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AFWAL-TR-|-3139

ADVANCED |VIRONMENTAL CONTROL SYSTEM (AECS) SIMULATION PROGRAM:
IMPROVED |D NEW COMPONENTS FOR REFRIGERATION SYSTEMS AND
AN ADDITI|AL SOLUTION PROCEDURE

Theory an Users Manual

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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Block 19 (continued)

Roots Compressors
Refrigerant Boilers
Refrigerant Evaporators
Refrigerant Control Valves
Coefficient of Performance
Refrigerant Condensers
Solution Procedures
Refrigerant Pumps
Sensors
Refrigerant Separators
Refrigerant Lines
Maximum Rate of Descent

Block 20: Abstract

This document represents the final contractual reporting requirement of the subject contract on the improvements and modifications to the AECS environmental-control-system simulation program. New components were added to the AECS program to simulate the performance of equipment used in refrigeration systems. Two-phase flow and heat transfer are included in the simulations. Existing components were modified to incorporate the capability of simulating refrigerant flows and heat transfer. To accommodate the highly non-linear characteristics of refrigerants, a new alternative solution procedure was added, based on the maximum-rate-of-descent method of minimizing the RMS error. Previously, on the Newton-Raphson method was used by the program.

Sample cases are included for each new and modified component. In addition, the new solution procedure is demonstrated on a simple refrigeration system. Two examples illustrate the use of the simulation method for (1) a complex refrigeration cycle with mulitple evaporators and intercoolers and (2) a combination of a refrigeration cycle and a power cycle in which the working fluid is a refrigerant.

FOREWORD

This document was developed by Frederick A. Costello, Inc., Herndon, Virginia, under Air Force Contract F33615-80-C-3407: Advanced Environmental Control System Simulation Program: Improved and New Components for Refrigeration Systems and an Additional Solution Procedure. The work was conducted under the sponsorship of the Air Force Flight Dynamics Laboratory with Mr. Carl Feldmanis as Program Manager. The work was performed during the period September 1980 through February 1982.

The document contains descriptions of the program modifications, the users manual for the program modifications, and the supporting theory.

TABLE OF CONTENTS

1. Introduction

Prior to the work and changes reported herein, the AECS computer simulation for aircraft environmental control systems could not adequately simulate the performance of systems with vapor-compression refrigeration subsystems. The few vapor-compression cycle components that were simulated were treated in too simple a manner to be useful. In addition, the solution procedure would not converge except for a few cases. The present work corrects these deficiencies.*

Three types of changes were made to AECS: (1) new subroutines were added to simulate components not previously considered; (2) revisions were made to existing components to make the simulation models more realistic; and (3) new subroutines were added and existing subroutines were modified so the solution procedure would converge for reasonable user-defined trial solutions (Exhibit 1.1). The most dramatic new component is the intercooler (NRCLR), because it has two inlet ports such that the inlet fluid states cannot be determined for both ports prior to the NRCLR computations. A new solution procedure was devised using a new "component" called INDATA, which permits the user to estimate the inlet conditions for the second port. The most dramatic change in an existing component pertained to the vapor compressor, which can now simulate a Roots compressor with pocket feed, a new concept being developed by the Air Force. Many of the modifications made to ensure convergence of the solution procedure were corrections to errors found in the code; however, in addition, an entirely new solution procedure was introduced as an alternative. The new method is based on the maximum-rate-of-descent theory. It is particularly useful in cases where the primary solution procedure (Newton-Raphson) fails to converge. Therefore, it adds considerably to the strength of AECS as an analytical tool.

The users manual presented in the following pages is divided between the every-day portion (Section 2) and the detailed portion (Sections 3 to 19). The every-day portion contains the input data forms on a component-by-component basis. The detailed portion contains brief descriptions of the models and how these models differ from the previous models; the theoretical basis for the new models; and a highly annotated FORTRAN listing of the subroutine for computing the

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*In addition to the AECS improvements, an interactive, refrigerant-properties computer program was written under this contract to assist the user of AECS. The manual for REFRIG is a separate document. The user enters two thermodynamic properties and the computer returns with the other four.

component performance. The user can refer to the FORTRAN listing to determine the equations and logic used in the model. Once the user has become familiar with the models as presented in the detailed portion of this report, he should be able to work entirely with the every-day portion, as described in the next section. Appendix A illustrates the use of AECS for a complicated refrigeration system. The discussion includes advice on solving problems with AECS. Appendix B illustrates the skillful use of the new maximum-rate-of-descent solution procedures. Appendix C gives some advice on entering tables; Appendix D, on estimating the values for entering into the tables. AECS is applied to a combined power/refrigeration cycle in Appendix E.

Exhibit 1.1: Summary of Changes Made to AECS

Subroutine Name	Description of the Change
COND (Refrigerant Condenser)	Prior simulation limited to saturated vapor in and saturated liquid out; new simulation not restricted. Single and two-phase pressure-drop computations added.
COP (Coefficient of Performance)	New routine to permit computation of the coefficient of performance of a refrigeration system for any user-defined group of evaporators and compressors.
CVALVE (Control Valve)	Prior simulation limited to single-phase fluids. Two-phases now possible.
EVAP (Refrigerant Evaporator)	Prior simulation limited to saturated liquid in and saturated vapor out; new simulation not restricted. Single and two-phase pressure-drop computations added.
INDATA (Entering Data for a New Inlet Port)	New routine to permit solution with a component having two inlet ports with one port not the outlet of a previously computed component.
LOOPS (Loop start).	Prior simulation used temperature as possible state variable. Enthalpy now used instead, if the fluid is a refrigerant
NRCLR (Refrigerant Intercooler)	New routine to simulate a refrigerant-to-refrigerant heat exchanger.
QBOILR (Refrigerant Boiler)	New routine to simulate a heat exchanger with refrigerant on the cold side and a specified heat input on the hot side.

Exhibit 1.1: Summary of Changes Made to AECS (continued)

Subroutine Name	Description of the Change
RINLET (Refrigerant Inlet)	New entry point in INLET used for refrigerants so enthalpy can be specified rather than temperature and so a refrigerant is a permissible fluid.
ROUTLT (Refrigerant Outlet)	New entry point in OUTLET used for refrigerants so temperature is computed rather than enthalpy and so a refrigerant is a permissible fluid.
RPMP (Refrigerant Pump)	New component to simulate a refrigerant pump, pumping liquid only.
SENSOR (State sensor)	Prior simulation restricted to flow, pressure and temperature. Modification permits also enthalpy, quality, superheat and subcooling.
SEPAR (Refrigerant Separator)	New routine to simulate a liquid/vapor separator for refrigerants.
SOLN (Solution Procedure)	Prior solution procedure used only the Newton-Raphson technique. New procedure also permits the use of maximum-rate-of-descent techniques
VCOMP (Refrigerant-Vapor Compressor)	Prior simulation restricted to dynamic compression. Modification permits also positive displacement and Roots compressor, including pocket feed.
VLINE (Refrigerant Line)	Prior simulation restricted to vapor only. Modification permits any state.
XPAND (Refrigerant Expander)	New routine to simulate a refrigerant dynamic, positive-displacement or Roots expander to produce power.

2. New Component (Input) Cards

The input cards for the new or revised components are presented in the following pages. The explanations of the changes, the relevant equations, sample cases, and sample input cards are presented in Sections 3 to 19 of this report for each of the components.

Once the user is familiar with the logic and equations used for each component, he should be able to refer only to the component (input) cards presented in this section of the report. To assist the user in this regard, we have included on the input cards a brief description of the variables and their usage. Should these descriptions be too brief at first, the user can refer to Sections 3 to 19 of this report, which contain complete explanations of each model. These sections also contain sufficient detail to permit the user to judge the suitability of the simulation to his particular case.

The component (input) cards are presented in the following pages in alphabetical order. For easy reference, the component name is listed at the bottom of the page. Only the new or revised components are presented. The appendices illustrate the application of the new components to several cases, to assist the reader in developing the new skills required to obtain a solution with AECS. However, the reader must refer to previous documents for the other AECS components and for a complete discussion of the AECS procedures.

Exhibit 2.1-1: Performance Component COND Data Card Format

p 23 description

Card Column	Symbol	Value
1-4	CN	COND component name
8	CC	change code
12 1	NC	card number
16 2	NLR	leg number on refrigerant side
20 3	NSIR	inlet-station number on refrigerant side
24 4	NSOR	outlet-station number on refrigerant side
28 5	NLS	leg number on sink side
32 6	NSIS	inlet station number on sink side
36 7	NSOS	outlet station number on sink side
40 8	ISIG	option for sink side only: = 0: use delta P = 1: use sigma times delta P
44 9	IPD	sink-side pressure-drop-table relative number (Type = 1), psi as a function of sink-side flow rate in lb/min (Argument = 41)
48 10	IE	sink-side temperature-effectiveness-table relative number (Type = 5), a function of sink-side flow rate in lb/min (Argument = 41)
52 11	RPD	refrigerant-side friction-pressure-drop-table relative number (Type = 1), psi as a function of refrigerant-side flow rate in cfm with 100% vapor flowing (Argument = 42) ✓
56 12	(AFR)	flow area on the refrigerant side, sq.ft.

Notes:
The relative number, type number and argument number are required on the TABID card for the input tables.

generates no SV or EV

COND (Refrigerant Condenser)

Exhibit 2.1-2: Performance Component COP
Data Card Format

Card Column	Symbol	Value
1-3	CN	COP component name
8	CC	change code
12	NC	card number
16	NE	number of evaporators in this COP computation
20	NVC	number of vapor compressors in this COP computation
24	IE1	inlet station number for first evaporator

Continue with the inlet station numbers for the evaporators, with the inlet station numbers ending in columns 28, 32, etc. Then enter the inlet station numbers for the compressors. The following card column is based on having only one evaporator:

28	IVC1	inlet station number for first compressor

Continue with the inlet station numbers for the compressors, with the inlet station numbers ending in columns 32, 36, etc. The card column shown is based on having only one evaporator and one compressor.

Notes:
1. If the number of evaporators is entered as zero, the COP subroutine will print the sum of the Btu/min input (flow rate times enthalpy increase) to the compressors. In this case there will be no IE1 entry.
2. If the number of vapor compressors is entered as zero, the COP subroutine will print the sum of the Btu/min absorbed in the evaporators. In this case there will be no IVC1 entry.
3. The COP "component" must be inserted in the computational sequence (the list of component cards) after all of the related compressors and evaporators.
4. Any number of COP cards may be used. The output will show the evaporator and compressor inlet stations along with the coefficient of performance, so the user can easily identify which COP is being reported.
5. The following components can be used as evaporators: EVAP, QBOILR, and NRCLR. The cold leg of the NRCLR is assumed to be the evaporator. Note that NRCLR can act as a simple heat exchanger, so evaporation need not occur. Only VCOMP can be used as the compressor.

Exhibit 2.1-3: Performance Component CVALVE
Data Card Format

Card Column	Symbol	Value
1-6	CN	CVALVE component name
8	CC	change code
12	NC	card number
16	NL	leg number
20	NSI	inlet-station number
24	NSO	outlet-station number
28	ISIG	option for pressure drop = 0: use delta P = 1: use sigma times delta P
32	(KM)	minimum value of K (K=delta P in psi, or sigma times delta P, divided by flow rate squared, in lb/min)
36	(K)	initial guess for K

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Exhibit 2.1-4: Performance Component EVAP Data Card Format

Card Column	Symbol	Value
1-4	CN	EVAP component card
8	CC	change code
12 1	NC	card number
16 2	NLR	leg number on refrigerant side
20 3	NSIR	inlet-station number on refrigerant side
24 4	NSOR	outlet-station number on refrigerant side
28 5	NLS	leg number on source side
32 6	NSIS	inlet-station number on source side
36 7	NSOS	outlet-station number on source side
40 8	ISIG	option for source side only: = 0: use delta P = 1: use sigma times delta P
44 9	IPD	source-side pressure-drop-table relative number (Type = 1), psi as a function of source-side flow rate in lb/min (Argument = 41)
48 10	IE	source-side bypass factor-table relative number (Type = 5), a function of source-side flow rate in lb/min (Argument = 41)
52 11	(DSH)	refrigerant-outlet degrees of superheat, deg R (not used if IOP = 0)
56 12	RPD	refrigerant-side friction-pressure-drop-table relative number (Type = 2), psi as a function of refrigerant-side flow rate in cfm, with 100% vapor flowing (Argument = 42)
60 13	(AFR)	flow area on the refrigerant side, sq.ft.
64 14	IOP	error-variable option TYPE 3 = 0: no error variable established = 1: error variable = superheat discrepancy

para 6.A on p 46 implies this should not be used (does not have to)

EVAP (Refrigerant Evaporator)

Exhibit 2.1-5: Performance Component INDATA
Data Card Format

Card Column	Symbol	Value
1-6	CN	INDATA component card
8	CC	change card
12	NC	card number
16	NL	leg number for leg with undefined flow rate
20	NS	station number for inlet with undefined P,T,H
24	(W)	initial guess for flow rate, lb/min, in NL
28	(P)	initial guess for pressure, psia, at NS
32	(T)	initial guess for temperature, deg R, at NS
36	(H)	initial guess for humidity, lb water per lb of dry air, or enthalpy, Btu/lb, at NS

Note: This card must precede each component for which there is an inlet leg or station for which the flow rate, pressure, temperature or humidity (or enthalpy) has not been calculated as the outlet condition of a component appearing previously in the sequence of component cards. Although INDATA is required for solving some problems, its use should be minimized because INDATA decreases the speed of convergence.

INDATA (Input Data for Second Inlet Port)

Exhibit 2.1-6: Performance Component LOOPE
Data Card Format

Card Column	Symbol	Value
1-5	CN	LOOPE component card
8	CC	change code
12	NC	card number
16	NLI	leg number at the start of the loop
20	NSI	station number at the start of the loop
24	NLO	leg number at the end of the loop
28	NSO	station number at the end of the loop
32	IOP	option = ijkl i = 0: no flow error = 1: flow rate used as error variable (Note: This option will not work because the flows always match at the two ends of a leg.) j = 0: pressure is not an error variable = 1: pressure mismatch with LOOPS used as error variable k = 0: temperature is not an error variable = 1: temperature mismatch with LOOPS used as error variable l = 0: humidity (or enthalpy) is not an error variable = 1: humidity (or enthalpy) mismatch with LOOPS used as error variable

Exhibit 2.1-7: Performance Component LOOPS
Data Card Format

Card Column	Symbol	Value
1-5	CN	LOOPS component card
8	CC	change code
12	NC	card number
16	NLI	leg number at the start of the loop
20	NSI	station number at the start of the loop
24	NLO	leg number at the end of the loop
28	NSO	station number at the end of the loop
32	IFT	fluid type
36	IFN	fluid-property-table relative number (Type = 10)
40	IOP	option = ijkl i = 0: flow rate known = 1: flow rate unknown j = 0: pressure known = 1: pressure unknown k = 0: temperature known = 1: temperature unknown l = 0: humidity (or enthalpy) known = 1: humidity (or enthalpy) unknown
44	(W)	flow rate in lb/min in the outlet leg
48	(P)	pressure in psia at the outlet station
52	(T)	temperature in degrees R at the outlet station
56	(H)	humidity (lb/lb dry air) if fluid type = 1 or enthalpy (Btu/lb) if fluid type = 3, at the outlet station (not used if fluid type = 2)

Notes:
1. The parameter numbers for the loop starting values and/or initial guesses are to be inserted in Card Columns 44 to 56. The parameter value is the starting value if the option is 0 and the initial guess if the option is 1.
2. For fluid type 1, the temperature and humidity are specified by T and H and the enthalpy is computed. For fluid type 3, the pressure and enthalpy are used to compute the temperature, which overrides the value input in column 52.

Exhibit 2.1-8: Performance Component NRCLR Data Card Format

Card Column	Symbol	Value
1-5	CN	NRCLR component name
8	CC	change code
12 1	NC	card number
16 2	NLC	leg number on the cold side
20 3	NSIC	inlet-station number on cold side
24 4	NSOC	outlet-station number on cold side
28 5	NLH	leg number on the hot side
32 6	NSIH	inlet-station number on hot side
36 7	NSOH	outlet-station number on the hot side
40 8	(AFC)	flow area on the cold side, sq.ft.
44 9	(AFH)	flow area on the hot side, sq.ft.
48 10	IPD	relative number of tables for friction-pressure-drop tables (Type = 61 for cold side; Type = 62 for hot side), with pressure drop in feet of head of the fluid as a function of the flow rate for vapor only, in cfm (Argument = 101 for ~~hot~~ cold side; Argument = 102 for ~~cold~~ hot side) see code, p. 73
52 11	(HTCL)	heat-transfer coefficient in either channel if only liquid is flowing, Btu/hr-sq.ft.-deg R
56 12	(HTC2)	heat-transfer coefficient in either channel if the flow is two-phase, Btu/hr-sq.ft.-deg R
60 13	(HTCV)	heat transfer coefficient in either channel if only vapor is flowing, Btu/hr-sq.ft.-deg R
64 14	(AHTC)	heat transfer area on the cold side, sq.ft.
68 15	(AHTH)	heat transfer area on the hot side, sq.ft.

Exhibit 2.1-9: Performance Component QBOILR
Data Card Format

Card Column	Symbol	Value
1-6	CN	QBOILR component name
8	CC	change code
12	NC	card number
16	NL	leg number for refrigerant
20	NSI	inlet station number for refrigerant side
24	NSO	outlet station number for refrigerant side
28	ISIG	option for pressure-drop computation = 0: use delta P = 1: use sigma times delta P
32	IPD	friction-factor-table relative number (Type = 32), with friction factor as a function of Reynolds number (Argument = 21)
36	IHT	Colburn-factor-table relative number (Type = 33), with Colburn factor as a function of Reynolds number (Argument = 21)
40	(AF)	heat-exchanger flow area, sq.ft.
44	(Q)	heat-input-rate, Btu/min
48	(L)	heat-exchanger flow-path length, ft.
52	(AH)	heat-exchanger heat-transfer area, sq.ft., including fins
56	(DH)	heat-exchanger hydraulic diameter, ft.
60	IERR	error-variable option = 0: no error variable is generated = 1: an error variable is generated, equal to the difference between the calculated maximum wall temperature and TMAX
64	(TMAX)	maximum wall temperature (at the exit of the boiler), deg R (used only if IERR = 1) Note: the outlet must be superheated for this type of control to function properly.

Exhibit 2.1-10: Performance Component RINLET
Data Card Format

Card Column	Symbol	Value
1-6	CN	RINLET component name
8	CC	change code
12	NC	card number
16	NL	leg number
20	NS	station number
24	IOP	state-variable (s.v.) option = ijkl i = 0: flow rate known (not a s.v.) = 1: flow rate is to be a state variable j = 0: pressure known (not a s.v.) = 1: pressure is to be a state variable k = 0: temperature known (not a s.v.) = 1: not permitted. Use only k=0. l = 0: enthalpy known (not a s.v.) = 1: enthalpy is to be a state variable
28	(W)	inlet flow rate, lb/min
32	(P)	inlet pressure, psia
36	(T)	inlet temperature, deg R
40	(H)	inlet enthalpy, Btu/lb
44	IFT	inlet fluid type
48	IFN	inlet fluid property table relative number (Type = 10)

Notes:
1. The temperature cannot be used as a state variable, because there would be ambiguity in the two-phase region. The option format was retained the same as for INLET only for the convenience of the user. The temperature entry (T) is ignored by the computer; instead the temperature is calculated from the enthalpy and pressure for the refrigerant designated by IFN.
2. The entries for W, P, and H are the known values if the option is zero and the user's estimate of the solution if the option is 1.

Exhibit 2.1-11: Performance Component ROUTLT
Data Card Format

Card Column	Symbol	Value
1-6	CN	ROUTLT component name
8	CC	change code
12	NC	card number
16	NL	leg number
20	NS	station number
24	IOP	error-variable (e.v.) option = ijkl i = 0: flow rate is not to be an e.v. = 1: flow rate is to be an error variable j = 0: pressure is not to be an e.v. = 1: pressure is to be an error variable k = 0: temperature is not to be an e.v. = 1: not permitted. Use only k=0. l = 0: enthalpy is not to be an e.v. = 1: enthalpy is to be an error variable
28	(W)	outlet flow rate, lb/min
32	(P)	outlet pressure, psia
36	(T)	outlet temperature, deg R
40	(H)	outlet enthalpy, Btu/lb

Notes:

1. The temperature cannot be used as an error variable, because there would be ambiguity in the two-phase region. The option format was retained the same as for OUTLET only for the convenience of the user. The temperature entry (T) is ignored by the computer; instead the temperature is calculated from the refrigerant properties, the enthalpy and the pressure.
2. The entries for W, P, and H are the required values. The error variable is the difference between these values and the values computed in the simulation.

Exhibit 2.1-12: Performance Component RPMP (Refrigerant Pump)

Card Column	Symbol	Value
1-4	CN	RPMP component name
8	CC	change code
12	NC	card number
16	NL	leg number
20	NSI	inlet station number
24	NSO	outlet station number
28	NST	shaft number
32	IPT	relative number for pressure-rise table (Type = 8), with pressure-rise, DP as a function of shaft speed, RPM, (Argument = 101) and flow-rate, (lb/min) (Argument = 102)
36	IE	relative number for pump static-efficiency table (Type = 9), as a function of shaft speed, RPM, (Argument = 101) and flow rate, (lb/min) (Argument = 102)
40	IME	mechanical-efficiency table (Type = 10), as a function of the pump input horsepower, HP (Argument = 101)

Notes:

1. The pressure rise, DP, is the difference, not the ratio, between the pump outlet and inlet pressures.

NEW (costello vapor cycle improvements)

SEN PP

SENPZ

Exhibit 2.1-13: Performance Component SENSOR Data Card Format

Card Column	Symbol	Value
1-6	CN	SENSOR component name
8	CC	change code
12	NC	card number
16 2	NL	leg number
20 3	NS	station number
24 4	ICT	option: sensed & controlled variable
		= 1: flow rate, lb/min
		= 2: pressure, psia
		= 3: temperature, deg R
		= 4: humidity, lb vapor/lb dry air or enthalpy, Btu/lb
		= 5: superheat, deg R
		= 6: subcooling, deg R
		= 7: quality, lb vapor/lb mixture
28 5	(CV)	set point (control value) of the sensor

p 42 → no change to CVALVE

SENSOR

Exhibit 2.1-14: Performance Component SEPAR (Refrigerant Separator) Data Card Format

Card Column	Symbol	Value
1-5	CN	SEPAR component name
8	CC	change code
12	NC	card number
16	NLI	inlet leg number
20	NSI	inlet station number
24	NLOG	number of outlet leg having vapor only
28	NSOG	number of outlet station having vapor only
32	NLOF	number of outlet leg having liquid only
36	NSOF	number of outlet station having liquid only

Exhibit 2.1-15: Performance Component SOLN

Data Card Format

Card Column	Symbol	Value
1-4	CN	SOLN component name
8	CC	change code
12	NC	card number
16	MRD	solution-technique option code = 0; use Newton-Raphson (KOPT defaults to 0) = 1: use MRD1, minimizing with respect to each state variable, one at a time = 2: use MRD2, minimizing with respect to the state variables, one pair at a time = 3: use MRD, minimizing with respect to all state variables simultaneously

If MRD is greater than 0, then enter the following:

Card Column	Symbol	Value
20	KSV	relative number for one-dimensional table giving state-variable scale factors (Type = 50 and Dimension = -1 (See App. C))
24	KEV	relative number for one-dimensional table giving error-variable scale factors (Type = 51 and Dimension = -1 (See App. C))
28	[STEP]	initial step size, a fraction of the diagonal
32	[RST]	ratio of step sizes if in same direction

If MRD = 1 or MRD = 2, then enter the following:

Card Column	Symbol	Value
36	LIST	number of the (state) variable over which the first minimization is to be performed

Continue with the state-variable numbers (up to NSV). Enter in Column 40 the number of the state variable over which the second minimization is to be performed; etc.

