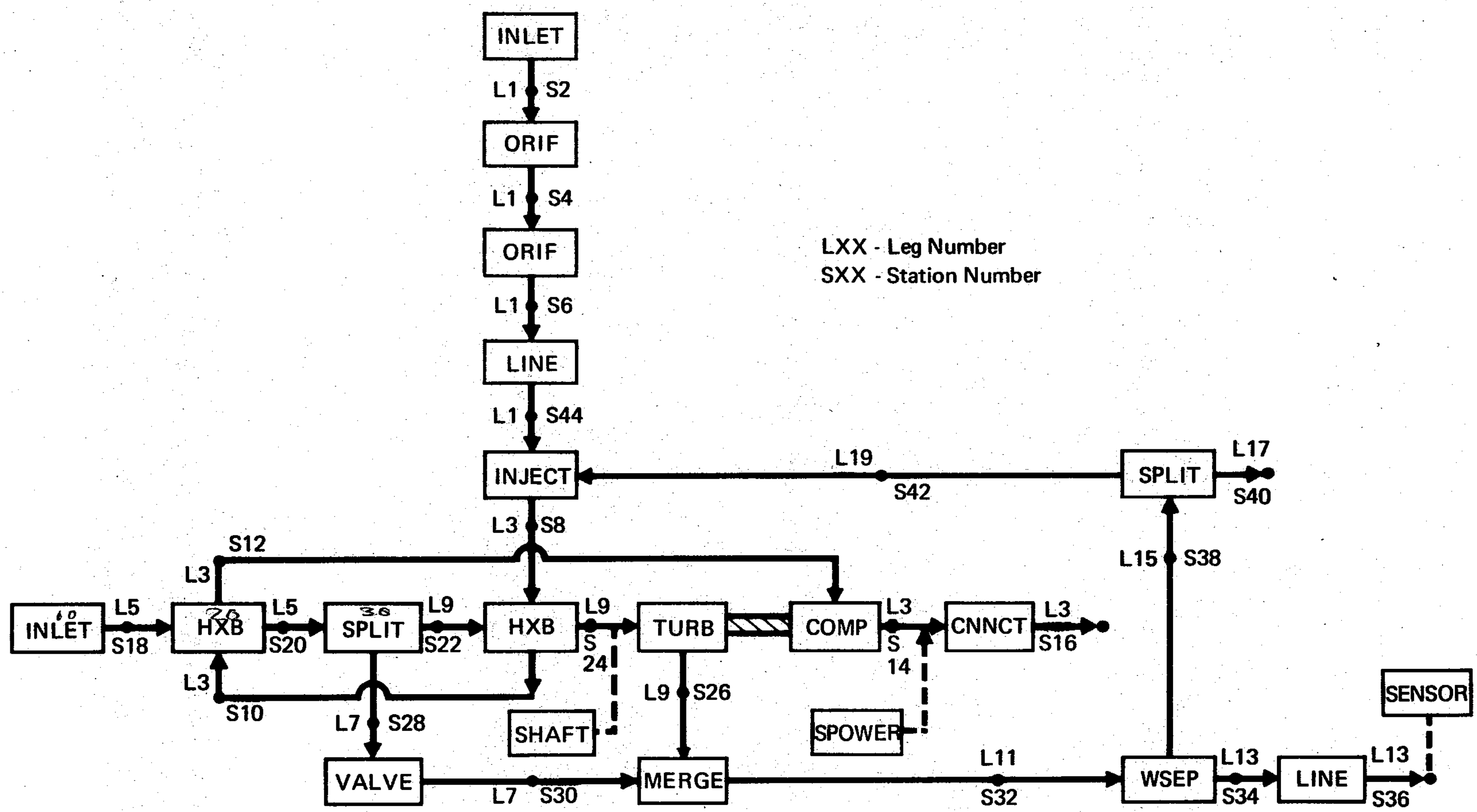

Figure 13 Schematic of B-52H ECS Performance Model

CASE B-52H

COMPONENT(S)

1 6 8	12	16	20	24	28	32	36	40	44	48	52	56	60	64	68	72	76	80	
INLET	10	5	18	100	1	2	3	4	2	-1	0	0	0	0	0	0	0	0	SV N 1 T 2
HXB1	20	5	18	20	3	10	12	1	1	1	5	6	0	0	0	0	0	0	SV N 2 T 1 SV N 3 T 3
SPLIT	30	5	20	9	22	7	28	0	9	0	0	0	0	0	0	0	0	0	
VALVE	40	7	28	30	0	0	5	0	0	0	0	0	0	0	0	0	0	0	
HXB1	50	9	22	24	3	8	10	1	2	2	7	8	0	0	0	0	0	0	SV N 4 T 1 SV N 5 T 3
SHAFT	60	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
TURB	70	9	24	26	1	0	10	1	11	0	0	0	0	0	0	0	0	0	
MERGE	80	9	26	7	30	11	32	0	0	0	0	0	0	0	0	0	0	0	
WSEP	90	11	32	13	34	15	38	1	6	1	0	0	0	0	0	0	0	0	
LINE	100	13	34	36	0	0	7	0	0	0	0	0	0	0	0	0	0	0	
SENSOR	110	2	36	12	0	0	0	0	0	0									EV N 1 T 2
SPLIT	120	15	38	19	42	17	40	0	13	0	0	0	0	0	0	0	0	0	
INLET	130	1	2	1000	14	15	16	4	2	-1	0	0	0	0	0	0	0	0	SV N 6 T 1
ORIF	140	1	2	4	0	9	0	0	0	0	0	0	0	0	0	0	0	0	
ORIF	150	1	4	6	0	10	0	0	0	0	0	0	0	0	0	0	0	0	
LINE	160	1	6	44	0	0	8	0	0	0	0	0	0	0	0	0	0	0	
INJECT	170	1	44	19	42	3	8	0	0	0	0	0	0	0	0	0	0	0	
HXB2	180	3	8	10	9	22	24	1	3										EV N 2 T 1 EV N 3 T 3
HXB2	190	3	10	12	5	18	20	1	4	0	0	0	0	0	0	0	0	0	EV N 4 T 1 EV N 5 T 3
COMP	200	3	12	14	1	0	17	1	11	0	0	0	0	0	0	0	0	0	
SPOWER	210	1	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	EV N 6 T 5
CNNCT	220	3	14	3	16	0	0	0	0	0	0	0	0	0	0	0	0	0	