Notes:

1. SOLN is to be entered as the last component.
2. If SOLN is omitted, the Newton-Raphson method will be used. This is the method that was used by AECS prior to this modification.
3. If KSV is omitted (or, equivalently, entered as 0) and MRD . 0, all state-variable scale factors will be 1.0. The program will accept up to 20 state variables in the MRD solutions.
4. If KEV is omitted (or, equivalently, entered as 0) and MRD . 0, all error-variable scale factors will be 1.0. Note that if KSV is omitted, KEV must still be in Column 24 if it is entered. Note also that the error-variable scale factors are used as the iteration limit.
5. If LIST is omitted, MRD1 and MRD2 will use the state variables in the order of the state-variable numbers. If the list of KSV's does not include all state variables, MRD1 and MRD2 will use the remaining state variables in the order of the remaining state-variable numbers.
6. In MRD methods, after each step, STEP is reset to STEP*RST**DSUM, where DSUM is the cosine of the angle between successive steps.
7. COMMON cards can be used to change C(373) from the default limit of 3 iterations per variable in MRD1 and pair of variables in MRD2 and to change C(76) from the default limit of 40 system iterations (changes in the complete set of state variables) for all four solution options.

SOLN (Solution Procedure)

Exhibit 2.1-16: Performance Component VCOMP
Data Card Format

Card Column	Symbol	Value
1-5	CN	VCOMP component name
8	CC	change code
12	NC	card number
16	NLI	leg number for inlet (lowest pressure)
20	NSI	station number for inlet (lowest pressure)
24	NSO	station number for outlet (highest pressure)
28	NST	shaft number
32	IOP	state-variable (s.v.) option = 0: no state variable is set up and pressure ratio is held fixed = 1: pressure ratio is set up as s.v. = 2: no state variable is set up and pressure ratio is determined from the Type = 4 table specified below
36	(PR)	pressure ratio If IOP = 0: fixed = 1: initial guess for s.v. = 2: not used
40	IPT	relative number for pressure ratio table (Type = 4), in the form pressure ratio vs. shaft speed (RPM, Argument = 101) and inlet flow rate (CFM, Argument = 28)
44	ICT	relative number for efficiency table (Type = 6) in the form efficiency vs. shaft speed (RPM, Argument = 101) and inlet flow rate (CFM, Argument = 28)
48	(ME)	mechanical efficiency
52	KT	compressor-type option = 0: conventional dynamic or positive-displacement compressor = 1: conventional Roots compressor = 2: Roots compressor with pocket feed

VCOMP creates 6A28= cfm

If KT is 1 or 2, the following additional entry is required:

Card Column	Symbol	Value
56	(DISP)	compressor displacement per revolution (cu.ft.)

If KT is 2, the following additional entries are required:

Card Column	Symbol	Value
60	NLP	number of the leg feeding the pocket (intermediate pressure)
64	NSP	number of the station at the pocket inlet
68	NLO	leg number of the compressor outlet (highest pressure)
72	(FH)	fraction of the leakage flow (from highest pressure to inlet pressures) that passes to the intermediate (pocket-feed) pressure

Notes:

1. If KT=2, an error variable is set up equal to the deviation between the pocket pressure and the pocket pressure required to balance the flows between the inlet and the pocket.
2. If KT,1, the output will show ***** for the pocket leg number.

VCOMP (Refrigerant Compressor)

Exhibit 2.1-17: Performance Component VLINE Data Card Format

Card Column	Symbol	Value
1-5	CN	VLINE component name
8	CC	change code
12	NC	card number
16	NL	leg number
20	NSI	inlet-station number
24	NSO	outlet-station number
28	-	
32	IPD	friction-factor-table relative number (Type = 3), in the form of friction factor as a function of Reynolds number (Argument = 21)
36	(UAPDL)	heat-loss factor, ~~Btu/min per foot of line length per degree difference between fluid temperature and surrounding temperature~~ BTU/ft^{2}hr°F see p 173
40	(DH)	hydraulic diameter, ft.
44	(L)	line length, ft.
48	(K)	velocity-head loss coefficient for valves, bends, orifices, etc., not otherwise simulated
52	(LE)	equivalent length of line due to valves, bends, orifices, etc., not otherwise simulated and not included in the K factor, ft.
56	(TS)	temperature of surroundings, deg R

VLINE (Refrigerant Line)

Exhibit 2.1-18: Performance Component XPAND
Data Card Format

Card Column	Symbol	Value
1-5	CN	XPAND component name
8	CC	change code
12	NC	card number
16	NL	leg number
20	NSI	inlet-station number
24	NSO	outlet-station number
28	NS	shaft number
32	IOP	option for computational technique = 0: pressure ratio is fixed (no error variable is set up). Flow rate and shaft speed are assumed to be compatible with this pressure ratio = 1: shaft speed and flow rate will be known upon entering this component (pressure ratio is determined from the tables) = 2: pressure ratio and flow rate will be known upon entering this component. Discrepancy between shaft speed from component SHAFT and as computed in XPAND is an error variable
36	(PR)	ratio: outlet pressure to inlet pressure (,1.0)
40	IQ	relative number for two tables: the flow-rate table (Type = 8), having the flow rate (CFM) as a function of shaft speed (RPM, Argument = 102) and pressure ratio (PR, Argument 101); and the efficiency table (Type = 7), having the efficiency as a function of shaft speed (RPM, Argument 102) and flow rate (CFM, Argument = 101)
44	(ME)	mechanical efficiency
48	(D3)	displacement per revolution, cu.ft.
52	(AO)	ratio: outlet area of expander to D3**(2/3)

Notes:

1. The flow rate is given by:
Flow rate = (lb/min)*(inlet cu.ft./lb.)
2. The pressure ratio is the outlet pressure divided by the inlet pressure.

3. Condenser Subroutine COND

3.1. Subroutine Description

The COND subroutine simulates a refrigerant condenser in which the refrigerant is cooled from a superheated or saturated vapor down to a liquid or two-phase mixture. The cooling fluid can be air or any other single-phase fluid. The inlet on the refrigerant side would normally be downstream from a compressor. The outlet on the refrigerant side would normally be upstream of an expansion valve or an intercooler. A controller might be used to regulate the coolant supply so the refrigerant pressure would not become so low that the expansion valve could not control. The coolant would normally enter the condenser on one side and leave on the other; there would be no phase change on the coolant side.

3.2. Prior Simulation Method

The previous condenser model was based on the heat loss by the refrigerant being the heat of condensation (latent heat of vaporization). It did not include the refigerant-side pressure drop. The heat-transfer in the condenser was characterized by the effectiveness, which was entered as a function of the coolant-side flow rate.

3.3. New Simulation Method

The new model again characterizes the condenser heat exchange by its effectiveness. However, the inlet state of the refrigerant can now be superheated; the outlet state can range from superheated to subcooled. The outlet state is determined by an energy balance, with the heat transfer being calculated from the coolant-side flow rate and temperature rise, as computed from the effectiveness. The effectiveness is based on the condensing temperature, which is assumed equal to the saturation temperature at the inlet pressure. Adjustments are made to the effectiveness to account for the refrigerant being in the pure liquid state near the exit.

The pressure drop on the refrigerant side is entered as a table for vapor-only flow; corrections for condensation and two-phase flow are contained within the subroutine.

The pressure drop on the air side is computed as before, on the basis of a table of pressure drop versus air flow rate.

3.4. Computational Procedure

The computational procedure is presented in the form of a heavily annotated FORTRAN program listing (Exhibit 3.4-1).

Exhibit 3.4-1: Performance-Program Logic and Listing

```
      SUBROUTINE CONDPP
      COMMON /CC/ C(400)
      EQUIVALENCE (IRCD,C(45)),(IW,C(27)),(IP,C(28)),(IT,C(29))
     *,(IH,C(30)),(SCR(1),C(151)),(IFB,C(55)),(IGA,C(35))
     *,(IEVT,C(48)),(IEV,C(49)),(IFP,C(22)),(ICPP,C(88))
     *,(PASS,C(17)),(OUT,C(7)),(GC,C(370))
      INTEGER PASS,OUT
      EQUIVALENCE (SCR(1),NLR),(SCR(2),NSIR),(SCR(3),NSOR)
     *,(SCR(4),NLS),(SCR(5),NSIS),(SCR(6),NSOS),(SCR(7),JEVI)
      DIMENSION SCR(30),ERR(3),EL(3)
      COMMON /DC/ DZ(2),D(2)
      DIMENSION ID(2)
      EQUIVALENCE (ID(1),D(1))
      EQUIVALENCE (D(51),H),(D(52),QUAL),(D(53),VOUT),(D(54),PB),
     *(D(55),PDGO),(D(56),PDR),(D(57),VRATIO),(D(58),PDLO),
     *(D(59),HFG),(D(60),PHI),(D(61),TC),(D(62),V),(D(63),HSV),
     *(D(64),VMOMIN),(D(65),HSL),(D(66),EFF),
     *(D(68),Q),(D(69),TOUT),(D(70),TAVG),(D(71),PD)
C  1 COMP CODE
C  2 LEG NO R
C  3 INLET STATION NO R
C  4 OUTLET STATION NO R
C  5 LEG NO S
C  6 INLET STATION NO S
C  7 OUTLET STATION NO S
C  8 PRESS DROP OPTION
C  9 PRESS DROP TABLE NO .
C 10 EFFECTIVENESS TABLE NO.
C***TWO NEW PARAMETERS FOR THE COMPONENT CARD
C 11 REFRIG-SIDE PRESS DROP TABLE(FT OF VAPOR VS CFM, VAPOR FLOW ONLY)
C 12 FLOW AREA ON REFRIGERANT SIDE, SQ FT
C***SET UP THE INTERNAL VARIABLES IN TERMS OF THE STORED ARRAY
      IRCD = IRCDB(13)
      NLR = ID(IRCD+2)
      NSIR = ID(IRCD+3)
      NSOR = ID(IRCD+4)
      NLS  = ID(IRCD+5)
      NSIS = ID(IRCD+6)
      NSOS = ID(IRCD+7)
      D(IH+NSOS) = D(IH+NSIS)
      LOCT = ID(IFB+NLR)
      LOCS = ID(IFB+NLS)
      LOCS = ID(LOCS+1)
      LOCT = ID(LOCT+3)
C***SET UP THE THREE TLUP VARIABLES
      D(IGA+41) = D(IW+NLS)
      D(IGA+42) = D(IW+NLR)
      D(IGA+43) = D(IP+NSIS)
```

sink flow
lbm/min
becomes CFM on p. 25

```
***COMPUTE THE SATURATION CONDITIONS
      TC = VTS(LOCT,D(IP+NSIR))
      V = VSV(LOCT,D(IP+NSIR),TC)
      D(IGA+42)=D(IGA+42)*V
      HSV = VH(LOCT,D(IP+NSIR),TC,V)
      HFG = VHFG(LOCT,D(IP+NSIR),TC,V)
      HSL = HSV - HFG
      IF(TC.LT.D(IT+NSIS)) GO TO 25
***DETERMINE SINK-SIDE EFFECTIVENESS FROM TLUP WITH EFF A
  FUNCTION OF SINK-SIDE FLOW RATE ONLY
      EFF =  TLUP(ID(IRCD+10))
***COMPUTE SINK-SIDE OUTLET TEMPERATURE FROM EFFECTIVENESS
      D(IT+NSOS) = D(IT+NSIS) + EFF * (TC - D(IT+NSIS) )
***COMPUTE THE REFRIG OUTLET ENTHALPY BY ENERGY BALANCE
      CAPSINK = D(IW+NLS)*SHP(NLS,D(IP+NSIS),D(IT+NSIS),D(IH+NSIS))
      Q = CAPSINK*EFF*(TC-D(IT+NSIS))
      H == D(IH+NSIR)-Q/D(IW+NLR)
      D(IH+NSOR)=H
***DETERMINE IF IN SINGLE-PHASE REGION AT THE OUTLET CONDITIONS
      IF (H.LE.HSL) GO TO 20
      IF (H.GE.HSV) GO TO 30
***IN TWO-PHASE REGION
      QUAL = (H-HSL)/HFG
      TOUT=TC
      VOUT = QUAL * V + (1.-QUAL)/VDL(LOCT,TOUT)
      GO TO 40
*** IN SINGLE-PHASE REGION, SO DETERMINE WHERE THE TWO-PHASE ENDED
   20 TOUT=VTLIQ(LOCT,D(IP+NSIR),H)
      QUAL=0.0
      CPREF=(HSL-H)/(TC-TOUT)
      CAPR=D(IW+NLR)*CPREF/CAPSINK
*** SET UP FOR STRADDLE SOLUTION TO LOCATION OF POSITION (EL) WHERE
    THE TWO-PHASE FLOW ENDED
      EMAX=D(IW+NLR)*(D(IH+NSIR)-HSL)/(CAPSINK*(TC-D(IT+NSIS)))
      EL(1)=EMAX
      EL(2)=EMAX/(EMAX+CAPR)
      IF (EL(2).EQ.EL(1)) EL(2)=1.1*EL(1)
      I=1
*** TAKE UP TO 30 ITERATIONS TO FIND EL, COMPUTING THE EFFECTIVENESS
    IN THE SINGLE-PHASE (EFF1) AND TWO-PHASE (EFF2) REGIONS
      DO 570 ITER=1,30
      EFF1=1.-(1.-EFF)**((1.-EL(I))/(2.*CAPR))
      EFF2=1.-(1.-EFF)**EL(I)
      ERR(I)=EMAX-EFF2*(1.-CAPR*EFF1)
      IF(ITER.GT.2) GO TO 559
      I=I+1
      IF(ITER.LT.2) GO TO 570
      GO TO 563
*** IF THE EFFECTIVENESSES BALANCE WITHIN 0.001, END ITERATION
  559 IF(ABS(ERR(3)).LT.0.00001) GO TO 571
      IF(ERR(3).GT.0.0) GO TO 561
      ERR(2)=ERR(3)
```

ICFM on Refrig side

```
      EL(2)=EL(3)
      GO TO 563
  561 EL(1)=EL(3)
      ERR(1)=ERR(3)
  563 EL(3)=EL(1)-ERR(1)*(EL(2)-EL(1))/(ERR(2)-ERR(1))
  560 CONTINUE
C*** BASED ON THE BALANCED EFFECTIVENESSES, COMPUTE THE OUTLET CONDITIONS
      EFF=EMAX+CAPR*EFF1
      Q=CAPSINK*EFF*(TC-D(IT+NSIS))
      H=D(IH+NSIR)-Q/D(IW+NLR)
      TOUT=VTLIQ(LOCT,D(IP+NSIR),H)
C*** IF TOUT.LT.TSINK, WRITE A WARNING
      IF(TOUT.LT.D(IT+NSIS)) GO TO 27
      D(IH+NSOR)=H
      IF(ITER.GE.30) WRITE(OUT,640) D(IT+NSIS),TOUT,TC,EL(1),
     * EL(2),EL(3)
  640 FORMAT (" *** WARNING FROM CONDPP: ITERATION FAILED"/
     *"      SINK INLET TEMPERATURE =",F8.2,"  REFRIG OUTLET TEMP =",
     *F8.2,"  CONDENSING TEMP =",F8.2,/,"  RATIO OF TWO-PHASE",
     *" LENGTH TO TOTAL LENGTH WAS COMPUTED TO BE GREATER THAN",F9.6,
     *" AND LESS THAN",F9.6,/," WITH LAST ESTIMATE BEING",F9.6)
C***IN SUBCOOLED REGION AT OUTLET
   26 VOUT=1./VDL(LOCT,TOUT)
      GO TO 40
   25 TOUT=D(IT+NSIS)
      H=HSV
      Q=D(IW+NLR)*(D(IH+NSIR)-H)
      D(IT+NSOS)=D(IT+NSIS)+Q/(D(IW+NLS)*SHP(NLS,D(IP+NSIS),D(IT+NSIS),
     * D(IH+NSIS)))
      QUAL=1.
      WRITE(OUT,1103)TC,D(IT+NSIS)
 1103 FORMAT(" *** WARNING IN CONDPP REFRIGERANT  COND. TEMP = ",F10.3/
     * " *** LESS THAN INLET SINK TEMPERATURE ",F10.3/
     * " *** REFRIGERANT OUTLET TEMP RESET TO INLET SINK TEMP AND"/
     * " *** OUTLET SINK TEMPERATURE IS RECOMPUTED")
      GO TO 40
   27 WRITE(OUT,1105)TOUT,ITER,D(IT+NSIS),TC
      TOUT=D(IT+NSIS)
      H=VHLIQ(LOCT,D(IP+NSIR),TOUT)
      D(IH+NSOR)=H
      Q=D(IW+NLR)*(D(IH+NSIR)-H)
      D(IT+NSOS)=D(IT+NSIS)+Q/(D(IW+NLS)*SHP(NLS,D(IP+NSIS),
     *D(IT+NSIS),D(IH+NSIS)))
 1105 FORMAT(" *** WARNING IN CONDPP REFRIGERANT OUTLET TEMP = ",F10.3/
     *" *** EVEN AFTER",I8,"  ITERATIONS, IS STILL"/
     *" *** LESS THAN INLET SINK TEMPERATURE ",F10.3/
     *" *** CONDENSING TEMPERATURE = ",F10.3/
     *" *** REFRIGERANT OUTLET TEMP RESET TO INLET SINK TEMP AND"/
     *" *** OUTLET SINK TEMPERATURE IS RECOMPUTED")
      VOUT=1./VDL(LOCT,TOUT)
      GO TO 40
   30 QUAL = 1.
```

```
***IN SUPERHEAT REGION AT OUTLET
      CALL VTAV2(LOCT,TOUT,VOUT,D(IP+NSIR),H)
***REFRIG-SIDE PRESS DROP VS MASS FLOW RATE AS IF VAPOR ONLY
   40 D(IT+NSOR)=TOUT
      PDGO = TLUP(ID(IRCD+11))  — psi refrig ΔP vs. CFM @100% vapor
      PDR=PDGO
      IF (QUAL.GE.1.) GO TO 80
      VRATIO = V*VDL(LOCT,TC)
      SLIP = (VRATIO-1.)**0.25     (use V)
      CALL VTAV2(LOCT,TIN,VIN,D(IP+NSIR),D(IH+NSIR))
***REFRIG-SIDE PRESS DROP LIQUID ONLY USING SAME FRICTION FACTOR
      PDLO=PDGO/VRATIO                               use V  add divisor of 2
***MOMENTUM AT INLET BASED ON VAPOR-ONLY FLOW                (as in q=1/2 ρ V²)
      VMOMIN=(D(IW+NLR)/D(ID(IRCD+12))/60.)**2*VIN/(GC*144.)
***TWO-PHASE PRESSURE DROP PER FAC CORRELATION OF BAROCZY
      PB=-0.25*ALOG10(VRATIO)
      IF (PB.LT.-1) PB=-1.
      PHI=-PB*(1.-QUAL**2.65)/2.65+(1.+PB)*((1-QUAL**1.7)/1.7+
     *    (1.-QUAL)**2.3*QUAL/2.3+(1.-QUAL)**3.3/2.3/3.3)
      PHI=PHI/(1.-QUAL)
      PDR=PDLO+PHI*(PDGO-PDLO)
***PRESSURE RECOVERY DUE TO MOMENTUM DECREASE
      VOIDF = QUAL/(QUAL+SLIP*(1.-QUAL)/VRATIO)
      XMOM=((1.-QUAL)/(1.-VOIDF))**2*(1.-VOIDF*(1.-SLIP*SLIP/VRATIO))
      DELTAM=(XMOM/VRATIO-1.)*VMOMIN
      PDR=PDR+DELTAM
***OUTLET PRESSURE
   80 D(IP+NSOR) = D(IP+NSIR) - PDR
      IF(D(IP+NSOR).GT.0.0)GO TO 82
       WRITE(OUT,7655)D(IP+NSOR),D(IP+NSIR)
 7655 FORMAT(" *+* OUTLET PRESSURE IN COND WAS ",E14.7,
     * "  RESET PRESSURE TO INLET VALUE ",E14.7)
      D(IP+NSOR)=D(IP+NSIR)
   82 CONTINUE
***PRESSURE DROP ON SINK SIDE
      TAVG = (D(IT+NSIS) + D(IT+NSOS)) / 2.      sink ΔP vs W
      PD = TLUP(ID(IRCD+9))
      IF(ID(IRCD+8).NE.0) PD = PD / SIG(NLS,D(IP+NSIS),TAVG)
      D(IP+NSOS) = D(IP+NSIS) - PD
***BECAUSE WE NOW BALANCE THE ENERGY, THE SINK OUTLET TEMPERATURE
    WILL BE COMPUTED CORRECTLY, SO THERE WILL BE NO ERROR.
    THE PRIOR METHOD INCURRED AN ERROR BECAUSE THE REFRIGERANT
    ENTHALPY WAS ALWAYS HFG AND THE REFRIG MASS FLOW WAS COMPUTED
    EXTERNALLY FOR THE LEG.

          TO MAINTAIN THE PARALLEL WITH THE PRIOR METHOD,
    WE ASSUME THE OUTLET TEMPERATURE WAS COMPUTED EXTERNALLY,
    SO THE ERROR VARIABLE IS THE DIFFERENCE BETWEEN WHAT IS
    COMPUTED HERE AND WHAT WAS COMPUTED EXTERNALLY.
***  IF THE HUMIDITY IS NON-ZERO AND THE FLUID TYPE IS A GAS,
     COMPUTE THE DRY-BULB TEMPERATURE
      IF(D(IH+NSIS).NE.0.0.AND.LOCS.EQ.2) CALL TDB(NLS,NSIS,NSOS,HS)
```

```
      IF(IFP.NE.1 .OR. ICPP.NE.Ø) GO TO 99
      CALL PIOP(1,NLR,NSIR,NSOR)
      CALL PIOP(2,NLS,NSIS,NSOS)
      IF(D(IH+NSIS).EQ.Ø.Ø ) GO TO 9Ø
      IF (D(IH+NSOS).GT.HS) CALL HSOP(HS)
   90 CONTINUE
      CALL LINES(2)
      WRITE(OUT,1ØØ1) EFF,Q
 1001 FORMAT(1HØ,5X,3HEFF,F7.4,3X,1HQ,F9.2 )
   99 CONTINUE
      RETURN
      CONDPP
```

The pressure-drop computation for the two-phase flow is based on the FAC, Inc., correlation of Baroczy's method, as was used in QBOILR and the other routines developed under this contract. The pressure-drop computation includes the momentum change between the inlet and outlet. Slip velocities and void fractions are based on a correlation with the liquid-to-vapor density ratio only.

There is no error variable generated in condenser. A sensor should be used if the condensing pressure or the subcooling is to be controlled. The prior simulation generated an error variable as the difference between the heat gained by the air and the heat lost by the refrigerant. Because a heat balance is now used to determine the exit state of the refrigerant, this error is now always zero.

3.5. Program Listing

Exhibit 3.4-1, which presents the program computational procedure, also is the program listing as used in AECS. However, so computer storage space is conserved, the AECS program does not include the comment cards.

3.6. Sample Case

The sample case, as depicted in Exhibit 3.6-1, is based on having the condenser alone as the total system. The input data are shown in the required format for AECS input. The corresponding output data are shown in the system schematic (Exhibit 3.6-1) as well as in the output format (Exhibit 3.6-2), starting with Page 7 of the output, the beginning of the computed data. Previous pages contain the headers and a repeat of the input data.

3.7. Technical Background

The technical basis for the pressure-drop computation on the refrigerant side is contained in the section on QBOILR. The method is not standard but correlates well respected data. The momentum recovery is assumed to be 100%.

The remainder of the theory is the same as used in the prior simulation method and is in the standard literature on heat exchangers. The effectiveness is based on the condensing temperature:

$$\text{Effectiveness} = (T_{cool,out} - T_{cool,in})/(T_{condensing} - T_{cool,in})$$

where Tcool is the coolant temperature. If most of the heat transfer is in the superheated region, an adjustment will be required in the effectiveness table, perhaps including an effectiveness greater than 1.0. Otherwise, AECS will predict a required condenser size larger than will be found necessary in practice.

The effectiveness as entered in the tables is adjusted depending on the location of the beginning of the liquid-only flow region on the refrigerant side. The effectiveness as entered in the user-defined tables is applied to the two-phase region. The overall heat-transfer coefficient (U) in the two-phase region is deduced from the equation for the effectiveness:

E2 = Effectiveness = 1 - EXP(-U*A*LR/(M*CP))

where M = mass flow rate of the sink
CP = specific heat of the sink
LR = ratio of the length of the two-phase region to the total length of the heat exchanger

The heat-transfer coefficient in the liquid-only region is assumed to be U/2, and the effectiveness in the two-phase region is assumed to be given by the equation for counter-flow heat exchangers:

E1 = Effectiveness = (1 - E) / (1 - C*E)

where E = EXP(-U*A*(1 - LR)/(2*MR*CPR))
MR = mass flow rate of the refrigerant
CPREF CPR = specific heat of the liquid refrigerant
C = MR*CPR/M*CP
CAPR

Because C is much less than 1.0 for all practical cases, this equation is simplified within the computer routine to:

E1 = Effectiveness = 1 - E

If ED is the effectiveness as entered in the user-defined tables, then the equations for E1 and E2 can be written:

E1 = 1 - (1 - ED)**((1 - LR)/(2*C))

and

E2 = 1 - (1 - ED)**LR

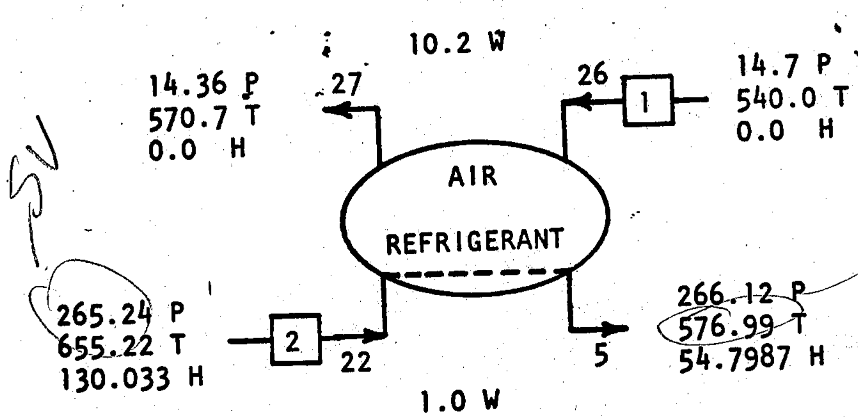
The value of LR is determined iteratively within the condenser simulation routine, with the iteration being terminated when the heat loss from the refrigerant side equals the heat gain on the sink side.

Exhibit 3.6-1: Input Cards and Flow Diagram for the Sample Case

```
ERFORM
TI    EXAMPLE CASE FOR CONDENSER
ASE     COND      0000    2    4    0
ASEB      0    0    0    0    0
ASEC      0.0               0.0          0.0
ASED      0.0
ARAM   20
ALUES   1   10.202      14.7       540.00       0.0        0.0001
ALUES   6   14.202      14.5       565.00       0.0        0.0
ALUES  11    1.0      275.6962     656.92     130.033      0.0
ALUES  16    1.0      272.1834     577.00      44.82       0.0
LET      10    1   260000    1    2    3    4    2   -1
LET      20    2   220100   11   12   13   14    3  -22
ID       30    2   22    5    1   26   27    0    1    2    3    5
TLT      40    2    50010   16   17   18   19
LET      50    1   270000    6    7    8    9
ID        1    1    2    0    0   410101    2
T        AIR SIDE PRESS DROP T=1 RN=1 (IND.VAR.=AIR FLOW)
V           0.0           0.0          30.0         1.0
ID        2    5    2    0    0   410101    2
T        AIR SIDE EFFECTIVENESS T=5 RN=2 (IND.VAR.=AIR FLOW)
V           0.0           1.0          30.0         0.5
ID        3    1    2    0    0   420101    2
T        REFRIG SIDE PRESS DROP T=1 RN=3 (IND.VAR.=REFRIG FLOW)
V           0.0           0.0           2.0         6.0
AB        1    0    1    0
CASE
```

R-22 press = SV

R-22 outlet temp = EV = 577°R



Note: Not all of the parameter values listed are used.

Exhibit 3.6-2: AECS Output for the Sample Case

```
BVT
(   1)    2

EVT
(   1)    3

PASS      1

S.V.
(    1) 2.75696E+02

E.V.
(    1) 3.00001E+00

W
(    1) 1.02020E+01 (    2) 1.00000E+00

P
(   26) 1.47000E+01 (   22) 2.75696E+02 (    5) 2.76658E+02 (   27) 1.43599E+01

T
(   26) 5.40000E+02 (   22) 6.56925E+02 (    5) 5.80000E+02 (   27) 5.73199E+02

H
(   26) 0.            (   22) 1.30033E+02 (    5) 4.86869E+01 (   27) 0.

COMPONENT  COND

     NL         2   NSI      22   NSO       5   FT        3   FN      -22

     W      1.00   PI   265.24   PO   266.12   TI   655.22   TO   576.99   HI130.0330   HO 54.7987

     NL         1   NSI      26   NSO      27   FT        2   FN       -1

     W     10.20   PI    14.70   PO    14.36   TI   540.00   TO   570.70   HI   0.0000   HO   0.0000

     EFF   .8300   Q     75.23
*AECS*  EXAMPLE CASE FOR CONDENSER                                                PAGE        8
    1  CASE  COND                                                                 DATE 09/06/81

TIME E       92.91

FLOW RATE(S)-LB/MIN

(    1)    10.20 (    2)     1.00

PRESSURE(S)-PSI

(    5)   266.12 (   22)   265.24 (   26)    14.70 (   27)    14.36

TEMPERATURE(S)-DEG R

(    5)   576.99 (   22)   655.22 (   26)   540.00 (   27)   570.70

HUMIDITY(S)/ENTHALPY(S)-LBW/LBA / BTU/LB
```

```
(    .7987 (  22)130.0330 (  26)  0.0000 (  27)  0.0000

STATE VARIABLE TYPE(S)
(    1)    2

STATE VARIABLE(S)
(    1) 2.65239E+02

ERROR VARIABLE TYPE(S)
(    1)    3

ERROR VARIABLE(S)
(    1)-5.36060E-03

SOLUTION CONVERGED IN       5 TRY(S)

     0 ERROR(S) DETECTED

CASE END
```

4. Subroutine COP (Coefficient of Performance)

4.1. Subroutine Description

The COP subroutine is a computational subroutine, rather than a simulation subroutine. It computes the coefficient of performance of the vapor-compression refrigeration system for any user-specified group of evaporators and compressors. More than one COP component can be included in a simulation. If no evaporator is included in the COP component specification, the COP subroutine simply sums (and prints) the compressor powers. If no compressor is included in the COP component specification, the COP subroutine simply sums (and prints) the evaporator heat transfer rates.

4.2. Prior Simulation Method

The COP subroutine is a new subroutine with no prior counterpart. Previously, the COP could be computed with the MISC component.

4.3. New Simulation Method

The COP subroutine first sums the heat transfer rates in each of the user-specified evaporators. It then sums the compressor power in each of the user-specified compressors. The Coefficient of Performance (COP) is defined as the ratio of the sum of the heat-transfer rates to the sum of the compressor powers. COP is a dimensionless measure of the effectiveness of the vapor-compression refrigeration cycle.

In the computations, the heat-transfer rates are computed from the enthalpy increase of the refrigerant passing through the evaporators. The compressor powers are computed from the enthalpy increase of the refrigerant passing through the compressor. The corresponding flow rates are evaluated at the inlets to the components. Note that, if a Roots compressor with pocket feed is used, the user must enter the data as if for two compressors: one compressing from the conventional inlet to the exhaust and one compressing from the pocket inlet to the exhaust.

4.4. Computational Procedure

The computational procedure is presented in the form of a heavily annotated FORTRAN program in Exhibit 4.4-1.

4.5. Program Listing

Exhibit 4.4-1 not only defines the computational procedure; it also presents the program listing. However, so computer storage space might be conserved, the AECS program does not include the comment cards.

```
      SUBROUTINE COPPP
      COMMON/CC/C(400)
      EQUIVALENCE (OUT,C(7)),(IW,C(27)),
     * (IH,C(30)),(ISN,C(38)),(ICDB,C(43)),
     * (NCOMP,C(44)), (IRCD,C(45)), (IFP,C(22)), (ICPP,C(88)),
     * (SCR(1),C(151))
      INTEGER OUT
      DIMENSION SCR(30)
      EQUIVALENCE (SCR(1),NE), (SCR(2),NVC), (SCR(3),QCOOL),
     * (SCR(4),QWORK), (SCR(5),IRET), (SCR(6),ISTA
                              ), (SCR(7),LOC),
     * (SCR(8),LCOMP), (SCR(9),NSI), (SCR(10),NS0), (SCR(11),NL)
      COMMON/DC/DZ(2),D(2)
      DIMENSION ID(2)
      EQUIVALENCE (ID(1),D(1))
C   1 COMP CODE
C   2 NUMBER OF EVAPORATORS
C   3 NUMBER OF COMPRESSORS
C 4-18 INLET STATION NUMBERS OF EVAPORATORS AND VAPOR COMPRESSORS
C*** THE FOLLOWING FUNCTION COMPUTES THE WORK OR HEAT TRANSFER
      QFUNC(NSI,NSO,NL) = D(IW+NL)*(D(IH+NSO)-D(IH+NSI))
      IF (IFP.NE.1 .OR. ICPP.NE.0) GO TO 99
      IRCD=IRCDB(18)
      NE=ID(IRCD+2)
      NVC=ID(IRCD+3)
      QCOOL=0.
      QWORK=0.
      IRET=0
C*** IF THE NUMBER OF EVAPORATORS IS ZERO, GO TO 1
                              00 TO COMPUTE THE POWER
      IF (NE.EQ.0) GO TO 100
C*** IF NO. OF COMPRESSORS = 0, GO TO 200 TO COMPU
                              TE THE HEAT TRANSFER
      IF (NVC.EQ.0) GO TO 200
    5 DO 50 J=1,NE
C*** GET THE COMPONENT TYPE FOR THE INPUT STATION NUMBER
      ISTA=ID(IRCD+3+J)
      DO 40 K=1,NCOMP
      LOC=ID(ICDB+K)
      LCOMP=ID(LOC+1)
C*** IF THE COMPONENT IS NOT A EVAP AT THIS STATION, PRINT ERROR
      IF (LCOMP.EQ.37 .OR. LCOMP.EQ.39 .OR. LCOMP.EQ.40) GO TO 10
      GO TO 40
   10 NSI=ID(LOC+3)
      NSO=ID(LOC+4)
      NL=ID(LOC+2)
C*** IF THE STATION NUMBERS DO NOT AGREE, PRINT ERROR MESSAGE
      IF (ID(ISN+NSI).NE.ISTA) GO TO 40
C*** ADD THIS EVAP HEAT TRANSFER TO THOSE COMPUTED
                              FOR THE OTHER EVAPS
      QCOOL=QCOOL+QFUNC(NSI,NSO,NL)
      GO TO 50
   40 CONTINUE
      WRITE(OUT,1000) ISTA
```

```
 1000 FORMAT(" WARNING IN COP - NO EVAPORATOR FOUN
                              D FOR STATION",I4)
   50 CONTINUE
      IF (IRET.EQ.1) GO TO 210
   52 DO 80 J=1,NVC
C*** FIND THE COMPONENT NUMBER FROM THE INPUT DATA
      ISTA=ID(IRCD+3+NE+J)
      DO 60 K=1,NCOMP
      LOC=ID(ICDB+K)
      LCOMP=ID(LOC+1)
C*** IF THE COMPONENT IS NOT A COMPRESSOR, PRINT ERROR
      IF(LCOMP.EQ.35) GO TO 55
      GO TO 60
   55 NSI=ID(LOC+3)
      NSO=ID(LOC+4)
      NL=ID(LOC+2)
C*** CHECK TO MAKE SURE THE STATION NUMBERS AGREE
      IF (ID(ISN+NSI).NE.ISTA) GO TO 60
C*** ADD THE WORK OF THIS COMPRESSOR TO THE WORK OF OTHERS
      QWORK=QWORK+QFUNC(NSI,NSO,NL)
      GO TO 80
   60 CONTINUE
      WRITE(OUT,1100) ISTA
 1100 FORMAT(" WARNING IN COP - NO VAPOR COMPRESSO
                              R FOUND FOR STATION",
     * I4)
      RETURN
   80 CONTINUE
      IF (IRET.EQ.1) GO TO 110
C*** COMPUTE THE COEFFICIENT OF PERFORMANCE
      CP=QCOOL/QWORK
      CALL LINES(5)
      WRITE(OUT,1200) CP
 1200 FORMAT(1H0,"COEFFICIENT OF PERFORMANCE =",G10.4)
      WRITE(OUT,1300) (ID(IRCD+3+J),J=1,NE)
 1300 FORMAT(" EVAPORATOR STATIONS",8X,15I4)
      WRITE(OUT,1400) (ID(IRCD+3+NE+J),J=1,NVC)
 1400 FORMAT(" VAPOR COMPRESSOR STATIONS",15I4)
      RETURN
  100 IRET=1
      GO TO 52
  110 CALL LINES(2)
      WRITE(OUT,1500) QWORK
 1500 FORMAT(" VAPOR COMPRESSOR WORK =",G10.4," BTU/MIN")
      WRITE(OUT,1400) (ID(IRCD+3+J),J=1,NVC)
      RETURN
  200 IRET=1
      GO TO 5
  210 CALL LINES(2)
      WRITE(OUT,1600) QCOOL
 1600 FORMAT(" COOLING LOAD =",G10.4," BTU/MIN")
      WRITE(OUT,1300) (ID(IRCD+3+J),J=1,NE)
   99 RETURN
C     COPPP
```

4.6. Sample Case

The sample case for the COP subroutine is a simple refrigeration cycle (Exhibit 4.6-1), with a compressor, condenser, expansion valve, and evaporator. This same example illustrates the use of the CVALVE and the new compressor routine with a centrifugal compressor. In the description of the component SOLN later in this report, the same example is used to illustrate the MRD solution routines.

Exhibit 4.6-1 shows not only a schematic of the system, but the input data as well. The numerical values on the schematic are the solution values as determined by AECS. The detailed output sheets are presented in Exhibit 4.6-2, starting with Page 7, the beginning of the computed data. Previous output pages contain headers and a repeat of the input data.

4.7. Technical Background

The heat transfer in the evaporator is computed from the energy balance on the refrigerant side. Therefore,

Heat Transfer (Btu/min) = (Refrigerant flow rate into the evaporator) * (Enthalpy of the refrigerant leaving the evaporator - Enthalpy of the refrigerant entering the evaporator)

The compressor power is also computed from an energy balance:

Power (Btu/min) = (Refrigerant flow rate into the compressor) * (Enthalpy of the refrigerant leaving the compressor - Enthalpy of the refrigerant entering the compressor)

The COP is then computed from:

COP = Heat Transfer / Power

with the heat transfer and power first being summed for each evaporator and compressor, respectively. Note that the COP does not include the mechanical inefficiency of the compressor, because the mechanical losses do not increase the enthalpy of the refrigerant.

Exhibit 4.6-1 (a): Input Cards for the Sample Case

```
 EXAMPLE OF COP PROGRAM
  COPPP  0000   3   9   0
    0   0   0   0   0
    0.0          0.0         0.0
    0.0
 20
  1      0.43      92.0        519.7       111.20    10000.
  6      3.26      0.85         4.0        14.7       540.0
 11       0.0     0.001         1.0       1119.0       1.8
 16      14.7     540.0        0.015        11.0       0.01
   10   1   1   1   5   3 -220000   1   2   3   4
   20   1   0   5
   30   1   1   2   1   0   6   1  72   7   0
   40   2  210000   8   9  10  11   2  -1
   50   1   2   3   2  21  22   0   1   2   3  12
   60   1   3   4   0  13  14
   70   3  311000  15  16  17  18   2  -1
   80   1   4   5   3  31  32   0   4   5  19 . 6  20   0
   90   1   1   1   50101
  100   1   1   4   1
   72   6  33   0   0  280001   2   0 101 101   2
   VCOMP: EFFICIENCY = F(FLOW RATE,SHAFT SPEED)
   0.0        1.0
   0.0         11.0
   1000.       11000.
    0.85       0.85        0.85        0.85
    1   1   2   0   0  410001   2
   AIR SIDE PRESS DROP T=1 RN=1 (IND.VAR.=AIR FLOW)
      0.0        0.0          30.0        1.0
    2   5   2   0   0  410001   2
   AIR SIDE EFFECTIVENESS T=5 RN=2 (IND.VAR.=AIR FLOW)
      0.0        1.0          30.0        0.5
    3   1   2   0   0  420001   2
   REFRIG SIDE PRESS DROP T=1 RN=3 (IND.VAR.=REFRIG FLOW)
      0.0        0.0           2.0        6.0
    4   1   2   0   0  410001   2
   AIR SIDE PRESS DROP T=1 RN=1 (IND VAR = AIR FLOW)
     0.0       0.0          5.0         0.1
    5   5   2   0   0  410001   2
   AIR SIDE BYPASS FACTOR T=5 RN=2 (IND VAR = AIR FLOW)
     0.0       0.0          5.0         0.3
    6   2   2   0   0  420001   2
   REFRIG SIDE PRESS DROP T=1 RN=3 (IND VAR = )
     0.0       0.0          1.0        10.0
CASE
JOB
```

Exhibit 4.6-1 (b): Flow Diagram for the Sample Case

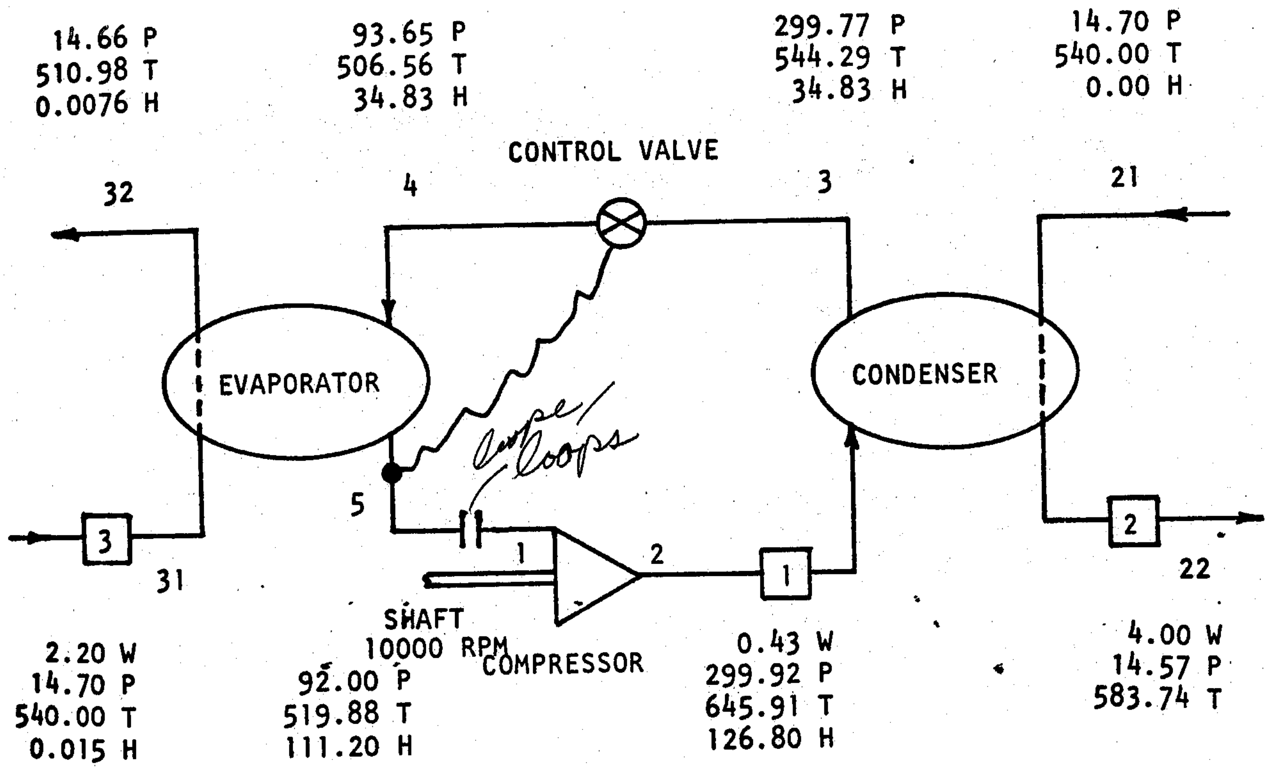


Exhibit 4.6-2: AECS Output for the Sample Case

ΔH $\dot{m}$
$15.604 \times .43 = \frac{6.71}{.19} = 35.3$

```
THE F[illegible]ING LISTING IN FOR FILE COP

COMPONENT SHAFT
     SHAFT     1   N    10000.
COMPONENT VCOMP
     NL        1   NSI       1   NSO       2   FT  .     3   FN     -22
     W       .43   PI    92.00   PO   299.92   TI   519.88   TO  645.91   HI111.2000   HO126.8038
     NL********    NSI       3   NSO       2   FT        0   FN       0
     W      0.00   PI     2.20   PO   299.92   TI    14.66   TO  645.91   HI510.9760   HO126.8038
     SHAFT     1   PR   3.2600   EFF   .8500   HP     -.19
COMPONENT COND
     NL        1   NSI       2   NSO       3   FT        3   FN     -22
     W       .43   PI   299.92   PO   299.77   TI   645.91   TO  544.29   HI126.8038   HO 34.8313
     NL        2   NSI      21   NSO      22   FT        2   FN      -1
     W      4.00   PI    14.70   PO    14.57   TI   540.00   TO  583.54   HI  0.0000   HO  0.0000
*AECS*  REFRIGERANT TEST CASE                                                                     PAGE        9
   1  CASE R22-01                                                                                 DATE 01/23/82

     EFF   .8824   Q     39.55
COMPONENT CVALVE
     NL        1   NSI       3   NSO       4   FT        3   FN     -22
     W       .43   PI   299.77   PO    93.65   TI   544.29   TO  506.56   HI 34.8313   HO 34.8313
     K   1.114781E+03
COMPONENT EVAP
     NL        1   NSI       4   NSO       5   FT        3   FN     -22
     W       .43   PI    93.65   PO    92.00   TI   506.56   TO  520.41   HI 34.8313   HO111.2000
     NL        3   NSI      31   NSO      32   FT        2   FN      -1
     W      2.20   PI    14.70   PO    14.66   TI   540.00   TO  510.98   HI   .0150   HO   .0077
      BYPASS FACTOR  .1321   Q     32.84
```

```
VAPOR COMPRESSION STATIONS    1
*ALCS*  REFRIGERANT TEST CASE
   1  CASE R22-01                                                    PAGE        10
                                                                     DATE  01/23/82
TIME E      184.51

FLOW RATE(S)-LB/MIN

(   1)      .43 (   2)    4.00 (   3)    2.20

PRESSURE(S)-PSI

(   1)   92.00 (   2)  299.92 (   3)  299.77 (   4)   93.65 (   5)   92.00 (  21)   14.70
(  22)   14.57 (  31)   14.70 (  32)   14.66

TEMPERATURE(S)-DEG R

(   1)  519.88 (   2)  645.91 (   3)  544.29 (   4)  506.56 (   5)  520.41 (  21)  540.00
(  22)  583.54 (  31)  540.00 (  32)  510.98

HUMIDITY(S)/ENTHALPY(S)-LBW/LBA / BTU/LB

(   1)111.2000 (   2)126.8038 (   3) 34.8313 (   4) 34.8313 (   5)111.2000 (  21)  0.0000
(  22)  0.0000 (  31)   .0150 (  32)   .0077

STATE VARIABLE TYPE(S)
(   1)     6 (   2)     1

STATE VARIABLE(S)
(   1) 1.11478E+03 (   2) 2.20199E+00

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

ERROR VARIABLE(S)
(   1)-9.44546E-07 (   2)-2.60574E-05

SOLUTION CONVERGED IN      6 TRY(S)

     0 ERROR(S) DETECTED

CASE END
```

5. Subroutine CVALVE (Control Valve)

5.1. Subroutine Description

The CVALVE routine simulates a control valve that produces a pressure drop, usually in response to an error signal from a sensor. However, in the AECS solution procedure there is no mathematical connection between the control valve and any sensor except through the solution procedure. Therefore, CVALVE simply provides a state variable, the control-valve flow factor, that the solution procedure uses in conjunction with the other state variables to minimize all of the error variables simultaneously.