STATE/ERROR VARIABLE(S) 6

Figure 14 B-52H ECS Component Data Cards Output

The bleed air flow was started at INLET (card 10) with a flow rate of 130 lb/min (Reference 1), an unspecified pressure, a temperature of 450°F (out of a precooler heat exchanger described in Reference 6), and a humidity of 0.022 lb water/lb dry air. Since the heat exchanger has multiple-passes on the bleed air side it was represented by two heat exchangers. Since the water from the water separator is injected into the ram air side of this heat exchanger, the wet ram air flow rate was unknown for the first pass calculation, hence the heat exchanger analyses were made with the HXB subroutine. Thus, HXB1 (card 20) represented the bleed air (side 1) flow through this heat exchanger. It had a pressure drop ($\sigma\Delta P$) equal to 5% of the inlet bleed air pressure and a side 1 temperature effectiveness of 0.8 (described in Volume I). It's side 2 flow rate and inlet temperature were initially guessed values in the parameter table. The flow SPLIT (card 30) would allow for use of air to be removed between heat exchanger passes of the bleed air for temperature control. The flow through leg 7 was set at zero, the pressure drop through the VALVE (card 40) was set equal to the inlet pressure, and the flow would MERGE (card 80) downstream of the turbine. The remaining passes of bleed air through the heat exchanger were represented by the second HXB1 (card 50).

SHAFT (card 60) defined shaft number 1 for the turbine and compressor. The turbine (TURB, card 70) had a pressure ratio of 6.0, and an adiabatic efficiency of 0.76 (nominal design values discussed in Volume I). The water separator (WSEP, card 90) had a pressure drop ($\sigma\Delta P$) of 3.15 psi (high wet value from Volume I) and a water collection efficiency of 0.85 (design value in Reference 8). The LINE (card 100) represented the pressure drop to the cabin through 27 feet of ducting having a Mach number of 0.05. The SENSOR (card 110) was set at sea level pressure (14.7 psia) to represent cabin pressure. Part of the water collected by the separator goes to the injector in the ram air flow circuit (i.e., SPLIT, card 120, had 0.75 of the water flow to the injector).

The ram air INLET had an unspecified flow rate and a pressure, temperature, and humidity corresponding to the sea level Mach 0.6 flight conditions. The two ORIF (cards 140 and 150) represented a scoop inlet and nominal diffuser pressure ratio (obtained from Volume I information). The LINE (card 160) was 5 feet long with a Mach number of 0.15. Water from the separator was added to this line via INJECT (card 170). The next two HXB2 cards

(180 and 190) defined the ram air pressure drop through the heat exchanger as 0.05 P_{in}. All of the ram air flows through the compressor (COMP, card 200), which had a pressure ratio of 1.2 and an adiabatic efficiency of 0.64. The power between the compressor and turbine was balanced by SPOWER (card 210). CNNCT (card 220) defined station 16.

This B-52H ECS performance analysis had six state and error variables. The state variables were the bleed air pressure into the heat exchanger (SVN1), the ram air flow rate (SVN6), and the flow rates and temperatures into the ram air sides of the HXB1's (SVN2, 3, 4, and 5). The error variables were cabin pressure (EVN1), the turbine and compressor power balance (EVN6), and the flow rates and temperatures into HXB2's (EVN2, 3, 4, and 5).

The system performance output of this case is shown in Figure 15. The bleed air pressure into the heat exchanger is 106.19 psia. The ram air flow rate is 396.40 lb/min. To this is added 1.39 lb/min of water from the separator resulting in 397.79 lb/min wet ram air flow (i.e., humidity of 0.0256 lb water/lb dry air) through the heat exchanger. This system performance output was used to size the components discussed in the following section.

5.3.4 Sizing of Major Components of the B-52H ECS - Rough sizes of the following components of the B-52H ECS were computed with the computer program sizing segment: heat exchanger with water injector, turbine-compressor unit, pressure limiter valve with venturi, water separator bypass control valve, anti-ice valve, emergency ram air valve, three sections of ducting between the above components, and the water separator. The sum of the computer program calculated weights are compared to the weight of the air conditioning pack (i.e., no water separator), which is approximately 160 lb (from Reference 6), and to the weight of the water separators (i.e., 28.1 lb in Reference 1).