5.2. Prior Simulation Method

The pressure at the outlet station from CVALVE is given by the equation

$$Pout = Pin - AK * W**2$$

where W is the flow rate in lbs/min and AK is the control-valve flow factor. CVALVE always generates AK as a state variable. CVALVE was previously limited to single-phase fluids.

5.3. New Simulation Method

The only difference between the prior and present simulations is the addition of the capability of CVALVE to be used with two-phase fluids. The equation for Pout was left unchanged. However, the equation for the outlet temperature is based on the refrigerant-properties routines with the flow through the valve being a throttling (constant-enthalpy) process.

5.4. Computational Procedure

The computational procedure is presented in the form of a heavily annotated FORTRAN program listing (Exhibit 5.4-1).

5.5. Program Listing

The program listing is presented in Exhibit 5.4-1, except that the program listing does not include the comment cards.

5.6. Sample Case

The sample case for CVALVE is integrated into the sample case for the COP computation, presented in Exhibits 4.6-1 and 4.6-2.

5.7. Technical Background

The form of the pressure-drop equation has no bearing on how CVALVE enters the computations. CVALVE simply provides a pressure-reduction device. In two-phase flows, the AECS solution could be used to derive the characteristics of a physical valve that would give the desired pressure drop for the two-phase flow rate and thermodynamic state.

LINE 1938

```
      SUBROUTINE CVLVPP
      COMMON /CC/ C(400)
      EQUIVALENCE (IRCD,C(45)), (IW,C(27)), (IP,C(
                                 28)), (IT,C(29))
     *, (IH,C(30)), (SCR(1),C(151)), (ICPP,C(88)), (OUT,C(7))
     *, (ISV,C(47)), (PASS,C(17)), (ISVT,C(46))
     *, (IFP,C(22)), (ISVS,C(92)), (IIOP,C(90))
     *, (IFB,C(55))
      DIMENSION SCR(30)
      INTEGER PASS, OUT
      EQUIVALENCE  (SCR(1),NL), (SCR(2),NSI), (SCR(3),NSO)
     *, (SCR(4),JSVI), (SCR(5),PD), (SCR(6),AK), (SCR(7),HS)
     *, (SCR(8),NC), (SCR(9),LOCT), (SCR(10),V), (SCR(11),H)
     *, (SCR(12),PO), (SCR(13),TO)
      COMMON /DC/ DZ(2),D(2)
      DIMENSION ID(2)
      EQUIVALENCE (ID(1),D(1))
C    1 COMP CODE
C    2 LEG
C    3 STATION IN
C    4 STATION OUT
C    5 PRESS. DROP OPTION
C    6 MIN. K
C    7 INITIAL K
C    8 STATE VARIABLE INDEX
C*** SET UP INTERNAL VARIABLES IN TERMS OF STORED ARRAY
      IRCD = IRCDB(8)
      NL = ID(IRCD+2)
      NSI = ID(IRCD+3)
      NSO = ID(IRCD+4)
      JSVI = ID(IRCD+8)
      NC = ID(IFB+NL)
      LOCT = ID(NC+3)
      NC = ID(NC+1)
      IF(PASS.NE.1) GO TO 3
      ID(ISVT+JSVI) = 6
      D(ISV+JSVI) = D(ID(IRCD+7))
C*** IF AK IS LESS THAN THE LOWER LIMIT, SET AK EQ
                               UAL TO THE LOWER LIMIT
    3 IF (IIOP.NE.0 .OR. D(ISV+JSVI).GE.D(ID(IRCD+6))) GO TO 4
      D(ISV+JSVI) = D(ID(IRCD+6))
      D(ISVS+JSVI) = D(ISV+JSVI)
    4 AK = D(ISV+JSVI)
C*** COMPUTE THE PRESSURE DROP FOR THIS AK
      PD = AK*D(IW+NL)**2
      IF (NC.NE.3 .AND. ID(IRCD+5).NE.0 ) PD = PD/
                               SIG(NL,D(IP+NSI),
     * D(IT+NSI) )
      IF (IIOP.NE.JSVI) GO TO 1
      ITER = 0
C*** IF THE PRESSURE DROP IS LESS THAN 0.1% OR 0.0
                               1 PSI, DOUBLE IT-
    2 IF (PD.GE.0.01 .AND. PD.GE.0.001*D(IP+NSI)) GO TO 1
      PD = 2.0*PD
```

```
      D(ISV+JSVI) = 2.0*D(ISV+JSVI)
      ITER = ITER+1
      IF (ITER.EQ.100) GO TO 1
      GO TO 2
C*** COMPUTE THE OUTLET PRESSURE
    1 D(IP+NSO) = D(IP+NSI)-PD
      D(IRCD-6) = AK
C*** CHECK FOR NEGATIVE ABSOLUTE PRESSURES
      IF (D(IP+NSI).GT.0.0.AND.D(IP+NSO).LE.0.0)
     * GO TO 9
C*** IF THE FLUID IS A REFRIGERANT, BRANCH TO 5
      IF(NC.EQ.3) GO TO 5
      D(IT+NSO) = D(IT+NSI)
C*** THE THROTTLING IS AT CONSTANT ENTHALPY (ALSO
                          TEMP IF NOT A REFRIG)
    6 D(IH+NSO) = D(IH+NSI)
      IF (NC.EQ.3 ) GO TO 7
      IF (D(IH+NSI).NE.0.0) CALL TDB(NL,NSI,NSO,HS)
    7 IF (IFP.NE.1 .OR. ICPP.NE.0) GO TO 99
      CALL PIOP(1,NL,NSI,NSO)
      IF (NC.NE.3 .AND. D(IH+NSI).NE.0.0 .AND. D(IH+NSO).GT.HS)
     * CALL HSOP(HS)
      CALL LINES(2)
      WRITE (OUT,1001) AK
 1001 FORMAT(1H0,5X,1HK,1PE15.6)
   99 CONTINUE
      RETURN
C*** COMPUTE THE REFRIGERANT STATE
    5 QUAL=VQUALH(LOCT,D(IP+NSO),D(IH+NSI))
      IF(QUAL.LT.0.0)D(IT+NSO)=VTLIQ(LOCT,D(IP+NSO),D(IH+NSI))
      IF(QUAL.GE.0..AND.QUAL.LE.1.)D(IT+NSO)=VTS(LOCT,D(IP+NSO))
      IF(QUAL.GT.1.)CALL VTAV2(LOCT,D(IT+NSO),V,D(
     *                    IP+NSO),D(IH+NSI))
      GO TO 6
C*** TRY THE FOLLOWING FIX FOR THE ERROR SO THE SO
                          LUTION CAN PROCEED
    9 PO = 0.0
    8 D(ISV+JSVI) = 0.9*(D(IP+NSI)-PO)/D(IW+NL)**2
      IF (NC.NE.3 .AND. ID(IRCD+5).NE.0) D(ISV+JSV
                          I) = D(ISV+JSVI)*
     * SIG(NL,D(IP+NSI),D(IT+NSI))
      GO TO 4
C     CVLVPP
      END
```

new

[illegible]

D(IT+NSO)=VTS(LOCT, D(IP+NSO))

6. Subroutine EVAP (Refrigerant Evaporator)

6.1. Subroutine Description

The EVAP subroutine simulates a direct-expansion, refrigerant-to-source heat exchanger in which the source is cooled and possibly dehumidified. The inlet on the refrigerant side would normally be downstream from an expansion valve. The outlet would be controlled by the expansion valve such that the outlet temperature is approximately five degrees above the normal saturation temperature (evaporation temperature) in the heat exchanger. Warm moist air or other source would normally enter the heat exchanger on the source side. The leaving source fluid would have a lower temperature and, if a gas, a lower absolute humidity (lbs of water per lb of dry gas).

6.2. Prior Simulation Method

The previous evaporator model did not allow for dehumidification, was based on the heat gain by the refrigerant being the heat of vaporization, and did not include the refrigerant-side pressure drop. The model performed a heat balance on the evaporator, with the performance being characterized by the source-side effectiveness. The dependence of the effectiveness on the flow rate had to be pre-calculated and entered as a function of the source-side flow rate.

6.3. New Simulation Method

The new model characterizes the evaporator by the coil bypass factor, as used in conventional air-conditioning applications. The bypass factor is equal to the coil ineffectiveness (1.0 minus the effectiveness) if there is no dehumidification. If there is dehumidification, it is also equal to the ratio of the decrease in absolute humidity divided by the difference between the inlet absolute humidity and the absolute humidity at the coil temperature.

The evaporation temperature is assumed equal to the saturation temperature at the inlet pressure; however, any inlet quality or subcooling is permissible. The exit state for the refrigerant is computed by a heat balance, with the heat-transfer rate being computed by the source-side effectiveness. The refrigerant exit state can have any quality or degree of superheat.

Because the heat transfer is based on the user-supplied bypass-factor table and the saturation temperature of the refrigerant, inconsistent input data could result in a refrigerant temperature at the exit of the evaporator being higher than the inlet air temperature. A warning message is printed by EVAP if this occurs. The user should examine

CVALVE 42

the output data to determine if this occurence persisted through to the final solution. If not, the warnings were issued only during the iterations leading to the solution, so there will be no effect on the final results. If the occurence did persist, the user should revise his input and re-run the case.

The pressure drop on the source side is entered as a table, as in the prior simulation method. The pressure drop on the refrigerant side is entered as if only vapor were flowing. The tabular values are corrected for the two-phase flow as part of the simulation method.

6.4. Computational Procedure

The computational procedure is presented in the form of a heavily annotated FORTRAN program listing in Exhibit 6.4-1.

The computation of the absolute humidity is based on the molecular weight of the gas being 29, so it is exact only for air. However, the molecular weight enters only in relating the partial pressure to the absolute humidity, so the simulation can be used as a reasonable approximation for other gases as well. Greater accuracy could be obtained if a more elaborate model of gas/water mixtures were used; however, the greater accuracy would be inconsistent with the simple model being used for the heat exchanger itself.

The pressure-drop computation for the two-phase flow is based on the FAC, Inc., correlation of Baroczy's method, as is used in QBOILR and the other routines developed under this contract. The pressure-drop computation includes the momentum change between inlet and outlet. Slip velocities and void fractions are computed based on a correlation with the density ratio only.

In keeping with the contractural requirements, the EVAP can have an error variable generated that is equal to the difference between the exit temperature and a user-specified control temperature. The effect is the same as would be obtained if a SENSOR were placed downstream of the evaporator. In the prior simulation method such an error variable was needed to obtain an energy balance, with the solution routine (SOLN1) eventually balancing the flow rate and energy. In the present method the energy balance is guaranteed by the computational method, without the aid of an error variable.

6.5. Program Listing

Exhibit 6.4-1, which presents the program computational procedure, also is the program listing as used in AECS for the performance computation. However, the comment cards are omitted in the AECS program.

6.6 Sample Case

The sample case is based on having an evaporator alone as the total system, as depicted in Exhibit 6.6-1. The input data are shown in the

Exhibit 6.4-1: Performance-Program Logic and Listing

```
      SUBROUTINE EVAPPP
      COMMON /CC/ C(400)
      EQUIVALENCE (IRCD,C(45)),(IW,C(27)),(IP,C(28)),(IT,C(29))
     *,(IH,C(30)),(SCR(1),C(151)),(IFB,C(55)),(IGA,C(35))
     *,(IEVT,C(48)),(IEV,C(49)),(IFP,C(22)),(ICPP,C(88))
     *,(PASS,C(17)),(OUT,C(7)),(GC,C(370))
      INTEGER PASS,OUT
      DIMENSION SCR(30)
      EQUIVALENCE (SCR(1),NLR),(SCR(2),LOCT),(SCR(3),NSIR)
     *,(SCR(4),NSOR),(SCR(5),NLS),(SCR(6),NSIS),(SCR(7),NSOS)
     *,(SCR(8),JEVI),(SCR(9),V),(SCR(10),Q),(SCR(11),TOUT)
     *,(SCR(12),EFF),(SCR(13),TAVG),(SCR(14),PD)
     *,(SCR(15),HS)
      EQUIVALENCE (D(50),TE),(D(52),HSV),(D(53),HFG),
     *(D(54),HSL),(D(55),QUALIN),(ID(56),I1),(D(57),BF),
     *(D(58),TAIRO),(D(59),PW),(D(60),HCOIL),(D(61),HDIFF),
     *(D(62),CPWV),(D(64),H),(D(65),QUAL),
     *(D(67),VOUT),(D(68),VDGO),(D(69),PDGO),(D(70),VRATIO),
     *(D(71),PDLO),(D(72),PDR),(D(73),SLIP),(D(74),PB),
     *(D(75),PHI),(D(76),XMOMO),(D(77),XMOMI)
      COMMON /DC/ DZ(2),D(2)
      DIMENSION ID(2)
      EQUIVALENCE (ID(1),D(1))
C*** PRESSURE-DROP FUNCTION FOR TWO-PHASE FLOW BASED ON FAC,INC.,
C    CORRELATION OF BAROCZY'S METHOD
      DP2PH(X)=-PB*X**2.65/2.65+(1.+PB)*(X**1.7/1.7-(1.-X)**2.3*X
     *        /2.3 - (1.-X)**3.3/2.3/3.3)
C*** VOID-FRACTION CORRELATION
      VOIDF(X)=X/(X+SLIP*(1.-X)/VRATIO)
C*** RATIO OF MOMENTUM FLUX TO MOMENTUM OF LIQUID-ONLY FLOW
      VMOM(X)=((1.-X)/(1.-VOIDF(X)))**2*(1.-VOIDF(X)*
     * (1.-SLIP*SLIP/VRATIO)) - 1
C   1 COMP CODE
C   2 LEG NO R
C   3 INLET STATION NO R
C   4 OUTLET STATION NO R
C   5 LEG NO S
C   6 INLET STATION NO S
C   7 OUTLET STATION NO S
C   8 PRESS DROP OPTION
C   9 PRESS DROP TABLE NO
C  10 BYPASS-FACTOR TABLE NO
C  11 DEGREES SUPERHEAT
C  12 ERROR VARIABLE INDEX
C  13 R-SIDE PRESS DROP TABLE(FT OF VAPOR VS CFM, VAPOR FLOW ONLY)
C  14 FLOW AREA ON REFRIGERANT SIDE (AF) IN SQ.FT.
C*** NO ERROR VARIABLE IF OPTION=0; SUPERHEAT, IF OPTION=1
C  15 ERROR OPTION
```

?? not in data card formation p.8

```
C*** SET UP INTERNAL VARIABLES IN TERMS OF THE STORED ARRAY
      IRCD = IRCDB(15)
      NLR = ID(IRCD+2)
      NSIR = ID(IRCD+3)
      NSOR = ID(IRCD+4)
      NLS  = ID(IRCD+5)
      NSIS = ID(IRCD+6)
      NSOS = ID(IRCD+7)
      LOCT = ID(IFB+NLR)
      LOCS = ID(IFB+NLS)
      LOCS = ID(LOCS+1)
      LOCT = ID(LOCT+3)
      IOP=ID(IRCD+15)
C*** DEFINE THREE INDEPENDENT VARIABLES FOR TABLE LOOK-UP
      ITER=0
      D(IGA+41) = D(IW+NLS)
      D(IGA+42) = D(IW+NLR)
      D(IGA+43) = D(IP+NSIS)
      JEVI = ID(IRCD+12)
C*** COMPUTE THE SATURATION PROPERTIES
      TE=VTS(LOCT,D(IP+NSIR))
      V =VSV(LOCT,D(IP+NSIR),TE)
      AF=D(ID(IRCD+14))
      HSV=VH(LOCT,D(IP+NSIR),TE,V)
      HFG=VHFG(LOCT,D(IP+NSIR),TE,V)
      HSL=HSV-HFG
      D(IGA+42)=D(IGA+42)*V                    GA42 = CFM
      QUALIN=(D(IH+NSIR)-HSL)/HFG
      IF(QUALIN.GT.1.0)QUALIN=1.0
      IF(QUALIN.LT.0.0)QUALIN=0.0
      I1 = ID(IRCD+11)
C*** COMPUTE THE TEMPERATURE OF THE SUPERHEATED OUTLET FLOW
      TSH = TE + D(I1)
C*** USE TLUP FOR THE SOURCE-SIDE BYPASS FACTOR
      BF = TLUP(ID(IRCD+10))
C*** COMPUTE THE OUTLET SOURCE TEMPERATURE FROM THE BYPASS FACTOR
    5 CONTINUE
      D(IT+NSOS) = TE - BF *(TE - D(IT+NSIS) )
C*** COMPUTE THE OUTLET HUMIDITY BASED ON AIR/WATER PROPERTIES
      PW=EXP(-8083./TE+2.2615*ALOG(TE))
      HCOIL=18.*PW/(29.*(D(IP+NSIS)-PW))
      D(IH+NSOS)=D(IH+NSIS)
C*** COMPUTE THE DRY-SOURCE ENTHALPY DIFFERENCE
      HDIFF=SHP(NLS,D(IP+NSIS),D(IT+NSIS),D(IH+NSIS))*
     * (D(IT+NSIS)-D(IT+NSOS))
C*** IF THE FLUID IS NOT A GAS, NO DEHUMIDIFICATION OCCURS
      IF(LOCS.NE.2) GO TO 10
C*** IF THE COIL HUMIDITY GT THE INLET HUMIDITY, NO
C    DEHUMIFICATION OCCURS
      IF(D(IH+NSIS).LT.HCOIL) GO TO 10
      D(IH+NSOS)=HCOIL+BF*(D(IH+NSIS)-HCOIL)
C*** USE CP(WATER VAPOR)=0.42 TO COMPUTE THE VAPOR ENTHALPY
```

```
      CPWV=0.42
C*** ADD THE ENTHALPY DIFFERENCE OF THE MOISTURE REMOVED
      HCOND=1075.5-(1.-CPWV)*(TE-491.67)
      HDIFF=HDIFF+(D(IH+NSIS)-D(IH+NSOS))*(HCOND+CPWV*(D(IT+NSOS)-TE))
   10 CONTINUE
C*** COMPUTE THE HEAT TRANSFER BASED ON THE SOURCE-SIDE PERFORMANCE
      Q=D(IW+NLS)*HDIFF
C*** COMPUTE THE REFRIGERANT OUTLET ENTHALPY BY AN ENERGY BALANCE
      H = D(IH+NSIR)+Q/D(IW+NLR)
      D(IH+NSOR)=H
C*** CHECK THE STATE OF THE REFRIGERANT AT THE OUTLET
C    IF H.LE.HSL, IT IS LIQUID; IF H.GE.HSV, IT IS VAPOR
      IF (H.LE.HSL) GO TO 20
      IF (H.GE.HSV) GO TO 30
C*** IN THE TWO-PHASE REGION
      QUAL=(H-HSL)/HFG
      TOUT=TE
      VOUT=QUAL*V+(1.-QUAL)/VDL(LOCT,TOUT)
      GO TO 40
   20 TOUT=VTLIQ(LOCT,D(IP+NSIR),H)
C*** IN THE LIQUID REGION
      QUAL=0.
      VOUT=1./VDL(LOCT,TOUT)
      GO TO 40
C*** IN THE VAPOR REGION
   30 QUAL=1.
      CALL VTAV2(LOCT,TOUT,VOUT,D(IP+NSIR),H)
C*** IF REGRIG OUTLET TEMP.LE.SOURCE TEMP, THE PERFORMANCE IS
C    REASONABLE, SO GO TO 50
   40 IF(TOUT.LE.D(IT+NSIS))GO TO 50
C*** IF BYPASS FACTOR WAS PREVIOUSLY ADJUSTED, PROCEED AS IF
C    THE REFRIG OUTLET TEMP IS LOWER THAN SOURCE TEMPERATURE
      IF(ITER.GT.0) GO TO 50
C*** RECOMPUTE THE BYPASS FACTOR BECAUSE REFRIG OUTLET TEMP
C    IS HIGHER THAN SOURCE TEMPERATURE
      TAVG=TOUT
      BF1=1.
      ITER=ITER+1
C*** SET THE REFRIGERANT OUTLET TEMP EQUAL TO THE MAX OF TEVAP, TSOURCE
      TOUT=D(IT+NSIS)
      IF(TOUT.LT.TE) TOUT=TE
      VOUT=VSV(LOCT,D(IP+NSIR),TOUT)
      H=VH(LOCT,D(IP+NSIR),TOUT,VOUT)
C*** COMPUTE THE AMOUNT OF HEAT TRANSFERRED FOR THIS TOUT
C    THIS CAN BE USED TO DEDUCE THE EXCESS AMOUNT OF HEAT TRANSFER
      Q1=D(IW+NLR)*(H-D(IH+NSIR))
C*** ADJUST THE BYPASS FACTOR TO GIVE TOUT JUST 1% HIGHER THAN TSOURCE
      BF1=BF+0.99*(1.-Q1/Q)*(1.-BF)
   12 WRITE(OUT,1103)TAVG,D(IT+NSIS),BF,BF1
 1103 FORMAT(" *** WARNING IN EVAPPP - REFRIGERANT OUTLET TEMP ",F10.3,
     */," *** GREATER THAN SOURCE TEMPERATURE   ",F10.3/
     *" *** BYPASS FACTOR OF",F10.3," RESET TO",F10.3,/,"      TO MAKE ",
```

```
     *"TOUT=TSOURCE+0.01*(TOUT-TSOURCE)"/)
      BF=BF1
C*** WITH THE INCREASED BYPASS FACTOR, RECOMPUTE THE PERFORMANCE
      GO TO 5
C*** COMPUTE THE PRESSURE DROPS FOR LIQUID ONLY AND VAPOR ONLY
   50 PDGO=TLUP(ID(IRCD+13))
      VRATIO=V*VDL(LOCT,TE)
C*** ASSUME THE SINGLE-PHASE PRESSURE DROP IS PROPORTIONAL TO
C    THE SPECIFIC VOLUME
      PDLO=PDGO/VRATIO
      PDR=PDLO
      IF (QUAL.LE.0.) GO TO 80
      SLIP=(VRATIO-1.)**0.25
      PB=-0.25*ALOG10(VRATIO)
      IF (PB.LT.-1.) PB=-1.
      QDUM=QUALIN
C*** COMPUTE THE AVERAGE PHI, BUT WATCH FOR TOO SMALL
C    A QUALITY DIFFERENCE
      IF(QUALIN.EQ.QUAL)QDUM=ABS(QUAL-.01)
      PHI=(DP2PH(QUAL)-DP2PH(QDUM))/(QUAL-QDUM)
C*** COMPUTE THE FRICTION PRESSURE DROP, IGNORING THE PRESSURE
C    DROP IN THE SINGLE-PHASE REGIONS
      PDR=PDLO+PHI*(PDGO-PDLO)
C*** COMPUTE THE MOMENTUM CHANGES (PRESSURE DROP)
      XMOMI=VRATIO
      IF (QUALIN.LT.1.) XMOMI=VMOM(QUALIN)
      XMOMO=VRATIO
      IF (QUAL.LT.1.) XMOMO=VMOM(QUAL)
C*** ADD THE MOMENTUM AND FRICTION PRESSURE DROPS
      PDR=PDR+(XMOMO-XMOMI)*(D(IW+NLR)/AF/60.)**2/(VDL(LOCT,TE)*
     * GC*144.)
   80 D(IP+NSOR)=D(IP+NSIR)-PDR
C*** IF THE OUTLET PRESSURE IS NEGATIVE, SET DP TO ZERO
      IF(D(IP+NSOR).GT.0.0)GO TO 82
C     WRITE(OUT,7655)D(IP+NSOR),D(IP+NSIR)
 7655 FORMAT(" *** OUTLET PRESSURE IN EVAP WAS ",E14.7,
     * "  RESET PRESSURE TO INLET VALUE ",E14.7)
      D(IP+NSOR)=D(IP+NSIR)
   82 CONTINUE
      IF(IOP.EQ.0)GO TO 83
      IF(PASS.NE.1) GO TO 1
      ID(IEVT+JEVI) = 3
C*** COMPUTE THE ERROR VARIABLE AS THE SUPERHEAT DISCREPANCY
    1 D(IEV+JEVI)=(D(IH+NSOR)-HSV)/VCPV(LOCT,D(IP+NSIR),TE)-D(I1)
   83 TAVG = 0.5 * (D(IT+NSIS) + D(IT+NSOS) )
C*** COMPUTE THE SOURCE-SIDE PRESSURE DROP
      D(IT+NSOR)=TOUT
      PD = TLUP(ID(IRCD+9))
      IF(ID(IRCD+8).NE.0)PD=PD/SIG(NLS,D(IP+NSIS),D(IT+NSIS))
      D(IP+NSOS) = D(IP+NSIS) - PD
      IF(IFP.NE.1 .OR. ICPP.NE.0 ) GO TO 99
      CALL PIOP(1,NLR,NSIR,NSOR)
```

```
      CALL PIOP(2,NLS,NSIS,NSOS)
   85 CALL LINES(2)
      WRITE(OUT,1001) BF,Q
 1001 FORMAT (1H0,5X,14H BYPASS FACTOR,F7.4,3X,1HQ,F9.2   )
   99 CONTINUE
      RETURN
C     EVAPPP
```

required format for AECS input. The corresponding output data are shown in the system schematic (Exhibit 6.6-1) as well as in the output format (Exhibit 6.6-2), starting with Page 7, the beginning of the computed data. Previous output pages contain headers and a repeat of the input data.