Sizing of the heat exchanger (assumed to be steel) was based on a bleed air side fin geometry of 24.12 R(S) - 0.075/0.075 - 1/9 (0) - 0.004 and ram air side fin geometry of 15.61 R(S) - 0.251/0.250 - 1/8 (0) - 0.004 (from Volume I information). It also was assumed to be a two-pass design. The flow rates, pressures, temperatures, and humidities from Figure 15 were used to size the heat exchanger, as well as the turbine and compressor. The turbine was sized

```
CASE  B-52H

FLOW RATE(S)

(  1)  396.40 (  3)  397.79 (  5)  130.00 (  7)    0.00 (  9)  130.00 ( 11)  130.00
( 13)  128.15 ( 15)    1.65 ( 17)     .46 ( 19)    1.39

PRESSURE(S)

(  2)   18.75 (  4)   18.56 (  6)   18.21 (  8)   18.63 ( 10)   17.18 ( 12)   16.25
( 14)   19.50 ( 16)   19.50 ( 18)  106.19 ( 20)  105.07 ( 22)  105.07 ( 24)  104.16
( 26)   17.36 ( 28)  105.67 ( 30)     .00 ( 32)   17.36 ( 34)   14.79 ( 36)   14.70
( 38)   14.79 ( 40)   14.79 ( 42)   14.79 ( 44)   18.03

TEMPERATURE(S)

(  2)  604.00 (  4)  504.00 (  6)  604.00 (  8)  590.90 ( 10)  612.13 ( 12)  691.89
( 14)  749.15 ( 16)  749.15 ( 18)  910.00 ( 20)  671.70 ( 22)  671.70 ( 24)  608.05
( 26)  500.46 ( 28)  571.70 ( 30)  671.70 ( 32)  500.46 ( 34)  498.67 ( 36)  498.59
( 38)  500.46 ( 40)  500.46 ( 42)  500.46 ( 44)  604.00

HUMIDITY(S)/ENTHALPY(S)

(  2)   .0220 (  4)   .0220 (  6)   .0220 (  8)   .0256 ( 10)   .0256 ( 12)   .0256
( 14)   .0256 ( 16)   .0256 ( 18)   .0220 ( 20)   .0220 ( 22)   .0220 ( 24)   .0220
( 26)   .0220 ( 28)   .0220 ( 30)   .0220 ( 32)   .0220 ( 34)   .0075 ( 36)   .0075
( 38)  1.0000 ( 40)  1.0000 ( 42)  1.0000 ( 44)   .0220

STATE VARIABLE TYPE(S)
(  1)    2 (  2)    1 (  3)    3 (  4)    1 (  5)    3 (  6)    1

STATE VARIABLE(S)
(  1) 1.06190E+02 (  2) 3.97787E+02 (  3) 6.12130E+02 (  4) 3.97787E+02 (  5) 5.90903E+02 (  6) 3.96401E+02

ERROR VARIABLE TYPE(S)
(  1)    2 (  2)    1 (  3)    3 (  4)    1 (  5)    3 (  6)    5

ERROR VARIABLE(S)
(  1) 6.44509E-05 (  2)-3.75402E-04 (  3) 5.45623E-03 (  4)-3.75402E-04 (  5) 4.11253E-03 (  6) 7.73359E-04

SOLUTION CONVERGED IN      9 TRY(S)

     0 ERROR(S) DETECTED
```

Figure 15 B-52H ECS Performance Output

for radial flow, and the compressor was sized for axial flow because of the assumed low pressure ratio. The pressure limiter valve and venturi were sized with estimated inlet pressures just above the 106.19 psia into the heat exchanger, and also assuming the venturi length as 18 inches. The water separator bypass control valve was sized as a 1/4 inch steel poppet valve with an electrically operated solenoid, and no flow. The anti-ice valve was considered closed (i.e., no flow) since the air temperature out of the separator was greater than 38°F, as seen in Figure 15. The emergency ram air valve inlet pressure and temperature were ram air conditions, and flow was approximately the ratio of ram air load to refrigeration unit load (130 lb/min), given in Reference 1. The heat exchanger inlet duct was estimated as 30 inches long, 3 inches diameter, with a pressure drop of 0.5%; the anti-ice duct also was 30 inches long, 1 inch diameter, with a pressure drop of 0.5% and flow equal to 10% of the system flow; and the turbine inlet duct was 30 inches long, 2 inches diameter, with a pressure drop of 0.5%. Appropriate temperatures, flow, pressures, and humidities were taken from Figure 15, as were data for sizing the water separator.

The computer program output for these components is shown in Figure 16. The weights of these components are summarized in Table III. The predicted weight of the air conditioning package is seen to be less than the weight from Reference 6. Possible reasons for this difference are that the computer program weight estimates in Volume I are based on newer ECS (e.g., lighter) as well as older ECS, or that the 160 pounds in Reference 6 includes pack installation. The installed weight of the B-52H ECS which would be calculated by the computer program is 158.2 lb.

5.4 <u>C-9A Aircraft ECS</u>

The C-9A aircraft uses two bootstrap air cycle systems. Following brief descriptions of the operation of these systems and of system components, detailed system performance and sizing analyses are presented.

5.4.1 <u>C-9A ECS Operation</u> - Bleed air is taken from either the eighth or thirteenth engine compressor stages, or both stages. Eighth stage air passes through a check valve into a manifold (interconnecting the two engines) from which air for the ECS is taken. Engine bleed air from each thirteenth stage flows through augmentation valves (one on each side) into this manifold. Air from the APU or a ground pneumatic cart also may enter this manifold (through respective check valves). The thirteenth stage augmentation valve

```
COMPONENT HX
     WEIGHT    85.44     COST UNITS  177.71     RELIABILITY INDEX 0.00256     DEVELOPMENT RISK  1.00
     W   130.00   PI   106.19   PO   104.16   TI   910.00   TO   608.05   HI  0.0220   HO  0.0220   FT     2   FN    -1
     W   397.79   PI    18.03   PO    16.25   TI   590.90   TO   691.89   HI  0.0256   HO  0.0256   FT     2   FN    -1
     LH   13.96   LC    10.42   LN    11.51   VOL  1674.    WTC   63.5   EFF 0.9469   NTU  5.363
COMPONENT TURB
     WEIGHT    12.34     COST UNITS   67.88     RELIABILITY INDEX C.0         DEVELOPMENT RISK  1.0C
     W   130.00   PI   104.16   PO    17.36   TI   6C8.C5   TC   500.46   HI  0.0220   HC  0.0220   FT     2   FN    -1
     C     5.55   VOL   635.    N   60000.    EFF 0.7629    HP   136.15   L    1454.   NS   92.91   CS   1.40
COMPONENT COMP
     WEIGHT     9.27     COST UNITS   51.01     RELIABILITY INDEX C.06793     DEVELOPMENT RISK  1.CC
     W   397.79   PI    16.25   PO    19.50   TI   691.89   TC   749.15   HI  0.0256   HO  0.0256   FT     2   FN    -1
     C     4.82   VOL   358.    N   6CCCC.    EFF C.64CC    HP  -130.27   U    1261.   NS  808.67   CS   C.36
     DRIVE   1
COMPONENT VALVE
     WEIGHT     7.04     COST UNITS   33.38     RELIABILITY INDEX 0.04610     DEVELOPMENT RISK  1.00
     W   130.00   PI   120.00   PO   110.00   TI   910.00   TO   910.00   HI  0.0220   HO  0.0220   FT     2   FN    -1
     C     3.00   KT     0.43   V    124.C1   M   C.C843
COMPONENT LINE
     WEIGHT     3.59     COST UNITS    7.16     RELIABILITY INDEX 0.01164     DEVELOPMENT RISK  1.00
     W   130.00   PI   110.00   PO   106.72   TI   910.C0   TO   910.00   HI  0.0220   HC  0.0220   FT     2   FN    -1
     C     3.00   THK   0.024   V    137.34   M   0.0934
COMPONENT VALVE
     WEIGHT     C.73     COST UNITS    6.07     RELIABILITY INDEX 0.05291     DEVELOPMENT RISK  1.0G
     W     0.0    PI   1C4.16   PO     C.C    TI   910.00   TO     0.0    HI  0.0220   HO  0.0220   FT     2   FN    -1
     D     0.25   KT     2.74   V      C.C    M   C.0
COMPONENT VALVE
     WEIGHT     2.61     COST UNITS   27.CC     RELIABILITY INDEX 0.07649     DEVELOPMENT RISK  1.CC
     W     0.0    PI   105.C7   PO     0.C    TI   671.70   TO     C.0    HI  0.0220   HO  0.0220   FT     2   FN    -1
     D     1.50   KT     C.43   V      C.C    M   C.0
```

Figure 16 B-52H ECS Component Sizing Output

```
COMPONENT VALVE
   WEIGHT    3.34     COST UNITS    27.00     RELIABILITY INDEX 0.07649     DEVELOPMENT RISK  1.00
   W    80.00   PI   18.75   PO   18.50   TI   604.00   TO   604.00   HI   0.0220   HO   0.0220   FT   2   FN   -1
   C     4.00   KT    0.43   V   182.35   M    0.1515
COMPONENT LINE
   WEIGHT    4.19     COST UNITS    11.94     RELIABILITY INDEX 0.01164     DEVELOPMENT RISK  1.00
   W   130.00   PI  106.72   PO  106.19   TI   910.00   TO   910.00   HI   0.0220   HO   0.0220   FT   2   FN   -1
   C     3.00   THK  0.024   V   139.79   M    0.0950
COMPONENT LINE
   WEIGHT    2.14     COST UNITS     6.96     RELIABILITY INDEX 0.01164     DEVELOPMENT RISK  1.00
   W   130.00   PI  104.42   PO  103.90   TI   608.05   TO   608.05   HI   0.0220   HO   0.0220   FT   2   FN   -1
   C     2.00   THK  0.017   V   214.80   M    0.1778
COMPONENT LINE
   WEIGHT    0.77     COST UNITS     3.87     RELIABILITY INDEX 0.01164     DEVELOPMENT RISK  1.00
   W    13.00   PI   14.50   PO   14.40   TI   910.00   TO   910.00   HI   0.0220   HO   0.0220   FT   2   FN   -1
   D     1.00   THK  0.010   V   926.89   M    0.6301
COMPONENT WSEP
   WEIGHT   12.17     COST UNITS    44.13     RELIABILITY INDEX 0.00285     DEVELOPMENT RISK  1.00
   W   130.00   PI   17.36   PO   14.79   TI   500.46   TO   498.67   HI   0.0220   HO   0.0075   FT   2   FN   -1
   VOL   3128.
```

Figure 16 B-52H ECS Component Sizing Output (Continued)

TABLE III
B-52H ECS WEIGHT SUMMARY

Component	Weight - Lb Computer Program
Heat Exchanger	85.44
Turbine (and Compressor)	21.61
Pressure Limiter Valve and Venturi	10.63
Water Separator Bypass Control Valve	0.73
Anti-Ice Valve	2.61
Emergency Ram Air Valve	3.34
Ducting (3)	7.10
Air Conditioning Pack (160 Lb in Reference 6)	131.46 (± 18.27)*
Water Separator (28.1 Lb in Reference 1)	12.17 (± 2.11)*

*Tolerances based on standard errors in Volume I.

opens to provide air to the ECS when eighth stage bleed air pressure is low, and when higher temperature air is required for the ice protection system.

Air enters each bootstrap air cycle system through a pressure regulator and flow control valve. Then it flows through the primary heat exchanger, the air cycle compressor, the secondary heat exchanger, the turbine, and the water separator. The turbine has two inlets and two nozzles. Normally air from the secondary heat exchanger flows through two lines to the two turbine nozzles. During operation with the APU, one line is closed (by a valve) to provide low turbine outlet temperatures. The outlet air flow from the turbine passes through a screen used in conjunction with the water separator anti-ice control.