6.7. Technical Background

The technical basis for the pressure-drop computation on the refrigerant side is contained in the section on QBOILR. The method is not standard, having been developed by FAC, Inc., but correlates well respected data.

The heat-transfer characteristics of the evaporator are described by the bypass factor, which is given by the following formulas:

$$BF = (T_{source,out} - T_{coil})/(T_{source,in} - T_{coil})$$

and

$$BF = (M_{gas,out} - M_{coil})/(M_{gas,in} - M_{coil})$$

where M is the absolute humidity in lbs of moisture per lb of dry gas, with the lower-case letters defining the dew-point temperature at which M is to evaluated. If the source is not a gas, the second equation is ignored. Note that BF will be a function of the source-side flow rate; however, once assigned a value, BF determines both the heat- and mass-transfer rates. If no dehumidification occurs, BF is equal to the ineffectiveness (1.0 minus the effectiveness).

If the bypass factor is too low, the computed heat loss by the source can be so high that the computed refrigerant outlet temperature exceeds the source inlet temperature. The simulation routine checks for such an unrealistic outlet temperature and increases the bypass factor such that

$$T_{ref,out} = T_{source,in} + 0.01 * (T_{ref,out} - T_{source,in})$$

This correction reduces the outlet temperature so that it is closer to the source inlet temperature; however, the outlet is still unrealistic. Increasing the bypass factor by this technique permits the AECS solution routines to compute derivatives without encountering temperatures far in excess of what is realistic. In most cases, the correction is applied only in the process of solving the problem. If the correction persists to the final solution, the evaporator bypass factor table should be modified (corresponding to a change in the evaporator size). Therefore, any problem using an evaporator should be checked for the warning messages concerning the evaporator outlet temperature. If a warning is given, the converged solution should be checked to determine if the refrigerant outlet temperature exceeds the source inlet temperature. If so, the bypass factor table should be altered. Eventually, this correction process should be replaced by an iteration process that gives the end of the two-phase region, as was done for the condenser.

Exhibit 6.6-1: Input Cards and Flow Diagram for the Sample Case

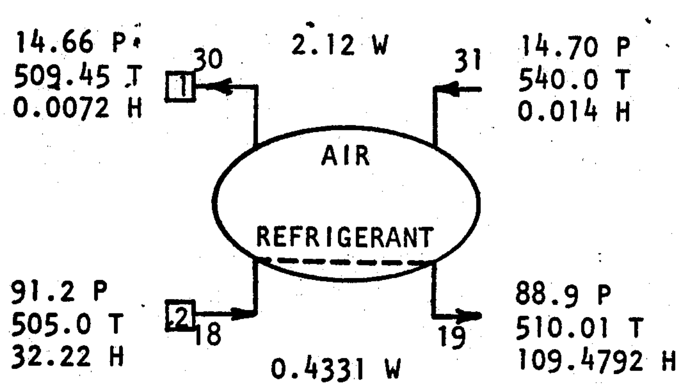
```
FORM
LE     TEST CASE FOR EVAP (EVADATA)
EA      EVAP      0000    2    4    0
EB        0    0    0    0    0
EC        0.0              0.0         0.0
ED        0.0
RAM     20
ES      1    2.395    14.7000    540.00    0.014     5.0000
LES     6    2.395    14.6000    510.00    0.0075    0.0001
UES     11   0.4331   91.2005    505.00    32.22     0.0
UES     16   0.4331   88.1249    510.00    109.665   0.0
LET       10    1   311000    1    2    3    4    2   -1
NLET      20    2   180000   11   12   13   14    3  -22
AP        30    2   18   19    1   31   30    0    1    2    5    3   10    1
TLT       40    2   190000   16   17   18   19
LET       50    1   300000    6    7    8    9
FID        1    1    2    0    0   410101    2
T         AIR SIDE PRESS DROP T=1 RN=1 (IND VAR = AIR FLOW)
V          0.0         0.0           5.0           0.1
ID         2    5    2    0    0   410101    2
T         AIR SIDE BYPASS FACTOR T=5 RN=2 (IND VAR = AIR FLOW)
V          0.0         0.0           5.0           0.3
ID         3    2    2    0    0   420101    2
T         REFRIG SIDE PRESS DROP T=1 RN=3 (IND VAR = )
V          0.0         0.0           1.0          10.0
AB         1    0    1    0
ASE
OB
```

superheat

36 44 52 60 64

air ΔP   air bypass   DSH   type 2 ΔP

A refrig flow = .0001 ft²



air flow = SV
TYP 1

°superheat = EV
Typ 3

Exhibit 6.6-2: AECS Output for the Sample Case

```
PERMANENT TABLE      1    10

PERMANENT TABLE     22    10

TABLE       1      1
    TITLE/    AIR SIDE PRESS DROP T=1 RN=1 (IND VAR = AIR FLOW)

    NDIM      2      IST     0
    ARGUMENT 1       TYPE    0      RELN    41      EXTRAP     1      INTERP     1      NPTS     2

             0.              0.                5.00000E+00    1.00000E-01

TABLE       2      5
    TITLE/    AIR SIDE BYPASS FACTOR T=5 RN=2 (IND VAR = AIR FLOW)

    NDIM      2      IST     0
    ARGUMENT 1       TYPE    0      RELN    41      EXTRAP     1      INTERP     1      NPTS     2

             0.              0.                5.00000E+00    3.00000E-01

TABLE       3      2
    TITLE/    REFRIG SIDE PRESS DROP T=1 RN=3 (IND VAR = )

    NDIM      2      IST     0
    ARGUMENT 1       TYPE    0      RELN    42      EXTRAP     1      INTERP     1      NPTS     2

             0.              0.                1.00000E+00    1.00000E+01

TABLE       1      0
    PTAB      1     0
*AECS*  TEST CASE FOR EVAP (EVADATA)                                                                    PAGE        7
    1  CASE EVAP                                                                                        DATE 09/19/81

TIME P     167.11

SVT
(    1)     1

EVT
(    1)     3

PASS        1

S.V.
(    1) 2.39500E+00

E.V.
(    1) 1.48780E+01

W
(    1) 2.39500E+00 (    2) 4.33100E-01

P
(   31) 1.47000E+01 (   18) 9.12005E+01 (   19) 8.88876E+01 (   30) 1.46521E+01
```

```
T
(  31) 5.40000E+02 (  18) 5.05000E+02 (  19) 5.25007E+02 (  30) 5.10029E+02

H
(  31) 1.40000E-02 (  18) 3.22200E+01 (  19) 1.12159E+02 (  30) 7.31695E-03

COMPONENT EVAP

     NL      2   NSI    18   NSO    19   FT      3   FN    -22

     W     .43   PI  91.20   PO  88.89   TI 505.00   TO 510.01   HI 32.2200   HO109.4792

     NL      1   NSI    31   NSO    30   FT      2   FN     -1

     W    2.30   PI  14.70   PO  14.65   TI 540.00   TO 509.83   HI   .0140   HO   .0073

      BYPASS FACTOR  .1380   Q   33.46
*AECS*  TEST CASE FOR EVAP (EVADATA)                                                PAGE       8
    1  CASE EVAP                                                                    DATE 09/19/81

TIME E     167.20

FLOW RATE(S)-LB/MIN

(   1)    2.30 (   2)     .43

PRESSURE(S)-PSI

(  18)   91.20 (  19)   88.89 (  30)   14.65 (  31)   14.70

TEMPERATURE(S)-DEG R

(  18)  505.00 (  19)  510.01 (  30)  509.83 (  31)  540.00

HUMIDITY(S)/ENTHALPY(S)-LBW/LBA / BTU/LB

(  18) 32.2200 (  19)109.4792 (  30)   .0073 (  31)   .0140

STATE VARIABLE TYPE(S)
(   1)    1

STATE VARIABLE(S)
(   1) 2.29940E+00

ERROR VARIABLE TYPE(S)
(   1)    3

ERROR VARIABLE(S)
(   1) 2.65898E-06

SOLUTION CONVERGED IN       6 TRY(S)

     0 ERROR(S) DETECTED
```

7. Subroutine INDATA (Initialize Leg and Station Data)

7.1. Subroutine Description

The INDATA subroutine does not simulate a physical component; instead it permits the user to define the flow rate, pressure, temperature and enthalpy at legs and stations not otherwise definable. The need for INDATA arises in systems with flows that double back on themselves. For example, systems with intercoolers frequently have the flow passing through one side, passing through another component, and then passing back through the intercooler. Previously, AECS could not solve problems of this type, because, when AECS performs the component computations, all inlet flow rates and thermodynamic states must be defined. INDATA permits the user to define the flow and states as an initial guess of the final solution. AECS will then correct these guesses in the course of the solution.

7.2. Prior Simulation Method

INDATA is a new subroutine that had no counterpart in the prior version of AECS. It is similar to LOOPS, INLET and RINLET in that it permits the definition of starting conditions; however, INDATA involves neither error nor state variables and the initial guesses have no effect on the final, converged solution.

7.3. Present Simulation Method

With INDATA, the user simply identifies the leg and station number and the values of flow rate, pressure, temperature and enthalpy. For refrigerants, the temperature is overridden by the computer, because the computer uses the refrigerant subroutines to deduce the temperature from the pressure and enthalpy. Notice that the values entered are all temporary and will be corrected by the computer in the course of the solution.

7.4. Computational Procedure

There is no performance computation for INDATA. Only a "PZ" routine is needed. The PZ subroutines initialize the component-by-component data and allocate storage space for the subsequent "PP" routines, which are the simulation routines. INDATA simply initializes the flow rate, pressure, temperature and enthalpy at the specified leg and station.

The flow rate, pressure, temperature and enthalpy at the leg and station defined by INDATA will always lag by one iteration all of the other legs and stations. For example, in the system of Appendix A, INDATA is needed to define the state at Station 14 (the low-temperature intercooler). As the computation proceeds down Leg 7 to Station 8, it encounters the intercooler. It combines the inlet data from

Exhibit 7.4-1: Input-Program Logic and Listing

```
      SUBROUTINE INDTPZ
      COMMON /CC/C(400)
      EQUIVALENCE (OUT,C(7)),(CERR,C(16)),(NSTA,C(
                                    26)),(NLEG,C(25))
     *,(IPAR,C(33)),(ILN,C(37)),(ISN,C(38)),(ILR,C
                                    (52)),(ISR,C(53))
     *,(IW,C(27)),(IP,C(28)),(IT,C(29)),(IH,C(30))
                                    ,(ICV(1),C(133))
      DIMENSION ICV(18)
      COMMON /DC/DZ(2),D(2)
      DIMENSION ID(2)
      EQUIVALENCE (ID(1),D(1))
      INTEGER OUT,CERR
C    1 COMP CODE
C    2 LEG NUMBER
C    3 STATION NUMBER
C    4 W
C    5 P
C    6 T
C    7 H
      I=IACDB(7)
C*** SET UP LEG AND STATION STORAGE LOCATIONS
      ID(I+1)=ICV(1)
      NL=ILEGN(ICV(2))
      ID(I+2)=NL
      CALL LEGRS(NL)
      ID(ILR+NL)=999
      NS=ISTAN(ICV(3))
      ID(I+3)=NS
      CALL STARS(NS)
      ID(ISR+NS)=999
C*** SET UP THE FLOW, PRESSURE, TEMPERATURE AND ENTHALPY/HUMIDITY
C     ON THE BASIS OF THE INPUT VALUES
      D(IW+NL)=D(IPAR+ICV(4))
      D(IP+NS)=D(IPAR+ICV(5))
      D(IT+NS)=D(IPAR+ICV(6))
      D(IH+NS)=D(IPAR+ICV(7))
      RETURN
C     INDTPZ
      END
```

add fluid def. to "INDATA" as in "LOOPS" or inlet"

CURRENT PC VERSION

```
      SUBROUTINE QBLRPP
      COMMON /CC/ C(600)
      EQUIVALENCE (IRCD,C(45)),(IW,C(27)),(IP,C(28)),(IT,C(29))
     *,(IH,C(30)),(SCR(1),C(151)),(GC,C(370)),(JC,C(371))
     *,(ICPP,C(88)),(IFP,C(22)),(OUT,C(7)),(IGA,C(35))
     *,(PASS,C(17)),(IEVT,C(48)),(IEV,C(49)),(ITAD,C(54))
     *,(IFB,C(55)),(ISN,C(38))
      DIMENSION SCR(30)
      INTEGER OUT,PASS
      REAL L,MU,K,JC,ME,MI,MP
      EQUIVALENCE  (SCR(1),NL),(SCR(2),NSI),(SCR(3),NSO)
     *,(SCR(4),IOP),(SCR(5),FFT),(SCR(6),COT),(SCR(7),AF)
     *,(SCR(8),Q),(SCR(9),L),(SCR(10),AH),(SCR(11),DH)
      DIMENSION MU(2),CPY(2),V(2),PR(2),T(5),TW(5),HT(5),DP(2)
     *,K(2)
      COMMON /DC/ DZ(2),D(32001)
      DIMENSION ID(2)
      EQUIVALENCE (ID(1),D(1))
     *,(D(51),T(1)),(D(56),TW(1)),(D(61),HT(1))
     *,(D(71),HFG),(D(72),ST),(D(73),PT)
     *,(D(75),TIN),(D(76),W),(D(77),IRET),(D(78),CO)
     *,(D(79),FF),(D(81),VR),(D(82),DV)
     *,(D(83),SL),(D(84),HSAT),(D(86),TSAT)
     *,(D(87),X1),(D(88),X2),(D(89),TNB),(D(90),DD)
     *,(D(91),FD),(D(92),B),(D(93),EM),(D(94),RS)
C    1 COMP CODE
C    2 LEG NO
C    3 INLET STATION NO
C    4 OUTLET STATION NO
C    5 OPTION NO
C    6 FRICTION FACTOR TABLE
C    7 COLBURN FACTOR TABLE
C    8 HEAT EXCHANGER FLOW AREA
C    9 HEAT INPUT RATE IN (BTU/MIN)
C   10 HEAT EXCHANGER FLOW PATH LENGTH (FEET)
C   11 HT EXCHG/HT TRANSFER AREA INCLUDING FINS (SQUARE FEET)
C   12 HEAT EXCHANGER HYDRAULIC DIAMETER
C   13 ERROR VARIABLE OPTION
C*** ERROR-VARIABLE OPTION: 0 IF NO ERROR VARIABLE; 1 IF SUPERHEAT
C   14 ERROR VARIABLE INDEX
C   15 MAXIMUM BOILER WALL TEMPERATURE
C*** SET UP INTERNAL VARIABLES IN TERMS OF STORED ARRAY
      IRCD = IRCDB(15)
      NL=ID(IRCD+2)
      NSI=ID(IRCD+3)
      NSO=ID(IRCD+4)
      IOP=ID(IRCD+5)
      IF (ID(IRCD+13).EQ.0) GO TO 107
      TMAX=D(ID(IRCD+15))
      JEVI=ID(IRCD+14)
  107 CONTINUE
      LOCT=ID(IFB+NL)
      LOCT=ID(LOCT+3)
      AF=D(ID(IRCD+8))
```

```
      Q=D(ID(IRCD+9))
      L=D(ID(IRCD+10))
      AH=D(ID(IRCD+11))
      DH=D(ID(IRCD+12))
C*** COMPUTE THE SATURATION PROPERTIES
      TSAT=VTS(LOCT,D(IP+NSI))
C*** COMPUTE THE TRANSPORT PROPERTIES BASED ON INLET CONDITIONS
      CPY(1)=VCPF(LOCT,D(IP+NSI),TSAT)
      CPY(2)=VCPV(LOCT,D(IP+NSI),TSAT)
      MU(1)=VVISCF(LOCT,D(IP+NSI),TSAT)
      MU(2)=VVISCV(LOCT,D(IP+NSI),TSAT)
      K(1)=VCONDF(LOCT,D(IP+NSI),TSAT)
      K(2)=VCONDV(LOCT,D(IP+NSI),TSAT)
      V(1)=1.0/VDL(LOCT,TSAT)
      V(2)=VSV('QBLRPP 1',LOCT,D(IP+NSI),TSAT)
      HFG=VHFG(LOCT,D(IP+NSI),TSAT,V(2))
      ST=VST(LOCT,TSAT)
      PT=VDPDT(LOCT,D(IP+NSI))
      TIN=D(IT+NSI)
      W=D(IW+NL)
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IRITE=1
      IF (IRITE .NE. 1) GO TO 9010
      WRITE (OUT,9911)
 9911 FORMAT(' ',/)
      WRITE (OUT,9011)
 9011 FORMAT(' *********WRITE 9011 FROM "QBLRPP" *********************
     *       ,'**************')
      WRITE (OUT,9012) AF     , Q      , L      , AH
     *                , DH     , TSAT   , CPY(1), CPY(2)
     *                , MU(1)  , MU(2)  , K(1)  , K(2)
     *                , V(1)   , V(2)   , HFG   , ST
     *                , PT     , TIN    , W
 9012 FORMAT(' AFLOW =', E12.5,  ' QRATE =', E12.5,  ' LFLOW =', E12.5
     *       ,' AHTRAN=', E12.5,/,' DHYD  =', E12.5,  ' TSAT  =', E12.5
     *       ,' CPY(1)=', E12.5,  ' CPY(2)=', E12.5,/,' MU(1) =', E12.5
     *       ,' MU(2) =', E12.5,  ' K(1)  =', E12.5,  ' K(2)  =', E12.5
     *   ,/ ,' V(1)  =', E12.5,  ' V(2)  =', E12.5,  ' HFG V2=', E12.5
     *       ,' ST    =', E12.5,/,' PTDPDT=', E12.5,  ' TIN   =', E12.5
     *       ,' W     =', E12.5)
 9010 CONTINUE
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      DO 1 I = 1,2
    1 PR(I)=3600.*CPY(I)*MU(I)/K(I)
      IRET=-1
C*** COMPUTE THE REYNOLDS NUMBER AS THE INDEPENDENT VARIABLE
      G=W/AF/60.0
C*** BASED ON 100% LIQUID FLOW
      D(IGA+21)=G*DH/MU(1)
C*** USE TULP FOR COLBURN FACTOR, THEN COMPUTE HEAT TRANSFER COEFF.
      CO=TLUP(ID(IRCD+7))
      HT(1)=CO*60.*G*CPY(1)/PR(1)**.67
C*** USE TULP FOR FRICTION FACTOR
      FF=TLUP(ID(IRCD+6))
```

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C*** COMPUTE VOLUME RATIO AND SLIP FOR LATER TWO-PHASE COMPUTATIONS
      VR=V(2)/V(1)
      DV=1.0-1.0/VR
      SL=SQRT(SQRT(VR-1.))
C*** COMPUTE PRESSURE DROP AS IF 100% LIQUID FLOW
      DP(1)=4.*FF*L*G*G*V(1)/(2.*DH*GC)
C*** REPEAT THE ABOVE COMPUTATIONS AS IF 100% VAPOR FLOW
      D(IGA+21)=G*DH/MU(2)
      CO=TLUP(ID(IRCD+7))
      HT(5)=CO*60.*G*CPY(2)/PR(2)**.67
      FF=TLUP(ID(IRCD+6))
      DP(2)=4.*FF*L*G*G*V(2)/(2.*DH*GC)
C*** DETERMINE WHICH FLUID-PHASE IS FLOWING AT THE INLET
      HSAT=VH(LOCT,D(IP+NSI),TSAT,V(2))-HFG
      TIN=D(IT+NSI)
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IRITE=1
      IF (IRITE .NE. 1) GO TO 9020
      REF=G*DH/MU(1)
      D(IGA+21)=REF
      COLBF=TLUP(ID(IRCD+7))
      FFF=TLUP(ID(IRCD+6))
      REV=G*DH/MU(2)
      D(IGA+21)=REV
      COLBV=TLUP(ID(IRCD+7))
      FFV=TLUP(ID(IRCD+6))
      VHPTV2=VH(LOCT,D(IP+NSI),TSAT,V(2))
      WRITE (OUT,9021)
 9021 FORMAT(' WRITE 9021 FROM "QBLRPP"      ')
      WRITE (OUT,9022) PR(1) , PR(2) , G     , REF
     *                , COLBF , HT(1) , FFF   , VR
     *                , DV    , SL    , DP(1) , REV
     *                , COLBV , HT(5) , FFV   , DP(2)
     *                , HSAT  , TIN   , VHPTV2
 9022 FORMAT(' PR(1) =', E12.5,  ' PR(2) =', E12.5,  ' G     =', E12.5
     *      ,' REF   =', E12.5,/,' COLBF =', E12.5,  ' HT(1) =', E12.5
     *      ,' FFF   =', E12.5,  ' VR    =', E12.5,/,' DV    =', E12.5
     *      ,' SL    =', E12.5,  ' DP(1) =', E12.5,  ' REV   =', E12.5
     *   ,/ ,' COLBV =', E12.5,  ' HT(5) =', E12.5,  ' FFV   =', E12.5
     *      ,' DP(2) =', E12.5,/,' HSAT L=', E12.5,  ' TIN   =', E12.5
     *      ,' VHPTV2=', E12.5)
 9020 CONTINUE
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IF(D(IH+NSI)-HSAT)360,332,332
  332 IF(D(IH+NSI)-HSAT-HFG)333,1272,1272
C$       LONGER COMMENTS
C*** IN TWO-PHASE REGION   AT INLET
  333 XI=(D(IH+NSI)-HSAT)/HFG
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IRITE=1
      IF (IRITE .NE. 1) GO TO 9023
      WRITE (OUT,9024)
 9024 FORMAT(' WRITE 9024 FROM "QBLRPP"      ')
      WRITE (OUT,9025) XI
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```
 9025 FORMAT(' XI     =', E12.5)
 9023 CONTINUE
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      TIN=TSAT
      GO TO 370
C*** IN LIQUID-ONLY REGION   AT INLET
  360 XI=0.0
  370 IF(D(IH+NSI)-HSAT)380,371,371
C*** IN TWO-PHASE REGION   AT INLET
  371 X1=0.0
      X2=0.0
      GO TO 750
C*** IN LIQUID-ONLY REGION   AT INLET
C*** COMPUTE FLUID TEMPERATURE (T) AND WALL TEMPERATURE (TW) AT OUTLET
  380 T(5)=TIN+Q/(W*CPY(1))
      TW(5)=T(5)+Q/(AH*HT(1))
C*** DETERMINE TEMPERATURE AT WHICH NUCLEATE BOILING BEGINS (TNB)
C    AND DETERMINE IF FLUID REACHES THE TEMPERATURE BEFORE OUTLET
      TNB=TSAT+SQRT(8.*60.*ST*Q/(K(1)*AH*PT))
      X1=(TNB-TIN)*W*CPY(1)*L/Q-W*CPY(1)*L/(HT(1)*AH)
C     WRITE(OUT,*) T(5),TW(5),TNB,X1
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IRITE=1
      IF (IRITE .NE. 1) GO TO 9030
      WRITE (OUT,9031)
 9031 FORMAT(' WRITE 9031 FROM "QBLRPP"     ')
      WRITE (OUT,9032) T(5)   , TW(5)  , TNB    , X1
 9032 FORMAT(' T(5)   =', E12.5,  ' TW(5) =', E12.5,  ' TNB   =', E12.5
     *       ,' X1     =', E12.5)
 9030 CONTINUE
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IF(X1)430,450,450
C*** SUBCOOLED BOILING BEGINS IMMEDIATELY AT THE INLET
  430 X1=0.0
      GO TO 485
  450 IF(TW(5)-TNB)460,480,480
C*** THERE IS NO BOILING WITHIN THE BOILER
  460 X1=L
      GO TO 1310
C*** COMPUTE THE TEMPERATURES AT THE END OF THE NON-BOILING REGION
  480 T(1)=TIN+Q*X1/(L*W*CPY(1))
      TW(1)=T(1)+Q/(HT(1)*AH)
C*** COMPUTE THE LENGTH OF THE SUBCOOLED-BOILING REGION
  485 X2=(TSAT-TIN)*W*CPY(1)*L/Q-X1
      IF(X2.GE.(L-X1))X2=L-X1
C*** COMPUTE THE BUBBLE DEPARTURE DIAMETER (DD) IN FEET
  490 DD=4.65E-4*SQRT(GC/GC*ST*V(1)/DV)*(VR*CPY(1)*TSAT/HFG)
     ***1.25
C*** COMPUTE THE FREQUENCY OF DEPARTURE OF BUBBLES, 1/SEC.
      FD=.6*SQRT(SQRT(ST*GC*GC*V(1)*DV))/DD
C*** ASSUME THE SURFACE FACTORS: B(SURFACE COFFICIENT); EM (EXPONENT
C    RELATING THE NUMBER OF NUCLEATION SITES GO THE TEMPERATURE
C    DIFFERENCE); AND RS(RADIUS, FT., OF SMALLEST SITE)
      B=400.
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      EM=2.0
      RS=0.0001
C*** COMPUTE THE NUMBER OF NUCLEATION SITES PER SQ. FT.
      XN=B*(JC*RS*HFG*(TNB-TSAT)/(2.*TSAT*ST*V(2)))**EM
C*** COMPUTE THE POOL BOILING HEAT-TRANSFER COEFFICIENT
      HP=3.5*(K(1)/DD/60.)*XN*DD*DD
      HP=HP*SQRT(PR(1))*SQRT(FD*DD*DD/(V(1)*MU(1)))
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IRITE=1
      IF (IRITE .NE. 1) GO TO 9040
      WRITE (OUT,9041)
 9041 FORMAT(' WRITE 9041 FROM "QBLRPP"     ')
      WRITE (OUT,9042) X1    , T(1)   , TW(1)  , X2
     *                , DD    , FD     , B      , EM
     *                , RS    , XN     , HP
 9042 FORMAT(' X1     =', E12.5,  ' T(1)   =', E12.5,  ' TW(1) =', E12.5
     *       ,' X2     =', E12.5,/,' DD     =', E12.5,  ' FD     =', E12.5
     *       ,' B      =', E12.5,  ' EM     =', E12.5,/,' RS     =', E12.5
     *       ,' XN     =', E12.5,/,' HP     =', E12.5)
 9040 CONTINUE
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IF(IRET)500,500,980
C*** COMPUTE THE COMBINED CONVECTION/BOILING COEFFICIENT
  500 HT(2)=(HP*HP+HT(1)*HT(1))/(2.*HP)
C*** ITERATIVELY COMPUTE THE WALL TEMPERATURE IN THE SUBCOOLED REGION
      A1=HP/(TNB-TSAT)**2
      A0=2.0*(Q/(A1*AH))**2
      A1=4.0*((HT(1)/A1)**2)/3.0
      S0=SQRT(A0*A0-A1**3)
      XX=ABS((A0-S0)/(A0+S0))
      IF(XX-.0001)650,670,670
  650 U=(A0+S0)**(1./3.)
      GO TO 680
  670 U=(A0+S0)**(1./3.)+(A0-S0)**(1./3.)
  680 TC=(SQRT(U)+SQRT(U-4.*(U/2.-SQRT((U/2.)**2-.75*A1))))/2.
      T(2)=TSAT
      TW(2)=TSAT+TC
      TW(5)=TW(2)
      X3=0.0
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IRITE=1
      IF (IRITE .NE. 1) GO TO 9050
      WRITE (OUT,9051)
 9051 FORMAT(' WRITE 9051 FROM "QBLRPP"     ')
      WRITE (OUT,9052) IRET   , HT(2) , A0     , A1
     *                ,S0     , XX    , U      , TC
     *                ,T(2)   , TW(2) , TW(5)
 9052 FORMAT(' IRET   =', I4,8X,   ' HT(2) =', E12.5,  ' A0     =', E12.5
     *       ,' A1     =', E12.5,/,' S0     =', E12.5,  ' XX     =', E12.5
     *       ,' U      =', E12.5,  ' TC     =', E12.5,/,' T(2)  =', E12.5
     *       ,' TW(2) =', E12.5,  ' TW(5) =', E12.5)
 9050 CONTINUE
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C*** GO TO 1280 IF THE EXIT IS 100% LIQUID (NO NET BOILING)
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      IF(X2.GE.(L-X1))GO TO 1280
C*** STARTING REGION 3: BULK BOILING
  750 XC=1.0
C*** COMPUTE THE DRYOUT POSITION
      X3=W*(CPY(1)*(TSAT-TIN)+HFG*(1.0-XI))*L/Q-X1-X2
C*** COMPUTE THE EXIT QUALITY
      XE=(Q/W-CPY(1)*(TSAT-TIN))/HFG+XI
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IRITE=1
      IF (IRITE .NE. 1) GO TO 9053
      WRITE (OUT,9054)
 9054 FORMAT(' WRITE 9054 BULK BOILING-DRYOUT POSITION  FROM "QBLRPP"'
      WRITE (OUT,9055) X3    , XE
 9055 FORMAT(' X3DRYO=', E12.5,  ' XE    =', E12.5)
 9053 CONTINUE
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IF(XE-1.)830,820,820
C*** FILM-BOILING OR VAPOR-ONLY HEATING OCCUR
  820 XE=1.0
      GO TO 1140
C*** COMPUTE THE CRITICAL EXIT QUALITY ABOVE WHICH FILM BOILING OCCURS
C$WAS COMPUTE THE CRITICAL EXIT QUALITY ABOVE WHICH VAPORIZATION OCCUR
  830 XC=JC*HFG*(XE-XI)/L
C$              NEED TO USE "REF" HERE AS ON P 97 COSTELLO
C$              CODE USED OLD "REV" VALUE... LINE BELOW SHOULD FIX
      D(IGA+21)=G*DH/MU(1)
      XC=1.04-1.14E-5*(D(IGA+21)*D(IGA+21)*XC)**.375
C*** COMPUTE LENGTH OF THE BULK-BOILING REGION (X3)
      X3=X3*(XC-XI)/(1.0-XI)
      IF (X3.LT.0.0) X3=0.0
      IF(X3.GT.(L-X1-X2))X3=L-X1-X2
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IRITE=1
      IF (IRITE .NE. 1) GO TO 9060
      WRITE (OUT,9061)
 9061 FORMAT(' WRITE 9061  FROM "QBLRPP"     ')
      WRITE (OUT,9062) X3    , XE    , XC
 9062 FORMAT(' X3    =', E12.5,  ' XE    =', E12.5,  ' XC    =', E12.5
 9060 CONTINUE
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IF(XE.GE.XC)GO TO 1140
C*** COMPUTE THE TWO-PHASE PARAMETER
      TT=(1.0/XE-1.0)**0.9*SQRT(DP(1)/DP(2))
      X3=L-X1-X2
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IRITE=1
      IF (IRITE .NE. 1) GO TO 9070
      WRITE (OUT,9071)
 9071 FORMAT(' WRITE 9071    XE LESS THAN XC    FROM "QBLRPP"      ')
      WRITE (OUT,9072) TT    , X3
 9072 FORMAT(' TT    =', E12.5,  ' X3    =', E12.5)
 9070 CONTINUE
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C*** GO TO 1090 IF XE AND TT INDICATE THE RANGE FOR ELLERBROOK'S FORMU
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      IF(XE.GT.0.7.OR.TT.LT.0.01)GO TO 1090
C*** USE CHEN'S FORMULA
      F=1.0+1.88/TT**0.8
      Y=F*(G*DH/MU(1)*(1.0-XE))**0.8/10000.
      S=EXP(-Y)
C*** COMPUTE TNB AS A FIRST APPROXIMATION TO THE WALL TEMPERATURE
C    THEN GO TO 490 TO COMPUTE THE POOL-BOILING HEAT-TRANSFER COEFF.
      TNB=TSAT+SQRT(.8*60.*ST*Q/(K(1)*AH*PT))
      IRET=1
      GO TO 490
C*** COMPUTE THE BULK-BOILING COEFFICIENT WITH CHEN'S FACTORS
  980 HT(3)=F*HT(1)+S*HP
C*** COMPUTE THE WALL TEMPERATURE AT THE END OF THE TWO-PHASE REGION
C    UNDER THE ASSUMPTION THAT EM IS APPROXIMATELY 2.0
      A1=HP/(TNB-TSAT)**2
      A0=Q/(AH*S*A1*2.0)
      A1=F*HT(1)/(3.0*S*A1)
      S0=SQRT(A0*A0+A1**3)
      T(3)=TSAT
      TW(3)=TSAT+(A0+S0)**(1./3.)-(S0-A0)**(1./3.)
      TW(5)=TW(3)
      T(5)=TSAT
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IRITE=1
      IF (IRITE .NE. 1) GO TO 9080
      WRITE (OUT,9081)
 9081 FORMAT(' WRITE 9081     CHEN''S FORMULA       FROM "QBLRPP"    '
      WRITE (OUT,9082) F      , Y      , S      , TNB
     *                 ,IRET  , A0     , A1     , S0
     *                 ,T(3)  , TW(3)  , TW(5)  , T(5)
     *                 ,HT(3)
 9082 FORMAT(' F      =', E12.5,  ' Y      =', E12.5,  ' S      =', E12.5
     *      ,' TNB    =', E12.5,/,' IRET   =', I4,8X,  ' A0     =', E12.5
     *      ,' A1     =', E12.5,  ' S0     =', E12.5,/,' T(3)   =', E12.5
     *      ,' TW(3)  =', E12.5,  ' TW(5)  =', E12.5,  ' T(5)   =', E12.5
     *      ,' HT(3)  =', E12.5)
 9080 CONTINUE
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C*** GO TO 1320 TO COMPUTE THE TWO-PHASE PRESSURE DROP
      GO TO 1320
C$     THE ELLERBROOK FORMULA GIVES AN H LOWER THAN FOR FILM BOILING
C$     AND LOWER THAN "HT(5)" (ALL VAPOR).  IS SOMETHING WRONG OR IS
C$     ELLERBROOK JUST A DAMN FLAKE??
C*** ELLERBROOK'S FORMULA FOR THE HEAT-TRANSFER COEFFICIENT
 1090 Y=2.35-ALOG(TT)*(.266+.0255*ALOG(TT))
      HT(3)=HT(5)*(Q/(AH*60.*G*HFG))**.4*EXP(Y)
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IRITE=1
      IF (IRITE .NE. 1) GO TO 9090
      WRITE (OUT,9091)
 9091 FORMAT(' WRITE 9091   ELLERBROOK''S HT(3) FORMULA FROM "QBLRPP"'
      WRITE (OUT,9092) Y      , HT(3)
 9092 FORMAT(' Y      =', E12.5,  ' HT(3) =', E12.5)
 9090 CONTINUE
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C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      GO TO 1180
C*** XE>XCRIT OR XE>1.  SO FILM BOILING OR VAPOR-ONLY HEATING OCCURS
C$WAS SO FILM BOILING OR VAPOR-ONLY HEATING OCCURS
 1140 HT(3)=HT(5)*(XE+SL/VR*(1.0-XE))**0.8
C*** FLUID AND WALL TEMPERATURES AT THE END OF THE TWO-PHASE REGION
C$WAS 1180 T(3)=TSAT+(Q*(X3+X2+X1)/W/L-CPY(1)*(TSAT-TIN)-HFG*(XE-XI))
C$          /CPY(2)
C$
C$   CERTAINLY WHILE TWO-PHASE, T=TSAT!!!
 1180 T(3)=TSAT
      TW(3)=T(3)+Q/(AH*HT(3))
      T(5)=T(3)
      TW(5)=TW(3)
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IRITE=1
      IF (IRITE .NE. 1) GO TO 9100
      WRITE (OUT,9101)
 9101 FORMAT(' WRITE 9101   FILM BOIL OR VAPOR ONLY HEATING   "QBLRPP"'
      WRITE (OUT,9102) T(3)   , HT(3)  , TW(3)  , T(5)
     *                ,TW(5)  , X1     , X2     , X3
     *                ,XI     , XE
 9102 FORMAT(' T(3)   =', E12.5,  ' HT(3) =', E12.5,  ' TW(3) =', E12.5
     *       ,' T(5)   =', E12.5,/,' TW(5) =', E12.5,  ' X1    =', E12.5
     *       ,' X2     =', E12.5,  ' X3    =', E12.5,/,' XI    =', E12.5
     *       ,' XE     =', E12.5)
 9100 CONTINUE
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C*** IF VAPOR-ONLY FLOW DOES NOT OCCUR, GO TO 1320 TO COMPUTE DELTA P
      IF(XE.LT.1.0)GO TO 1320
C*** COMPUTE OUTLET CONDITIONS FOR VAPOR-ONLY FLOW
      T(5)=(Q/W-CPY(1)*(TSAT-TIN)-HFG*(1.0-XI))/CPY(2)+TSAT
      XE=1.0
      TW(5)=T(5)+Q/(AH*HT(5))
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IRITE=1
      IF (IRITE .NE. 1) GO TO 9110
      WRITE (OUT,9111)
 9111 FORMAT(' WRITE 9111   VAPOR ONLY HEATING   "QBLRPP"')
      WRITE (OUT,9112) T(5)   , XE     , TW(5)
 9112 FORMAT(' T(5)   =', E12.5,  ' XE    =', E12.5,  ' TW(5) =', E12.5
 9110 CONTINUE
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      GO TO 1320
C*** COMPUTE OUTLET CONDITIONS FOR VAPOR-ONLY FLOW FROM INLET TO OUTLE
 1272 T(5)=TIN+Q/W/CPY(2)
      TW(5)=T(5)+Q/AH/HT(5)
C$   ADD 144 FACTOR; DO NOT COMPUTE "D(IP+NSO)" HERE AND LINE 1475
      XDP=DP(2)/144.
C$    D(IP+NSO)=D(IP+NSI)-DP(2)/144.
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IRITE=1
      IF (IRITE .NE. 1) GO TO 9120
      WRITE (OUT,9121)
```

```
 9121 FORMAT(' WRITE 9121   VAPOR ONLY INLET TO OUTLET   "QBLRPP"')
      WRITE (OUT,9122) T(5)   , TW(5)
 9122 FORMAT(' T(5)   =', E12.5,  ' TW(5) =', E12.5)
 9120 CONTINUE
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      GO TO 1475
C*** COMPUTE THE OUTLET TEMPERATURE FOR NO NET VAPOR GENERATION
 1280 T(5)= TIN+Q/(AH*CPY(1))
 1310 PB=0.0
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IRITE=1
      IF (IRITE .NE. 1) GO TO 9130
      WRITE (OUT,9131)
 9131 FORMAT(' WRITE 9131 TOUT FOR NO NET VAPOR GENERATED  "QBLRPP"')
      WRITE (OUT,9132) T(5)   , PB
 9132 FORMAT(' T(5)   =', E12.5,  ' PB    =', E12.5)
 9130 CONTINUE
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      GO TO 1350
C*** COMPUTE THE TWO-PHASE PRESSURE DROP BY FAC. INC. CORRELATION
C    OF BAROCZY'S GRAPHICAL CORRELATION
 1320 PF=0.25*ALOG10(DP(1)/DP(2))
      PB=XE**.7/1.7-(1-XE)**2.3/2.3+(1.-(1.-XE)**3.3)/(3.3*2.3*XE)
C*** COMPUTE THE FRICTION PRESSURE DROP
      PB=-XE**1.65*PF/2.65+(1.0+PF)*PB
 1350 FP=DP(1)*(X1+X2)/L+(DP(1)+PB*(DP(2)-DP(1)))*X3/L
      FP=FP+DP(2)*(1.-(X1+X2+X3)/L)
      IF(XE) 1382,1382,1385
C*** ADD THE MOMENTUM PRESSURE DROP
 1382 MP=0.0
      GO TO 1470
 1385 VE=XE/(XE+SL*(1.0-XE)/VR)
      IF(VE-1.0)1388,1386,1386
 1386 ME=VR
      GO TO 1390
 1388 ME=((1.-XE)/(1.-VE))**2*(1.-VE*(1.-SL*SL/VR))
 1390 IF(XI)1395,1395,1400
 1395 MI=1.0
      GO TO 1440
 1400 VI=XI/(XI+SL*(1.0-XI)/VR)
      IF(VI-1.0)1430,1425,1425
 1425 MI=VR
      GO TO 1440
 1430 MI=((1.-XI)/(1.-VI))**2*(1.-VI*(1.-SL*SL/VR))
 1440 MP=G*G*V(1)*(ME-MI)/GC
 1470 XDP=(FP+MP)/144.
 1475 D(IP+NSO)=D(IP+NSI)-XDP
CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IRITE=1
      IF (IRITE .NE. 1) GO TO 9140
      XFPPSI= FP/144.
      XMPPSI= MP/144.
      WRITE (OUT,9141)
 9141 FORMAT(' WRITE 9141     DELTA P CALC          FROM "QBLRPP"    '
```

```
      WRITE (OUT,9142) PF     , PB     , FP     , XE
     *                ,VE     , ME     , MI     , VI
     *                ,MP     , XMPPSI, XDP    , XFPPSI
 9142 FORMAT(' PF     =', E12.5,  ' PB     =', E12.5,  ' FP     =', E12.5
     *      ,' XE     =', E12.5,/,' VE     =', E12.5,  ' ME     =', E12.5
     *      ,' MI     =', E12.5,  ' VI     =', E12.5,/,' MP     =', E12.5
     *      ,' XMPPSI=', E12.5,  ' XDP    =', E12.5,  ' XFPPSI=', E12.5
 9140 CONTINUE
CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IF (D(IP+NSO).GT.0.0)GO TO 1476
      WRITE(OUT,7655) D(IP+NSO),D(IP+NSI)
 7655 FORMAT(' *+* OUTLET PRESSURE IN QBOILER WAS',E14.7,
     *   ' RESET PRESSURE TO INLET VALUE',E14.7)
      XDP=0.0
      D(IP+NSO)=D(IP+NSI)
 1476 CONTINUE
C$WAS IF(T(5)-TSAT)1478,1479,1479
      IF(T(5)-TSAT)1478,14785,1479
 1478 D(IH+NSO)=VHLIQ(LOCT,D(IP+NSI),T(5))
      GO TO 1480
C$      NEW LINE BELOW CALCULATES EXIT ENTHALPY WHEN TWO-PHASE AT EXIT
14785 D(IH+NSO)=HSAT+XE*HFG
      GO TO 1480
 1479 VV=VSV('QBLRPP 2',LOCT,D(IP+NSO),T(5))
      D(IH+NSO)=VH(LOCT,D(IP+NSO),T(5),VV)
 1480 CONTINUE
      D(IT+NSO)=T(5)
CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IRITE=1
      IF (IRITE .NE. 1) GO TO 9150
      WRITE (OUT,9151)
 9151 FORMAT(' WRITE 9151   ASSIGN HOUT AND TOUT    FROM "QBLRPP"     '
      WRITE (OUT,9152) T(5)   , VV     , TSAT   , HSAT
     *                ,XE     , HFG
 9152 FORMAT(' T(5)   =', E12.5,  ' VV     =', E12.5,  ' TSAT   =', E12.5
     *      ,' HSAT   =', E12.5,/,' XE     =', E12.5,  ' HFG    =', E12.5
 9150 CONTINUE
CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IF (ID(IRCD+13).EQ.0) GO TO 1579
      IF(PASS.NE.1) GO TO 1577
      ID(IEVT+JEVI)=3
 1577 IF (TMAX.GE.TSAT) GO TO 1576
      WRITE(OUT,1580) TMAX,TSAT,TW(5)
 1580 FORMAT(5X,'WARNING FROM QBOILER: ERROR VARIABLE CANNNOT BE '/
     *' CONTROLLED BECAUSE THE CONTROLLED WALL TEMPERATURE OF',E17.7/
     *' IS LESS THAN THE SATURATION TEMPERATURE OF',E17.7/
     *' THE WALL TEMPERATURE IS',E17.7)
 1576 IF(T(5).GT.TSAT)GO TO 1578
      WRITE(OUT,1590)XE
 1590 FORMAT(5X,'WARNING FROM QBOILER: TWO PHASE FLUID AT OUTLET',
     *' PROBABLY CANNOT CONTROL WALL TEMP. EXIT QUALITY IS',E12.4)
 1578 D(IEV+JEVI) = (TMAX-TW(5))/XE
 1579 CONTINUE
 1485 FORMAT(' OVERALL: DP,TW(5),T(5) ',3F10.3)
```

```
      IF (IFP.NE.1.OR. ICPP.NE.0) GO TO 99
      CALL PIOP(1,NL,NSI,NSO)
      CALL LINES(1)
      WRITE(OUT,1581) ID(ISN+NSO),TW(5)
 1581 FORMAT(5X,'BOILER AT STATION NO.',I4,' HAS A MAXIMUM WALL ',
     * 'TEMPERATURE OF',E15.5,' DEGREES R')
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      WRITE(OUT,9581) XI, XE
 9581 FORMAT('       INLET QUAL=', F8.3, '    EXIT QUAL=', F8.3)
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
   99 CONTINUE
      RETURN
C     QBLRPP
      END
```

Stations 8 and 14 to compute the intercooler performance. The computations then proceed to Station 9, then to Stations 11, 12, 13, and 14. The computations for Leg 10 terminate at Station 14, the cold-inlet side of the intercooler, because the cold-outlet side (Station 16) had been computed when the intercooler was first encountered. Therefore, on the first pass, Station 16 values were based on the INDATA guesses. In Pass 2, Station 16 values will be based on the Pass 1 values. Station 16 will, therefore, always have values based on the previous pass. When the solution converges, the values from two successive passes will be equal, so the lag will have no influence on the final solution.

Because there is a lag in the numerical values wherever INDATA is used, the number of iterations required is always greater with INDATA than without. Therefore, INDATA should be used as little as possible. The prior AECS unwritten rule should be observed as much as possible: LOOPS should be located such that all inlet states will have been calculated prior to encountering a component.

7.5. Program Listing

There is no simulation program for INDATA; however, the "PZ" subroutine is listed in Exhibit 7.4-1, except that comments have been added for the exhibit.

7.6. Sample Case

INDATA cannot stand alone in a sample case. The user should refer to Appendix A to see an example of the use of INDATA.

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8. Subroutine LOOP (Loop Start and Loop End)

8.1. Subroutine Description

The LOOPS (Loop Start) subroutine does not simulate a component; instead, it permits the user to define the flow rate, pressure, temperature, and enthalpy at some point in a closed-loop system. The AECS solution procedure will then minimize the difference between these values and those deduced from the computations as the loop closes back on itself, ending in LOOPE. The values entered in LOOPS, which is treated as a component (usually the first in the component list), are compared to those computed for LOOPE (usually the last in the component list).

8.2. Prior Simulation Method

The previous LOOPS permitted temperature to be used as a state variable. If the loop were to start with a two-phase refrigerant, the temperature and pressure would not define the thermodynamic state. Therefore, the previous LOOPS was of limited utility in refrigerant systems.

8.3. New Simulation Method

The new version of LOOPS permits enthalpy instead of temperature as the state variable, when the fluid is a refrigerant. The temperature is deduced from the pressure and enthalpy by virtue of the refrigerant-properties routines, so the user value is overridden by the computer if the fluid is a refrigerant.

The new version of LOOPE accepts enthalpy as an error variable, in its attempt to match LOOPS; it does not accept temperature if the fluid is a refrigerant.

8.4. Computational Procedure

The modification to LOOPS and LOOPE was almost trivial (Exhibit 8.4-1). A branch is made if the fluid is a refrigerant, so the temperature can be computed as a function of pressure and enthalpy. Any refrigerant state is permissible. The branch also establishes the enthalpy as the state variable, if the user so designates it.

8.5. Program Listing

The few lines that have been modified are easily identified (Fluid Type = 3). The annotated listing is presented in Exhibit 8.4-1.

8.6. Sample Case

LOOPS and LOOPE must be used in conjunction with other components. Therefore, a separate sample case is inappropriate. The reader can see examples of the use of LOOPS and LOOPE in refrigerant systems in Appendix A and in Section 4 (the COP example).

Exhibit 8.4-1: Performance-Program Logic and Listing