Hot air for cabin/cockpit temperature control is obtained downstream of the flow control valve. It is mixed with air from the water separator. Hot air for water separator temperature control (anti-icing) is obtained between the primary heat exchanger and compressor. The conditioned air is distributed to the cabin and cockpit through a mixing chamber. Cold air from the water separator also is available. Exhaust air from the occupied areas is routed under the floor to the avionics and lower cargo compartments.

Ram air from a scoop on the leading edge of the dorsal fin flows through a duct down into the fuselage. The duct splits for flow to each air cycle system. From this split the air enters a plenum which acts as a header for the primary and secondary heat exchangers. During ground operation air enters the plenum from a fan through a flapper type valve (one to each side). After passing through each heat exchanger the air flows into another plenum, and then through a duct to the flush outlet.

The cabin pressurization system provides any selected cabin pressure altitude from sea level to 8,000 feet up to an aircraft altitude of 35,000 feet, and a cabin pressure differential up to 7.46 psid. The cabin outflow valve includes a thrust recovery nozzle.

5.4.2 <u>C-9A ECS Components</u> - Brief descriptions of C-9A ECS components are presented.

The pressure regulator valve regulates to 27 ± 3 psig. It also functions as a system shutoff valve.

The flow control functions to control a butterfly valve to maintain essentially a constant ΔP between the upstream and the throat of a venturi which preceeds it. It closes if the ram air pressure upstream of the heat exchangers is too low.

The primary and secondary heat exchangers are cross-counter flow plate-fin designs made of aluminum alloys.

The compressor and turbine are radial flow designs. The turbine has two separate rings of nozzles. The speed of the unit normally is less than 60,000 rpm.

The water separator consists of a coalescer, swirl vanes, internal relief valve, and drain.

The APU provides shaft power to an electrical generator and bleed air to the ECS.

The cabin/cockpit temperature control valve is modulated in response to signals from the cabin/cockpit temperature controller. It is an electric motor driven butterfly valve. The controller receives signals from the temperature selector and several temperature sensors. The temperature selector is automatic with a manual override feature.

The water separator temperature control valve reacts to the back-pressure caused by ice on the screen in the turbine discharge duct. It is biased with cabin pressure differential, and allows a small amount of ice to form on the screen. At altitude it maintains approximately 40°F at the screen until it is wide open.

The cabin pressure control system includes a variable isobaric controller. It controls a butterfly valve and thrust recovery nozzle. The system includes two safety valves.

5.4.3 C-9A ECS Detailed Analysis - The detailed performance analysis for the C-9A ECS was made with the detailed performance characteristics of the system components, including ducting pressure drop determinations based on duct diameters, lengths, and number and type of bends. The analyses were made for comparison to available ECS performance data. A schematic of the computer program performance analysis model is shown in Figure 17. Analyses were made for the following four design point conditions:

(1) Sea level cruise, hot day, 0.0184 lb water/lb dry air humidity;
(2) 35,000 feet altitude cruise, cold day;
(3) 18,000 feet altitude idle descent, hot day, no humidity;
(4) Sea level static, hot day, 0.0184 lb water/lb dry air humidity, bleed air from APU.

The schematic in Figure 17 includes several components through which air flows only during APU operation.