```
      SUBROUTINE LPSPP
      COMMON /CC/ C(400)
      EQUIVALENCE (IRCD,C(45)), (ISVT,C(46)), (ISV
                              ,C(47)), (IEVT,C(48))
     *, (IEV,C(49)), (IW,C(27)), (IP,C(28)), (IT,C
                              (29)), (IH,C(30))
     *, (CERR,C(16)), (OUT,C(7)), (PASS,C(17)), (IFB,C(55))
      DIMENSION SCR(30)
      INTEGER CERR, OUT, PASS
      EQUIVALENCE (SCR(1),NLI), (SCR(2),NSI), (SCR
                              (3),NLO), (SCR(4),NSO)
     *, (SCR(5),ISV1,IEV1), (SCR(6),ISV2,IEV2), (S
                              CR(7),ISV3,IEV3)
     *, (SCR(8),ISV4,IEV4), (SCR(9),IRCD2), (SCR(1
                              0),NC), (SCR(11),LOCT)
     *, (SCR(12),P), (SCR(13),T), (SCR(14),TS), (SCR(15),V)
     *, (SCR(16),DSH)
      COMMON /DC/ DZ(2),D(2)
      DIMENSION ID(2)
      EQUIVALENCE (ID(1),D(1))
C     1 COMP CODE
C     2 LEG NO. - LOOP START
C     3 STATION NO. - LOOP START
C     4 LEG NO. - LOOP END
C     5 STATION NO. - LOOP END
C     6 IRCD NO. 2
C     7 SV W / EV W
C     8 SV P / EV P
C     9 SV T / EV T
C    10 SV H / EV H
C    11 W (LOOPS ONLY)
C    12 P (LOOPS ONLY)
C    13 T (LOOPS ONLY)
C    14 H (LOOPS ONLY)
C    15 DSH
      IE = 1
      GO TO 1
C*** ENTRY POINT FOR LOOP END
      ENTRY LPEPP
      IE = 2
C*** SET UP INTERNAL VARIABLES IN TERMS OF STORED ARRAY
    1 IRCD = IRCDB(15)
      NLI = ID(IRCD+2)
      NSI = ID(IRCD+3)
      NLO = ID(IRCD+4)
      NSO = ID(IRCD+5)
      IRCD2 = ID(IRCD+6)
C*** BRANCH TO 10 FOR LOOP END
      IF (IE.EQ.2) GO TO 10
      IF (PASS.EQ.1) CALL FLUIDP(NLI)
      LOCT = ID(IFB+NLI)
      NC = ID(LOCT+1)
      LOCT = ID(LOCT+3)
C*** SET UP W, P, T AND H PER INPUT DATA
```

```
      D(IW+NLI) = D(ID(IRCD+11))
      D(IP+NSI) = D(ID(IRCD+12))
      D(IT+NSI) = D(ID(IRCD+13))
      D(IH+NSI) = D(ID(IRCD+14))
C*** SET UP THE STATE VARIABLES
    9 ISV1 = ID(IRCD+7)
      ISV2 = ID(IRCD+8)
      ISV3 = ID(IRCD+9)
      ISV4 = ID(IRCD+10)
      IF (ISV1.EQ.0) GO TO 20
      IF (PASS.NE.1) GO TO 12
      ID(ISVT+ISV1) = 1
      D(ISV+ISV1) = D(IW+NLI)
   12 D(IW+NLI) = D(ISV+ISV1)
   20 IF(ISV2.EQ.0) GO TO 30
      IF (PASS.NE.1) GO TO 22
      ID(ISVT+ISV2) = 2
      D(ISV+ISV2) = D(IP+NSI)
   22 D(IP+NSI) = D(ISV+ISV2)
   30 IF (ISV3.EQ.0) GOT O 40
      IF (PASS.NE.1) GO TO 32
      ID(ISVT+ISV3) = 3
      D(ISV+ISV3) = D(IT+NSI)
   32 D(IT+NSI) = D(ISV+ISV3)
   40 IF (ISV4.EQ.0) GO TO 45
      IF (PASS.NE.1) GO TO 42
      ID(ISVT+ISV4) = 4
      IF(NC.EQ.3)ID(ISVT+ISV4)=10
      D(ISV+ISV4) = D(IH+NSI)
   42 D(IH+NSI) = D(ISV+ISV4)
   45 IF(NC.NE.3) GO TO 50
C*** IF FLUID IS A REFRIGERANT (TYPE = 3) RECOMPUT
                                E THE TEMPERATURE
C     FROM THE ENTHALPY AND PRESSURE.  OVERRIDE THE INPUT VALUE.
      QUAL=VQUALH(LOCT,D(IP+NSI),D(IH+NSI))
      IF(QUAL.LT.0.0)D(IT+NSI)=VTLIQ(LOCT,D(IP+NSI),D(IH+NSI))
      IF(QUAL.GE.0..AND.QUAL.LE.1.)D(IT+NSI)=VTS(LOCT,D(IP+NSI))
      IF(QUAL.GT.1.)CALL VTAV2(LOCT,D(IT+NSI),V,D(
                                IP+NSI),D(IH+NSI))
   50 IF (IRCD2.NE.0) GO TO 99
      CERR = CERR+1
      CALL LINES(2)
      WRITE (OUT,1000) CERR
 1000 FORMAT(6H0ERROR,I6,5X,21HLOOPS/LOOPE UNMATCHED)
      GO TO 99
C*** SET UP THE ERROR VARIABLES FOR LOOP END
   10 IEV1 = ID(IRCD+7)
      IEV2 = ID(IRCD+8)
      IEV3 = ID(IRCD+9)
      IEV4 = ID(IRCD+10)
      IF (PASS.NE.1) GO TO 3
      IF (IEV1.NE.0) ID(IEVT+IEV1) = 1
      IF (IEV2.NE.0) ID(IEVT+IEV2) = 2
      IF (IEV3.NE.0) ID(IEVT+IEV3) = 3
```

```
      IF (IEV4.NE.0) ID(IEVT+IEV4) = 4
C*** COMPUTE THE VALUES OF THE ERROR VARIABLES
    3 IF (IEV1.NE.0) D(IEV+IEV1) = D(IW+NLI)-D(IW+NLO)
      IF (IEV2.NE.0) D(IEV+IEV2) = D(IP+NSI)-D(IP+NSO)
      IF (IEV3.NE.0) D(IEV+IEV3) = D(IT+NSI)-D(IT+NSO)
      IF (IEV4.NE.0) D(IEV+IEV4) = D(IH+NSI)-D(IH+NSO)
   99 CONTINUE
      RETURN
C     LPSPP, LPEPP
      END
```

9. Subroutine NRCLR (Refrigerant Intercooler)

9.1 Subroutine Description

The NRCLR routine simulates a single- or two-phase-flow heat exchanger with refrigerant flowing on both sides. The hot side would normally contain the high-pressure, high-temperature discharge from the condenser; the cold side would normally contain the cold refrigerant vapor coming from the evaporator. The NRCLR is usually used to reduce the compressor power by providing cooling between successive stages of compression.

9.2 Prior Simulation Method

NRCLR is a new routine. Although two-phase-flow heat exchangers are used elsewhere in AECS, this is the only heat exchanger in which two-phase-flow heat transfer can occur on either or both sides.

9.3 New Simulation Method

The heat exchanger in NRCLR can be envisioned as a counterflow heat exchanger, with the cold fluid flowing from x=0 to x=1 and the hot fluid flowing from x=1 to x=0. The counterflow analysis used in the routine should be an adequate approximation if multi-pass cross-counterflow is used in practice.

The refrigerant can enter either side of the heat exchanger in subcooled, saturated, two-phase, or superheated states. The outlet states can also be subcooled, saturated, two-phase or vapor. The corresponding heat-transfer coefficients must be estimated by the user and entered in the parameter list. The decrease in saturation temperature due to the pressure drop through the heat exchanger is ignored.

The subroutine computes the temperatures, pressures, enthalpy and quality of the fluids leaving the two sides of the heat exchanger. Data computed internally but not normally printed include the x positions at which the flow turns from single- to two-phase or vice versa.

9.4 Computational Procedure

The computational procedure is presented in the form of a heavily annotated FORTRAN program in Exhibit 9.4-1.

The computations are started at x=0, where the cold fluid enters. The enthalpy of the hot fluid at x=0, where the hot fluid exits, is assumed, beginning with the enthalpy corresponding to the average between the enthalpy at the hot inlet and the hot-fluid enthalpy at the cold inlet temperature. In successive assumptions, this interval

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Exhibit 9.4-1: Performance-Program Logic and Listing

```
      SUBROUTINE NRCLRPP
      COMMON /CC/ C(400)
      EQUIVALENCE (IRCD,C(45)),(IW,C(27)),(IP,C(28)),(IT,C(29))
     *, (IH,C(30)), (SCR(1),C(151)), (ICPP,C(88)), (OUT,C(7))
     *, (IFP,C(22)), (IGA,C(35)), (ILN,C(37)), (PASS,C(17))
     *,(CERR,C(16)),(IIOP,C(90)),(DP(1),C(171)),(ITAD,C(54))
     *,(IFB,C(55)),(GVTY,C(370)),(CJ,C(371))
     *,(VRC,C(378)),(VRH,C(379)),(PCOLD,C(380)),(PHOT,C(381))
      DIMENSION SCR(30),DP(8)
      INTEGER PASS,OUT,CERR
      REAL MUR1,MUR2,MUAVG,MC,MH,NC,LC,LH
      EQUIVALENCE  (SCR(1),NLC), (SCR(2),NSIC), (SCR(3),NSOC)
     *, (SCR(4),NLH), (SCR(5),NSIH), (SCR(6),NSOH), (SCR(7),AC)
     *,(SCR(8),AH),(SCR(9),ITBL1),(SCR(10),ITBL2),(SCR(11),HTCL)
     *,(SCR(12),HTC2),(SCR(13),HTCV),(SCR(14),HTHL
                         ),(SCR(15),HTH2)
     *, (SCR(16),HTHV)
      COMMON /DC/ DZ(2),D(2)
      DIMENSION ID(2)
      EQUIVALENCE (ID(1),D(1))
     *,(D(41),VFC),(D(42),CFMC),(D(43),VGH),(D(44),VFH)
     *,(D(49),SC),(D(50),VSATC),(D(51),HSATC),(D(52),HSATH)
     *,(D(53),LC),(D(54),SH),(D(55),VSATH),(D(56),LH)
     *,(D(57),QC),(D(58),QH),(D(59),HN),(D(60),HH)
     *,(D(61),CQ),(D(62),HQ),(D(63),PINH),(D(64),PINC)
     *,(D(65),TTH),(D(67),HLOW),(D(68),V)
     *,(D(69),HIGH),(D(70),HTEST),(D(71),HOUTH),(D(72),TH)
     *,(D(73),KEY),(D(74),TVTC),(D(75),TVTH),(D(76),XCX)
C    1 COMP CODE
C    2 LEG COLD NLC
C    3 STATION IN COLD NSIC
C    4 STATION OUT COLD NSOC
C    5 LEG HOT NLH
C    6 STATION IN HOT NSIH
C    7 STATION OUT HOT NSOH
C    8 FLOW AREA COLD AC
C    9 FLOW AREA HOT AH
C   10 PRESSURE DROP TABLE RELATIVE NUMBER FOR TYPES 61 AND 62
C      (COLD AND HOT SIDES, RESPECTIVELY), FT OF VAPOR VS CFM WITH
C      VAPOR ONLY
C   11 HEAT TRANSFER COEFFICIENT,  LIQUID HTCL
C   12 HEAT TRANSFER COEFFICIENT,  2 PHASE HTC2
C   13 HEAT TRANSFER COEFFICIENT,  VAPOR   HTCV
C   14 HEAT TRANSFER AREA ON COLD SIDE (SQUARE FEET)
C   15 HEAT TRANSFER AREA ON HOT SIDE (SQUARE FEET)
C*** PRESSURE-DROP FUNCTION FOR TWO-PHASE FLOW BASED ON
C    FAC,INC., CORRELATION OF BAROCZY'S METHOD
      FNQ(X,PF)=-PF*X**1.65/2.65+(1.+PF)*(X**.7/1.7-(1.-X)**2.3
     */2.3+(1.-(1.-X)**3.3)/2.3/3.3/X)
C*** VOID-FRACTION CORRELATION
      FNV(X,VR)=X/(X+SL*(1.-X)/VR)
C*** RATIO OF MOMENTUM FLUX TO MOMENTUM OF LIQUID-ONLY FLOW
      FNM(X,VR)=((1.-X)/(1.-VE))**2*(1.-VE*(1.-SL*SL/VR))
C*** DERIVATIVE OF THE PRESSURE-DROP FUNCTION
```

PF = -.25 * ALOG10(VG/VF)

compare to p 90, 91 QBOILR + p 99

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VH gets (LIQ, P, T, V), gives H for superheat vapor

```
      IF(TC.GT.SH) HLOW=VH(LHOT,D(IP+NSIH),TC,VSV(
                                 LHOT,D(IP+NSO),TC))
      HIGH=HH
C*** BASE THE CONVERGENCE ON THE HOT-SIDE ENTHALPY DECREASE
      HTEST=HIGH-HLOW
      TVTC=VTS(LCOLD,PINC)
      TVTH=VTS(LHOT,PINH)
      FC=VCPF(LCOLD,PINC,TVTC)
      FH=VCPF(LHOT,PINH,TVTH)
      GC=VCPV(LCOLD,PINC,TVTC)
      GH=VCPV(LHOT,PINH,TVTH)
C*** FIRST ESTIMATE OF THE HOT SIDE ENTHALPY:
C    MIDWAY BETWEEN THE HIGHEST (INLET) AND COLDEST POSSIBLE
C*** RETURN HERE WITH EACH SUCCESSIVE APPROXIMATION
  200 HOUTH=0.5*(HLOW+HIGH)
      HH=HOUTH
      QH=0.0
C*** COMPUTE THE CORRESPONDING THERMAL PROPERTIES
      IF(HH.LT.HLIQH)TH=VTLIQ(LHOT,PINH,HH)
      IF(HH.GE.HLIQH)TH=SH
      QH=1.-(HSATH-HH)/LH
      IF(QH.GT.1.0)CALL VTAV2(LHOT,TH,VHOT,PINH,HH)
      T0=TH
      TC=D(IT+NSIC)
      HC=CN
      QC=CQ
      X0=0.0
      KEY=0
C*** BRANCH: IF HOT-SIDE IS LIQUID, TO 290; IF VAP
                                 OR, 310; OTHERWISE 300
  280 IF(HH.LT.HLIQH)GO TO 290
      IF(HH.GE.HLIQH.AND.HH.LT.HSATH) GO TO 300
      GO TO 310
C*** BRANCH: IF COLD-SIDE IS LIQUID, TO 320; IF VA
                                 POR, 770; OTHERWISE 610
  290 IF(HC.LT.HLIQC)GO TO 320
      IF(HC.GE.HLIQC.AND.HC.LT.HSATC)GO TO 610
      GO TO 770
C*** BRANCH: IF COLD-SIDE IS LIQUID, TO 970; IF VA
                                 POR, 1300; OTHERWISE 1150
  300 IF(HC.LT.HLIQC)GO TO 970
      IF(HC.GE.HLIQC.AND.HC.LT.HSATC)GO TO 1150
      GO TO 1300
C*** BRANCH: IF COLD-SIDE IS LIQUID, 1460; IF VAPO
                                 R, 1840; OTHERWISE 1680
  310 IF(HC.LT.HLIQC)GO TO 1460
      IF(HC.GE.HLIQC.AND.HC.LT.HSATC)GO TO 1680
      GO TO 1840
C*** HOT SIDE = LIQUID; COLD SIDE = LIQUID.  SET U
                                 P HEAT-TRANSFER COEF'S
  320 CHTCL=HTCL
      CH=HTHL
C*** COMPUTE THE CAPACITANCE RATE: COLD/HOT
      XCX=MC*FC/(MH*FH)
```

S/B NSOH

```
      TC=DC
      QH=1.0-(HSATH-HH) /LH
      QC=1.0-(HSATC-HC) / LC
C*** DETERMINE WHERE THE COMPUTATIONS ARE TO PROCE
                                        ED, BASED ON THE
C    THE NEXT FLOW REGION
      GO TO 1990
C*** COLD SIDE TWO PHASE; HOT SIDE LIQUID
C    COMPUTE USING THE SAME LOGIC AS ABOVE FOR LIQ
                                        UID-LIQUID FLOWS
  610 CHTCL=HTC2
      CH=HTHL
      XCX=MC*LC/(MH*FH*(TH-TC))
      NC=1.0/(MH*FH*XCX*(1./(AHTC*CHTCL)+1./(AHTH*CH)))
      XH=(SH-TC)/(TH-TC)
      IF(XH) 651,651,652
  651 XH=1.1
      GO TO 660
  652 XH=ALOG(XH)/(XCX*NC)
  660 XC=(1.+XCX*(1.-QC))
      IF (XC) 661,661,662
  661 XC=1.1
      GO TO 670
  662 XC=ALOG(XC)/(XCX*NC)
  670 X=XC
      IF(XC.GT.XH)X=XH
      IF((X+X0)-1.) 690,690,680
  680 X=1.-X0
      KEY=1
      QTY=XCX*NC*X
  690 DH=TC+(TH-TC)*EXP(XCX*NC*X)
      HH=VHLIQ(LHOT,PINH,DH)
      IF(X.NE.XH)GO TO 695
      DH=SH
      HH=HLIQH
  695 TH=DH
      QH=1.0-(HSATH-HH) / LH
      QC=QC-(1.-EXP(XCX*NC*X))/XCX
      IF(X.NE.XC) GO TO 750
      QC=1.0
      TC=SC
      HC=HSATC
      GO TO 1990
  750 HC=HSATC-(1.-QC)*LC
      GO TO 1990
C*** COLD SIDE VAPOR, HOT SIDE LIQUID
  770 CHTCL=HTCV
      CH=HTHL
      XCX=MC*GC/(MH*FH)
      NC=1./(MC*GC*(1./(AHTC*CHTCL)+1./(AHTH*CH)))
      IF(XCX.EQ.1.) GO TO 840
      XH=(XCX*(TH-TC)/(TH-XCX*TC-(1.-XCX)*SH))
      IF(XH) 821,821,822
  821 XH=1.1
```

```
      GO TO 850
  822 XH=ALOG(XH)/(NC*(1.-XCX))
      GO TO 850
  840 XH=(SH-TH)/(NC*(TH-TC))
  850 X=XH
      IF((X+X0)-1.) 870,870,860
  860 X=1.0-X0
      KEY=1
  870 IF(XCX.EQ.1.0) GO TO 910
      QTY= -NC*(1.0-XCX)*X
  880 DH=(TH-XCX*TC+XCX*(TC-TH)*EXP(-NC*(1.-XCX)*X))/(1.-XCX)
      DC=(TH-XCX*TC+(TC-TH)*EXP(-NC*(1.-XCX)*X))/(1.-XCX)
      GO TO 930
  910 DH=TH+NC*(TH-TC)*X
      DC=TC+NC*(TH-TC)*X
  930 HH=VHLIQ(LHOT,PINH,DH)
      IF(X.NE.XH)GO TO 940
      DH=SH
      HH=HLIQH
  940 TH=DH
      V=VSV(LCOLD,PINC,DC)
      HC=VH(LCOLD,PINC,DC,V)
      QH=1.0-(HSATH-HH) / LH
      TC=DC
      GO TO 1990
  970 CH=HTH2
      CHTCL=HTCL
      XCX=MC*FC*(SH-TC)/(MH*LH)
      NC=1./(MC*FC*(1./(AHTC*CHTCL)+1./(AHTH*CH)))
      XH=(XCX/(XCX-1.+QH))
      IF(XH)1020,1020,1030
 1020 XH=1.1
      GO TO 1040
 1030 XH=ALOG(XH)/NC
 1040 XC=(TC-TH)/(SC-TH)
      IF(XC) 1041,1041,1042
 1041 XC=1.1
      GO TO 1050
 1042 XC=ALOG(XC)/NC
 1050 X=XC
      IF(XC.GT.XH) X=XH
      IF((X+X0)-1.) 1070,1070,1060
 1060 X=1.0-X0
      KEY=1
      QTY= -NC*X
 1070 QH=QH+XCX*(1.0-EXP(-NC*X))
      HH=HSATH - (1.0-QH)*LH
      IF(X.EQ.XH)HH=HSATH
      DC=TH+(TC-TH)*EXP(-NC*X)
      HC=VHLIQ(LCOLD,PINC,DC)
      IF(X.NE.XC)GO TO 1090
      DC=SC
      HC=HLIQC
 1090 TH=SH
```

```
      TC=DC
      QC=1.0-(HSATC-HC) / LC
      GO TO 1990
C*** BOTH SIDES TWO PHASE
 1150 CH=HTH2
      CHTCL=HTC2
      XCX=MC*LC/(MH*LH)
      NC=(SH-SC)/(MC*LC*(1./(AHTC*CHTCL)+1./(AHTH*CH)))
       XC=(1.-QC)/NC
      XH=(1.-QH)/(XCX*NC)
      X=XC
      IF(XC.GT.XH)X=XH
      IF((X+X0).LE.1.0) GO TO 1230
      X=1.-X0
      KEY=1
 1230 QC=QC+NC*X
      QH=QH+NC*XCX*X
      HC=HSATC-(1.0-QC)*LC
      HH=HSATH-(1.0-QH)*LH
      IF(X.EQ.XH)HH=HSATH
      IF(X.EQ.XC)HC=HSATC
      TC=SC
      TH=SH
      GO TO 1990
C*** HOT SIDE IS TWO PHASE; COLD SIDE IS A VAPOR
 1300 CH=HTH2
      CHTCL=HTCV
      XCX=MC*GC/(MH*LH/(TH-TC))
      NC=1./(MC*GC*(1./(AHTC*CHTCL)+1./(AHTH*CH)))
      XH=(XCX/(XCX-1.+QH))
      IF(XH) 1350,1350,1360
 1350 XH=1.1
      GO TO 1370
 1360 XH=ALOG(XH)/NC
 1370 X=XH
      IF((X+X0)-1.) 1390,1390,1380
 1380 X=1.-X0
      KEY=1
      QTY=-NC*X
      IF(NC*X.GT.14./0.4343) GO TO 2070
 1390 QH=QH+XCX*(1.-EXP(-NC*X))
      DC=TH+(TC-TH)*EXP(-NC*X)
      HH=HSATH-(1.0-QH)*LH
      IF(X.EQ.XH)HH=HSATH
      V=VSV(LCOLD,PINC,DC)
      HC=VH(LCOLD,PINC,DC,V)
      TC=DC
      TH=SH
      GO TO 1990
C*** HOT SIDE VAPOR, COLD SIDE LIQUID
 1460 CH=HTHV
      CHTCL=HTCL
      XCX=MC*FC/(MH*GH)
      HH=HSATH-(1.0-QH)*LH
```