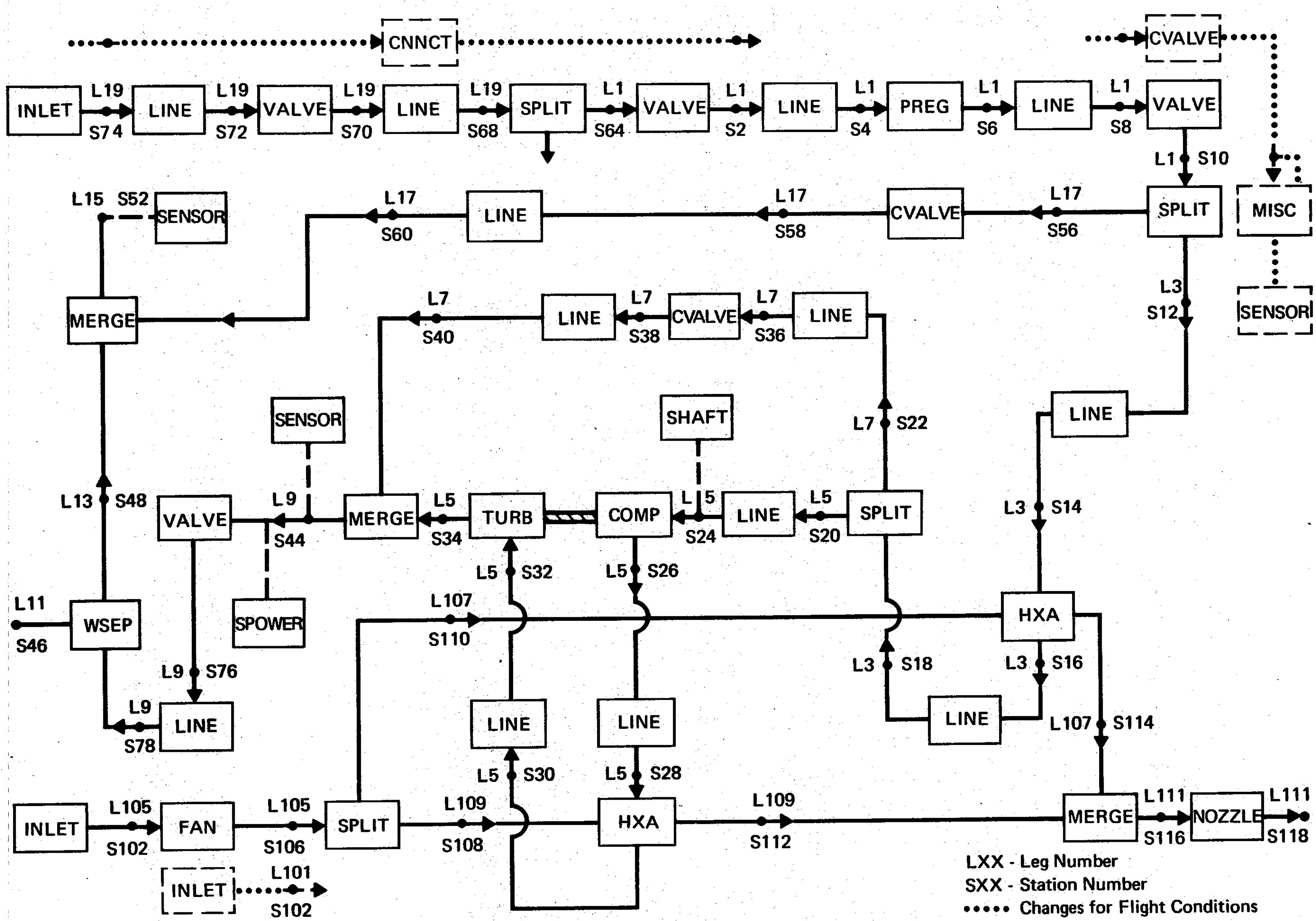

Figure 17 Schematic of C-9A ECS Performance Model

The computer program output of the component data cards for the sea level static condition is shown in Figure 18. The bleed air temperature, pressure, and humidity from the APU were specified by INLET (card 1). The flow was SPLIT to the other ECS package before it went through the pressure regulator (card 30) and open flow control VALVE (card 50).

Detailed performance maps were used for the ram air fan, the primary and secondary heat exchangers, the bootstrap compressor and turbine, and the water separator. The cabin/cockpit and water separator temperature control valves were represented by CVALVE in leg 17 and leg 7, respectively. Since a full cold performance analysis was desired for the static condition represented in Figure 18, leg 17 and leg 7 are not used. Instead the CNNCT subroutine was used. Pressure drops in all lines were computed with the friction factor and the 90° bend loss factor versus Reynolds number as tables; and line length, diameter, and bend angle factor (C) as parameter table values. The pressure drop through the dry screen (for the water separator control) was represented with VALVE subroutine (card 364).

Component data cards representing the plumbing from the APU to the LINE upstream of the pressure regulator (card 30) and the ram air fan were deleted for analyses of the flight conditions. (See also Figure 17.) The CNNCT was used in order to maintain the same leg and station numbers. The open flow control VALVE (card 50) also was replaced by a CVALVE and a flow SENSOR for analyses of the flight conditions. The MISC was used to define the appropriate flow control function.

Results of these four analyses are compared to MDC data for the same conditions in Table IV. The first five items in the table are input information. The computer program bleed air flow deviates most from the MDC data for the 18,000 feet descent condition. Total ram flow (i.e., twice the flow for the one ECS analyzed) is close at all conditions, although the ram flow split through the primary and secondary heat exchangers differs a little from the MDC data. The heat exchanger effectivenesses obtained with the computer program are within two percent of the MDC data for all conditions. The computer program predicted turbomachine speeds were higher than the available MDC data, resulting in higher pressure ratios than the MDC data. The higher speeds and pressure ratios for conditions (2) and (3) are due to the fact that the turbomachine performance had to be extrapolated from the available performance maps. The results shown in Table IV are based on manual extrapolation of the available performance maps in order to represent typical

C-9A DETAILED ANALYSIS

COMPONENT(S)

1 6	8	12	16	20	24	28	32	36	40	44	48	52	56	60	64	68	72	76	80	
INLET	R	1	15	74	1000	46	47	48	49	2	-1	0	0	0	0	0	0	0	0	
LINE	A	1	15	74	72	0	1	-1	5	1	50	51	0	0	0	0	0	0	0	SV N 1 T 1
VALVE	A	0	15	72	70	1	0	7	0	0	0	0	0	0	0	0	0	0	0	
LINE	A	0	15	70	68	0	1	-1	5	1	52	53	0	0	0	0	0	0	0	
SPLIT	A	0	15	68	1	64	0	0	-1	0	0	0	0	0	0	0	0	0	0	
VALVE	A	0	1	64	2	1	0	8	0	0	0	0	0	0	0	0	0	0	0	
LINE		20	1	2	4	0	1	-1	5	1	6	7	0	0	0	0	0	0	0	
PREG		30	1	4	6	1	0	1	0	8	0	0	0	0	0	0	0	0	0	
LINE		40	1	6	8	0	1	-1	59	1	9	10	0	0	0	0	0	0	0	
VALVE		50	1	8	10	0	2	11	0	0	0	0	0	0	0	0	0	0	0	
CNNCT	R	60	1	10	3	12	0	0	0	0	0	0	0	0	0	0	0	0	0	
LINE		70	3	12	14	0	1	-1	60	1	13	14	0	0	0	0	0	0	0	
INLET	R	100	105	102	1000	15	16	17	18	2	-1	0	0	0	0	0	0	0	0	
SHAFT	A	100	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	SV N 2 T 1
FAN	A	0	105	102	106	2	3	58	0	0	0	0	0	0	0	0	0	0	0	
SPLIT		150	105	106	107	110	109	108	1	21	0	0	0	0	0	0	0	0	0	
HXA		170	3	14	16	107	110	114	3	4	5	2	0	0	0	0	0	0	0	SV N 3 T 5
LINE		180	3	16	18	0	1	-1	61	1	19	20	0	0	0	0	0	0	0	
CNNCT	A	180	3	18	5	20	0	0	0	0	0	0	0	0	0	0	0	0	0	
LINE		200	5	20	24	0	1	-1	62	1	23	24	0	0	0	0	0	0	0	
SHAFT		210	1	1	25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
COMP		220	5	24	26	1	2	0	1	26	0	0	0	0	0	0	0	0	0	SV N 4 T 7
LINE		230	5	26	28	0	1	-1	5	1	27	28	0	0	0	0	0	0	0	
HXA		250	5	28	30	109	108	112	3	2	3	1	0	0	0	0	0	0	0	
LINE		310	5	30	32	0	1	-1	5	1	29	30	0	0	0	0	0	0	0	
TURB		320	5	32	34	1	2	31	1	32	0	0	0	0	0	0	0	0	0	
CNNCT	A	320	5	34	9	44	0	0	0	0	0	0	0	0	0	0	0	0	0	EV N 1 T 1 SV N 5 T 8
VALVE		364	5	44	76	1	0	9	0	0	0	0	0	0	0	0	0	0	0	
LINE		366	5	76	78	0	1	-1	65	1	66	67	0	0	0	0	0	0	0	
HSEP		370	5	78	13	48	11	46	1	6	1	0	0	0	0	0	0	0	0	
CNNCT		380	13	46	13	50	0	0	0	0	0	0	0	0	0	0	0	0	0	
CNNCT	R	410	13	48	15	52	0	0	0	0	0	0	0	0	0	0	0	0	0	
SPOWER		420	1	43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
MERGE		460	107	114	109	112	111	116	1	0	0	0	0	0	0	0	0	0	0	EV N 2 T 5
SENSOR	A	LC 460	2 press	52 sta	$\boxed{77}$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	EV N 3 T 2
MISC	A	460	-1	55	0	5	0	0	0	1	0	0	0	0	0	0	0	0	0	EV N 4 T 2 PARA. 55 = Gen. Arg. 5
MISC	A	0	-1	76	3	116	-2	0	0	0	0	0	0	0	0	0	0	0	0	PARA 76 = $\sqrt{TEMP_{116}}$
MISC	A	0	-1	76	-1	76	3	1	111	0	0	0	0	0	0	0	0	0	0	PARA.-76 = PARA.76 x W111
MISC	A	0	0	101	-1	76	4	2	116	0	0	0	0	0	0	0	0	0	0	GP 101 = PARA.76 ÷ PRESS 116
NOZZLE	A	0	111	116	118	55	0	2	2	0	0	0	0	0	0	0	0	0	0	
																				EV N 5 T 2

STATE/ERROR VARIABLE(S) 5

Figure 18 C-9A ECS Component Data Cards Output

TABLE IV C-9A ECS PERFORMANCE COMPARISON

No.	Item	Units	(1) S.L. Cruise		(2) 35,000 ft Cruise		(3) 18,000 ft Descent		(4) Static with APU		No.
			MDC Data	Computer Program	MDC Data	Computer Program	MDC Data	Computer Program	MDC Data	Computer Program	
1	Altitude	ft	0	0	35,000	35,000	18,000	18,000	0	0	1
2	Mach Number		0.530	0.530	0.75	0.75	0.538	0.538	0	0	2
3	Ambient Temperature	°R	563	563	375	375	455	455	563	563	3
4	Ambient Humidity	lb water / lb dry air	0.0184	0.0184	0	0	0	0	0.0184	0.0184	4
5	APU Operation		No	No	No	No	No	No	Yes	Yes	5
6	Bleed Air Flow	lb/min	83.22	83.08	65.10	65.54	22.68	23.62	43.13	45.21	6
7	Total Ram Flow	lb/min	978.09	978.55	379.88	380.02	548.0	549.3	452.50	449.50	7
8	Primary Heat Exchanger Ram Air Flow	lb/min	226.18	234.94	87.72	86.53	127.65	126.8	104.96	103.12	8
9	Primary Heat Exchanger Effectiveness		0.845	0.862	0.913	0.905	0.947	0.945	0.863	0.852	9
10	Secondary Heat Exchanger Ram Air Flow	lb/min	262.86	254.33	102.22	103.5	146.37	147.8	121.29	121.63	10
11	Secondary Heat Exchanger Effectiveness		0.923	0.920	0.919	0.918	0.953	0.954	0.900	0.894	11
12	Compressor Air Flow	lb/min	83.22	83.08	26.23	26.55	22.68	23.62	43.13	45.21	12
13	Compressor Pressure Ratio		1.737	1.831	1.146	1.226	1.087	1.113	1.656	1.723	13
14	Compressor Efficiency	%	77.70	77.68	53.8	67.5	50.2	54.4	70.2	69.7	14
15	Turbine Air Flow	lb/min	83.22	83.08	26.23	26.55	22.68	23.62	43.13	45.21	15
16	Turbine Pressure Ratio		3.53	3.81	1.52	1.62	1.32	1.36	4.15	4.33	16
17	Turbine Efficiency	%	80.6	79.9	71.7	72.5	68.1	68.7	72.4	74.2	17
18	Turbomachine Speed	rpm	56,597	57,952	26,506	29,634	22,472	24,512	48,377	50,541	18
19	Water Separator Outlet Dry Bulb Temperature	°R	509.2	509.2	388.1	383.0	458.3	454.9	503.0	500.5	19
20	Water Separator Efficiency	%	81.3	80.4	–	–	–	–	76.9	77.4	20
21	Supply Air Humidity	lb water / lb dry air	0.0092	0.0090	0	0	0	0	0.0087	0.0082	21
22	Cabin Supply Temperature	°R	509.2	507.7	583.0	583.0	458.3	454.9	502.2	500.5	22

turbine and compressor performance at low speeds and low pressure ratios. Preliminary analyses of these two conditions based on the linear extrapolation available with the computer program were not good. These preliminary analyses output also contained the warning message that table data had been extrapolated. Investigation of the computer program extrapolation indicated it was not entirely reasonable. (Although up to seventh order extrapolation is available in the computer program, additional computer program extrapolation was not attempted.) However, an important result is that the airflow and temperature delivered to the cabin are quite close for both the 35,000 feet cruise condition and the 18,000 feet descent condition.

5.4.4 C-9A ECS Sizing - Sizing of the C-9A ECS (as shown schematically in Figure 17) was based on the results of the four performance analyses discussed previously and other detail information about the components. Other data about the components which were sized include:

(1) Lines - Actual line diameters and lengths were used.

(2) Valves - Valve types and actual diameters were used.

(3) Controls - The cabin temperature control NIAO, the number of sensors, a selector, and a technical requirements weighting factor were used. The cabin pressure control sizing was based on twice the flow from one ECS package.

(4) Heat Exchangers - Fin friction factor and Colburn modulus data, and separation plate thicknesses for the major portion of the heat exchanger cores were used.

(5) Turbine-Compressor - Radial flow designs were specified.

(6) Water Separator - Performance analysis output data were the only input used for the sizing calculation.

(7) Ram Air Fan - The fan speed and an a.c. motor drive were specified.

(8) APU - The shaft power for use by other systems was specified.

(9) Insulation - Blanket type insulation for the ducting was specified.

The performance data from the sea level cruise analysis were used to size most of the components. Exceptions were the components used only during analysis of the sea level static condition (e.g., APU, ram air fan, etc.). A summary of C-9A ECS component weights is given in Table V. The computer program system sizing output is shown in Figure 19. The installed system weight of 846 pounds from Figure 19 is less than the actual 907.8 pounds for these system components. This weight includes the fraction of APU weight "used" by the ECS. Figure 19 also shows an estimated

TABLE V
C-9A ECS WEIGHT SUMMARY

Component	Weight (lb) Computer Program
Pressure Regulator Valve	7.04
Flow Control Valve	8.64
Pilot Pressure Regulator Valve	1.68
Pressure Supply Ducts	12.29
Temperature Control Valve	4.32
Temperature Controller (Selector and Sensors)	4.00
Temperature Control Ducts	5.73
Primary Heat Exchanger	24.83
Secondary Heat Exchanger	30.85
Turbine (and Compressor)	17.77
Fan	40.42
Water Separator	7.78
Water Separator Temperature Control Valve	6.34
Turbine Nozzle Shutoff Valve	1.75
Anti-Ice Control and Sensors (2, Pneumatic)	3.25
Refrigeration Package Ducts	12.01
Cabin Pressure Control	67.65
APU (for ECS use)	212.61
	(468.96)
Insulation on Ducting*	12.80
Component Total	(481.76)

*Part of installation weight on actual C-9A weight summary, but separately considered in IECS Computer Program.

```
C-9A DETAILED SIZING CASE

********
*SYSTEM*
********
    WEIGHT     846.     COST UNITS   2215.    RELIABILITY INDEX  1.3045    DEVELOPMENT RISK  1.15
    WEIGHT STANDARD ERROR     43.6
    SHAFT POWER      0.0     HYDRAULIC POWER     0.0    ELECTRICAL POWER    12.4
    EQUIVALENT SHAFT POWER      15.
    BLEED AIR EXTRACTION      83.     FUEL CONSUMPTION    163.    DRAG      0.
    0 ERROR(S) DETECTED
CASE END
```

Figure 19 C-9A ECS System Sizing Output

weight standard error of 43.6 pounds, thus the predicted installed weight plus this predicted weight error is less than the actual installed weight. The summation of component weights was very comparable - 466.4 pounds actual and 468.96 pounds from the computer program. The difference between installed weights is attributed to the use of a different system packaging concept. (See also comments about installation weight factors in Section 4.1 of Volume I.) The predicted system reliability index of 1.3045 (from Figure 19) is greater than the actual RI of 0.60124. This is due to the inclusion of nominal ducting RI's in the computer program (but not in the actual RI), and to the nominal valve RI's in the computer program which are greater than those in the C-9A (which was designed initially as a commercial aircraft). Other output indicated on Figure 19 include the system cost units of 2215, the system development risk of 1.15, the 12.4 HP used by the fan electric motor (requiring an estimated 15 HP from the engine), the 83 lb/min bleed air extraction (per engine), and the APU fuel consumption of 163 lb fuel per hour. The system cost units is slightly less than the actual, possibly reflecting a higher cost for increased reliability (i.e., low actual RI).

SECTION 6
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13. ABSTRACT

This report presents the results of a study of environmental control system (ECS) designs for aircraft. The study was performed for the Air Force Flight Dynamics Laboratory. This volume describes the computer program developed to analyze aircraft ECS and several sample problems used to evaluate and to verify the computer program. Additional sample problems are presented in Volumes III and IV. Analyses with the computer program are set up in a general manner. It is able to analyze almost any ECS. The program computes the steady state performance, the size, and aircraft penalties of an ECS. Options provide for several data input levels from rough to refined. The sample problems presented in this volume are for the rough performance and sizing of three Air Force aircraft, and the detailed performance and sizing of one Air Force aircraft. The computer program has been demonstrated on the CDC 6600 computer facility at Wright Patterson Air Force Base.

Volume I of this report presents analytical ECS design information which has been incorporated into the computer program. Volume III of this report is the users manual for the IECS Computer Program which contains information on how to use the computer program and a complete description of sample problems for rough performance and sizing analyses, and detailed performance analysis. Volume IV of this report presents the laboratory demonstration ECS, the results obtained from the tests of this ECS, and setup information and results of the computer program detailed performance and sizing analyses which were used to evaluate this ECS.

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