```
      NC=1./(MC*FC*(1./(AHTC*CHTCL)+1./(AHTH*CH)))
      IF(XCX.EQ.1.0) GO TO 1530
      XC=((TH-TC)/(TH-XCX*TC-(1.-XCX)*SC))
      IF(XC) 1511,1511,1512
 1511 XC=1.1
      GO TO 1540
 1512 XC=ALOG(XC)/(NC*(1.-XCX))
      GO TO 1540
 1530 XC=(SC-TC)/(NC*(TH-TC))
 1540 X=XC
      IF((X+X0)-1.) 1560,1560,1550
 1550 X=1.0-X0
      KEY=1
 1560 IF(XCX.EQ.1.0) GO TO 1600
      DC=(TH-XCX*TC+(TC-TH)*EXP(-NC*(1.-XCX)*X))/(1.-XCX)
      DH=(TH-XCX*TC+XCX*(TC-TH)*EXP(-NC*(1.-XCX)*X))/
     * (1.-XCX)
      GO TO 1620
 1600 DC=TC+(TH-TC)*NC*X
      DH=TH+(TH-TC)*NC*X
 1620 V=VSV(LHOT,PINH,DH)
      HH=VH(LHOT,PINH,DH,V)
      HC=VHLIQ(LCOLD,PINC,DC)
      IF(X.NE.XC)GO TO 1630
      DC=SC
      HC=HSATC
 1630 TH=DH
      QC=1.0-(HSATC-HC) / LC
      TC=DC
      GO TO 1990
C*** HOT SIDE VAPOR, COLD SIDE TWO PHASE
 1680 CH=HTHV
      CHTCL=HTC2
      XCX=MC*LC/(MH*GH*(TH-SC))
      NC=1./(MH*GH*XCX*(1./(AHTC*CHTCL)+1./(AHTH*CH)))
      XC=(1.+XCX*(1.-QC))
      IF(XC) 1730,1730,1740
 1730 XC=1.1
      GO TO 1750
 1740 XC=ALOG(XC)/(XCX*NC)
 1750 X=XC
      IF((X+X0)-1.0) 1770,1770,1760
 1760 X=1.0-X0
      KEY=1
      QTY=XCX*NC*X
 1770 DH=TC+(TH-TC)*EXP(XCX*NC*X)
      QC=QC-(1.0-EXP(XCX*NC*X))/XCX
      V=VSV(LHOT,PINH,DH)
      HH=VH(LHOT,PINH,DH,V)
      TH=DH
      HC=HSATC-(1.-QC)*LC
      IF(X.NE.XC)GO TO 1990
      TC=SC
      HC=HSATC
```

```
      GO TO 1990
C*** BOTH SIDES VAPOR
 1840 CH=HTHV
      CHTCL=HTCV
      XCX=MC*GC/(MH*GH)
      NC=1./(MC*GC*(1./(AHTC*CHTCL)+1./(AHTH*CH)))
      X=1.-X0
      IF(XCX.EQ.1.0) GO TO 1930
      QTY=-NC*(1.0-XCX)*X
      IF (NC*(1.-XCX)*X.GT.14./0.4343) GO TO 2070
      DH=(TH-XCX*TC+XCX*(TC-TH)*EXP(-NC*(1.-XCX)*X))/(1.-XCX)
      DC=(TH-XCX*TC+(TC-TH)*EXP(-NC*(1.-XCX)*X))/(1.-XCX)
      GO TO 1950
 1930 DH=TH+NC*(TH-TC)*X
      DC=TC+NC*(TH-TC)*X
 1950 V=VSV(LHOT,PINH,DH)
      HH=VH(LHOT,PINH,DH,V)
      V=VSV(LCOLD,PINC,DC)
      HC=VH(LCOLD,PINC,DC,V)
      TH=DH
      TC=DC
      KEY=1
 1990 X0=X0+X
C*** TAKE UP TO 100 ITERATIONS TO DETERMINE THE HO
                              T-SIDE OUTLET ENTHALPY
      ITRTTN=ITRTTN+1
      IF(ITRTTN.GT.100)GO TO 2055
C*** IF THE FULL LENGTH OF THE HXR HAS BEEN ANALYZED,
C    PROCEED TO THE ENTHALPY CHECK; OTHERWISE GO TO 280
      IF(KEY) 280,280,2025
C*** SOLUTION HAS CONVERGED IF HOT-SIDE INLET ENTHLAPY IS NO
C    MORE IN ERROR THAN 0.01% OF THE MAXIMUM POSSIBLE CHANGE
 2025 IF(ABS(HH-HN).LT.(.0001*HTEST)) GO TO 2060
      IF(HH-HN) 2040,2040,2050
C*** CONTINUE WITH THE BINARY SEARCH FOR THE CORRECT HOT
C    OUTLET ENHTALPY.  REPLACE EITHER THE HIGH OR LOW LIMIT
 2040 HLOW=HOUTH
      GO TO 200
 2050 HIGH=HOUTH
      GO TO 200
 2055 CONTINUE
C*** THE FOLLOWING COMMENT CARDS CAN BE CHANGED FO
                              R DIAGNOSTIC OUTPUT
C     PRINT 2056,HH,HN
 2056 FORMAT(" ITERATION LIMIT IN INTERCOOLER HH/HN = ",2F10.2)
      GO TO 2072
 2060 CONTINUE
C     PRINT 2061
 2061 FORMAT(" THE INTERCOOLER HEAT TRANSFER ANALYSED COMPLETELY"
     * )
C     PRINT 2062
 2062 FORMAT("          TIN       HIN      TOUT      HOUT")
C     PRINT 2063,D(IT+NSIC),CN,TC,HC
 2063 FORMAT(" COLD",4F10.3)
```

```
C      PRINT 2064,TTH,HN,T0,HOUTH
 2064 FORMAT("   HOT",4F10.3)
      DO 2100 I=1,8
 2100 DP(I)=0.0
C*** BEGIN THE COMPUTATION OF THE PRESSURE DROP BY
C     COMPUTING THE SPECIFIC VOLUMES
      MC=MC/3600.
      MH=MH/3600.
      VGC=VSATC
      VFC=1./VDL(LCOLD,SC)
      VRC=VGC/VFC
      VGH=VSATH
      VFH=1./VDL(LHOT,SH)
      VRH=VGH/VFH
C*** ADJUST QUALITIES IF BEYOND THE SATURATION REGION
      IF(ABS(QH-1.0).LT..0001)QH=1.0
      IF(ABS(QC-1.0).LT..0001)QC=1.0
      IF(QC.LT.0.0)QC=0.0
      IF(QC.GT.1.)QC=1.0
      IF(QH.LT.0.)QH=0.0
      IF(QH.GT.1.)QH=1.0
      CFMC=D(IW+NLC)*VGC
      CFMH=D(IW+NLH)*VGH
C*** ENTER THE CFM RATES FOR A PRESSURE-DROP TABLE LOOK UP
      D(IGA+101)=CFMC
      D(IGA+102)=CFMH
      PCOLD=TLUP(ID(IRCD+10))*VGC
      PHOT=TLUP(ID(IRCD+11))*VGH
C*** COMPUTE THE SLIP RATIO
      SL=(VRC-1.)**.25
      PB=-0.25*ALOG10(VRC)
      IF(PB.LT.-1.)PB=-1.
C*** BRANCH ACCORDING TO THE QUALITY
      IF(CQ.EQ.0.0)GO TO 2290
      DP(1)=CQ*FNQ(CQ,PB)
      IF(CQ.EQ.1.0)GO TO 2282
      VE=FNV(CQ,VRC)
      DP(3)=FNM(CQ,VRC)
      GO TO 2290
 2282 DP(3)=VRC
 2290 IF(QC)2330,2330,2295
 2295 DP(2)=QC*FNQ(QC,PB)
      IF(QC.EQ.1.)GO TO 2298
      VE=FNV(QC,VRC)
      DP(4)=FNM(QC,VRC)
      GO TO 2310
 2298 DP(4)=VRC
 2310 IF((QC-CQ).LT.0.01)GO TO 2315
C*** COMPUTE THE AVERAGE PHI BAR (DP(1)) FOR IN AND OUT QUALITIES
      DP(1)=(DP(2)-DP(1))/(QC-CQ)
      GO TO 2330
 2315 DP(1)=FNP(QC,PB)
C*** COMPUTE THE PRESSURE DROP FROM THE FAC CORRELATION
 2330 DP(1)=PCOLD*((1./VRC)**2+(1.-(1./VRC)**2)*DP(1))
```

p77 says ratio of ΔP's = ratio of specific vols

PB = specific vol. ratio is being fed to FNQ

~~IS THIS DEF OK?~~

should be delta P ratio as in VLNEPP routine see p 77

ALSO P.99 shows +.25 * ALOG(DPF/DPG) not -.25 ALOG10(VRC) as here

code for VLNEPP is +.25×.4343 ALOG(DPF/DPG) (p65 missing)

QC= 1. - (HSATC - HC)/LC

LC=VHFG(~,~)

MISTAKE
changed
to (2*GVTY)

```
C*** ADD THE MOMENTUM DROP
      DP(1)=DP(1)+(DP(4)-DP(3))*(MC/AC)**2*VFC/GVTY/144.
C*** REPEAT THE SAME SEQUENCE OF COMPUTATIONS FOR THE HOT SIDE
      SL=(VRH-1.)**.25
      PB=-0.25*ALOG10(VRH)
      IF(PB.LT.-1.)PB=-1.
      IF(HQ.NE.0)GO TO 2370
      DP(2)=0.0
      DP(4)=0.0
      GO TO 2420
 2370 DP(2)=HQ*FNQ(HQ,PB)
      IF(HQ.NE.1.)GO TO 2371
      DP(4)=VRH
      GO TO 2380
 2371 VE=FNV(HQ,VRH)
      DP(4)=FNM(HQ,VRH)
 2380 IF(QH.NE.0.0)GO TO 2390
      DP(3)=0.0
      DP(5)=0.0
      GO TO 2400
 2390 DP(3)=QH*FNQ(QH,PB)
      IF(QH.NE.1.0)GO TO 2395
 2392 DP(5)=VRH
      GO TO 2400
 2395 VE=FNV(QH,VRH)
      DP(5)=FNM(QH,VRH)
 2400 IF((HQ-QH).GE..01)GO TO 2405
      DP(2)=FNP(HQ,PB)
      GO TO 2420
 2405 DP(2)=(DP(3)-DP(2))/(QH-HQ)
 2420 DP(2)=PHOT*((1./VRH)**2+(1.-(1./VRH)**2)*DP(2))
C*** COMPUTE THE HOT-SIDE PRESSURE DROP
      DP(2)=DP(2)+(DP(5)-DP(4))*(MH/AH)**2*VFH/GVTY/144.
C*** THE FOLLOWING EXTRA PRINTOUT IS FOR DIAGNOSTIC PURPOSES
C     WRITE(OUT,2500)DP(1)
 2500 FORMAT(" COLD SIDE PRESSURE DROP(PSI) = ",E12.5)
C     WRITE(OUT,2600)DP(2)
 2600 FORMAT("  HOT SIDE PRESSURE DROP(PSI) = ",E12.5)
      D(IP+NSOH)=PINH-DP(2)
      IF(D(IP+NSOH).GT.0.0)GO TO 2610
C     WRITE(OUT,7655)D(IP+NSOH),D(IP+NSIH)
 7655 FORMAT(" *** OUTLET PRESSURE IN NRCLR HOT SIDE WAS ",E14.7,
     * "  RESET PRESSURE TO INLET VALUE ",E14.7)
      D(IP+NSOH)=D(IP+NSIH)
 2610 D(IP+NSOC)=PINC-DP(1)
      IF(D(IP+NSOC).GT.0.0)GO TO 2620
C     WRITE(OUT,7654)D(IP+NSOC),D(IP+NSIC)
 7654 FORMAT(" *** OUTLET PRESSURE IN NRCLR COLD S
                                IDE WAS ",E14.7,
     * "  RESET PRESSURE TO INLET VALUE ",E14.7)
      D(IP+NSOC)=D(IP+NSIC)
 2620 D(IT+NSOH)=T0
      D(IT+NSOC)=TC
      D(IH+NSOH)=HOUTH
```

```
      D(IH+NSOC)=HC
      RETURN
 2070 DPRC=.4343*NC*(1.-XCX)
C     PRINT 2071,DPRC
 2071 FORMAT(" INTERCOOLER TOO LARGE FOR FLOW RATE, PRECISION= ",
     * F10.3)
C*** IF THE NTU'S ARE TOO HIGH, ASSUME EFFECTIVENSS = 1.0
 2072 D(IP+NSOH)=D(IP+NSIH)
      D(IP+NSOC)=D(IP+NSIC)
      TOUTH=D(IT+NSIC)
      TOUTC=D(IT+NSIH)
      IF(TOUTH-SH)2710,2720,2720
 2710 HOUTH=VHLIQ(LHOT,D(IP+NSOH),TOUTH)
      GO TO 2730
 2720 VHOT=VSV(LHOT,D(IP+NSOH),TOUTH)
      HOUTH=VH(LHOT,D(IP+NSOH),TOUTH,VHOT)
 2730 IF(TOUTC-SC)2740,2750,2750
 2740 HOUTC=VHLIQ(LCOLD,D(IP+NSOC),TOUTC)
      GO TO 2760
 2750 VCOLD=VSV(LCOLD,D(IP+NSOC),TOUTC)
      HOUTC=VH(LCOLD,D(IP+NSOC),TOUTC,VCOLD)
C*** BASE EFFECTIVENESS ON THE SIDE WITH THE LOWER EFFECTIVE
C    CAPACITANCE RATE
 2760 QHOT=D(IW+NLH)*(D(IH+NSIH)-HOUTH)
      QCOLD=D(IW+NLC)*(HOUTC-D(IH+NSIC))
      IF(QCOLD-QHOT)2770,2770,2810
 2770 D(IT+NSOC)=TOUTC
      D(IH+NSOC)=HOUTC
      D(IH+NSOH)=D(IH+NSIH)-QCOLD/D(IW+NLH)
      QHOT=VQUALH(LHOT,D(IP+NSOH),D(IH+NSOH))
      IF(QHOT)2780,2785,2785
 2780 D(IT+NSOH)=VTLIQ(LHOT,D(IP+NSOH),D(IH+NSOH))
      GO TO 2800
 2785 IF (QHOT.GT.1.0)GO TO 2790
      D(IT+NSOH)=SH
      GO TO 2800
 2790 CALL VTAV2(LHOT,D(IT+NSOH),V,D(IP+NSOH),D(IH+NSOH))
 2800 RETURN
 2810 D(IT+NSOH)=TOUTH
      D(IH+NSOH)=HOUTH
      D(IH+NSOC)=D(IH+NSIC)+QHOT/D(IW+NLC)
      QCOLD=VQUALH(LCOLD,D(IP+NSOC),D(IH+NSOC))
      IF (QCOLD)2820,2825,2825
 2820 D(IT+NSOC)=VTLIQ(LCOLD,D(IP+NSOC),D(IH+NSOC))
      GO TO 2800
 2825 IF(QCOLD.GT.1.0) GO TO 2830
      D(IT+NSOC)=SC
      GO TO 2800
 2830 CALL VTAV2(LCOLD,D(IT+NSOC),V,D(IP+NSOC),D(IH+NSOC))
      IF(IFP.NE.1 .OR. ICPP.NE.0) GOTO 99
      CALL PIOP(1,NLC,NSIC,NSOC)
      CALL PIOP(2,NLH,NSIH,NSOH)
      CALL LINES (2)
      Q1=D(IW+NLH)*(D(IH+NSIH)-D(IH+NSOH))
```

T hot out for hot inlet qual 0-1
"SH" comes from p 65 (missing)

SH=VTS(LHOT, D(IP+NSIH))

LHOT=LCOLD on p 65 !!

5/B

LHOT= ID(IFB+NLC)
LHOT = ID(LHOT +3)

```
      Q2=D(IW+NLC)*(D(IH+NSIC)-D(IH+NSOC))
      Q=AMIN1(Q1,Q2)
      WRITE(OUT,1718) Q
 1718 FORMAT(5X,"INTERCOOLER HEAT TRANSFER = ",E17.7," BTU/MIN")
   99 CONTINUE
 2090 RETURN
      END
```

is reduced, by replacing either the high or low values with the previous assumption. The high value is replaced if the computed hot-inlet enthalpy is above the input value; the low value is replaced otherwise.

By starting with the assumed hot-outlet enthalpy, we can compute explicitly the position of the transitions between single- and two-phase flow. Therefore, no iterations are required on these positions. Also, no arbitrary divisions of the heat exchanger are required, as might be used if the heat exchanger were divided, for example, into ten zones and a finite-difference procedure were to be used. The hot-outlet enthalpy becomes the iteration variable. In all of the test cases, except for one, the iteration converged within 15 steps. The computation time is minimal. The one exception occurred when a large heat exchanger was used (a high NTU value) in which the solution was highly sensitive to the assumed enthalpy. The exponential function used to evaluate the heat-exchanger effectiveness did not carry the precision required to locate the boundary between single- and two-phase flow. A note is included in the program to warn the user if a similar problem is encountered. In practice, few heat exchangers would be so oversized.

9.5 Program Listing

Exhibit 9.4-1, which presents the program computational procedure, also is the program listing as used in AECS. However, the AECS program does not include the comment cards.

9.6 Sample Cases

The sample case, as depicted in Exhibit 9.6-1, is based on having the intercooler alone as the total system. The input data are shown in the required format for AECS input. The corresponding system output data are shown on the system schematic (Exhibit 9.6-1) as well as in the output format (Exhibit 9.6-2), starting with Page 7 of the output, the beginning of the computed data. Previous output pages contain the headers and a repeat of the input data.

9.7 Technical Background

The pressure drop (DPGO) is entered as a table as if the fluid were 100% vapor. The computed pressure drop is based on the correlations for single- and two-phase flow as given in Section 10 of this report (on QBOILR), with the liquid-only pressure drop (DPLO) being given by the formula:

DPLO = DPGO * (Density of the vapor / Density of the liquid)

seems awfully crude

The heat-transfer coefficients are entered into the subroutine from the parameter list for the component. The temperature and enthalpy profiles are computed from these heat-transfer coefficients and the usual heat-exchanger relationships. However, unlike the usual heat-exchanger relationships, the length of each heat exchanger section is unknown. Different relationships exist depending on whether one or both of the flows is two-phase.

If both sides are single-phase, the usual counter-flow relationship holds for the temperatures. For discussion purposes, we will assume that we are computing the heat-exchanger performance starting at x=0 and moving in the direction of the cold-side flow, opposite to the direction of the hot-side flow. We let C be the ratio of the capacitance rates (cold side to hot side) and Nc be the number of transfer units based on the cold-side flow and based on having single-phase flow for the full length of the heat exchanger. Then for a section that has a length equal to a fraction, x, of the full length, the ineffectiveness, IE, is given by

$$IE = \exp (- Nc * (1 - C) * x)$$

The cold-side temperature, TC, at x is given by

$$TC = (Touth - C * Tinc + (Tinc - Touth) * IE) / (1 - C)$$

where Touth is the hot-side temperature at x=0 and Tinc, the cold-side temperature at x=0. The hot-side temperature, TH, at x is given by

$$TH = (Touth - C * Tinc + C * (Tinc - Touth) * IE) / (1 - C)$$

These equations can be solved algebraically for the value of x that gives any selected value of TC or TH. For example, if both sides have vapor flow, to find the value of x at the start of the two-phase region on the cold side, we would set TC equal to the saturation temperature (TSAT) on the cold side. We would solve the foregoing equation with TC = TSAT to determine IE. The equation for IE would then yield the value of x at which TC = TSAT.

If C=1, the equations for TC and TH are indeterminant. Instead, they are given by

$$TC = Tinc + Nc * (Touth - Tinc) * x$$

and

$$TH = Touth + Nc * (Touth - Tinc) * x$$

Again, for TC = TSAT, the second of these could be solved for x.

If one side of the heat exchanger is single phase and the other side is two phase, the temperature on the two-phase side will be known (equal to the saturation temperature) but the quality profile will be unknown. For simplicity, we again assume in our discussion that we

NRCLR

are starting at x=0 and proceeding to solve for the state at some other x in the direction of the cold-side flow. Also for simplicity, we will assume that the hot-side flow is two phase. The same equations would apply for the cold side being two phase, except for a rotation of indices. For the hot side being two phase, we have

$$TH = TSAT \text{ for all } x$$

and

$$TC = TH + (Tinc - TH) * IE$$

where, in this case,

$$IE = \exp (- Nc * x)$$

and Nc, the number of transfer units, is based on the cold side having the minimum capacitance rate. The quality on the hot side, XH, at any x is given by

$$XH = Xouth + C * (1 - \exp(Nc * x))$$

where

$$C = Mc * Cc * (TH - Tinc) / (Mh * hfg)$$

In the equation for C, Mc is the mass flow rate on the cold side; Cc, the specific heat of the fluid on the cold side; Mh, the mass flow rate on the hot side; and hfg, the heat of vaporization on the hot side. The other symbols are defined above.

These equations can be readily solved for x if one of the temperatures at x is known. For example, to find the value of x at which the hot-side flow is a vapor (i.e., XH = 1), we set XH = 1 and solve directly for x. The corresponding temperature on the cold side is obtained by inserting this value of x in the equation for TC.

If the cold side is two-phase and the hot side, single phase, the foregoing equations become

$$TC = TSAT \text{ (based on the saturation temperature on the cold side)}$$
$$TH = TC + (Touth - TC) * \exp (C * Nc * x)$$
$$C = Mc * hfg / (Mh * Ch * (Touth - TC)$$
$$Nc = UA * (Touth - TC) / (Mc * Cc)$$
$$XC = Xoutc - (1 - \exp (C * Nc * x)) / C$$

where hfg is now evaluated on the cold side and Ch is the specific heat of the hot-side fluid. We consistently define Nc based on the cold-side flow rate.

NRCLR

If both sides are two-phase, the temperatures equal the saturation temperatures. If we again assume we are solving for the conditions at x when we know the conditions at x=0, we have the following expressions for the qualities:

```
XC = Nc * x
XH = C * Nc * x
Nc = Mc * hfgc / ( Mh * hfgh )
```

where hfgc is the heat of vaporization on the cold side and hfgh, on the hot side.

The foregoing equations describe all possible heat-transfer processes. The program logic selects among the cases depending on the enthalpies of the two fluids.

The pressure-drop computations are performed using the theory presented in the discussion of QBOILR. As done in QBOILR, the lengths of the liquid-only, two-phase and vapor-only sections are computed as part of the heat-transfer analysis. These lengths are then used in the pressure-drop computations. The pressure drop with only vapor flowing is entered as a table; the simulation computes the pressure drop with only liquid flowing as equal to the vapor-only pressure drop multiplied by the ratio of the vapor density to the liquid density. The two-phase pressure drop is based on the FAC, Inc., modification of Baroczy's correlation (see QBOILR).

Exhibit 9.6-1: Input Cards and Flow Diagram for the Sample Case

```
PERFORM
TITLE    EXAMPLE CASE FOR INTERCOOLER
CASEA     NRCLR    0000    2    4    0
CASEB         0    0    0    0    0
CASEC         0.0            0.0         0.0
CASED         0.0
                       W          P              T              H          AFH
PARAM      28
VALUES     1     0.8662   272.1834       577.00        44.82     0.00010
VALUES     6     0.1     163.3089 P     541.79 T      44.82 H  0.00004   AFC
VALUES     11    0.1400 W 160.9219      550.79        112.141   0.0
VALUES     16    0.8662   265.2571       544.00        34.42     90.0 HTCL
VALUES     21   300.0 HTC2L  30.0 HTCV        1.0 AHT H,C    0.0      0.0
VALUES     26     2.0        90.0           3.0
INLET       10    1    50000    1    2    3    4    3  -22    HTCL  HTC 2-phase  HTC-vapor
INLET       20    2    61000   11    7    8    9    3  -22
NRCLR       30    2    6    7    1    5    8   10    5    4   20   21   22   23   23
OUTLT       40    2    70010   11   12   13   14 AFC   AFH  ΔP TAB      AHTC  AHTH
OUTLT       50    1    80000   16   17   18   19
TABID        4   61     2    0    0 1010101    2
TABT        PRESS-DROP, COLD SIDE:  TYPE=61  REL.NO=4
TABV         0.0           0.0            1.0          10.0
TABID        4   62     2    0    0 1020101    2
TABT        PRESS-DROP, HOT SIDE:  TYPE=62  REL.NO.=4
TABV         0.0           0.0            1.0          10.0
PTAB         1    0    1    0
ENDCASE
ENDJOB
```

vary W_h to get $T_7 = 550.79$

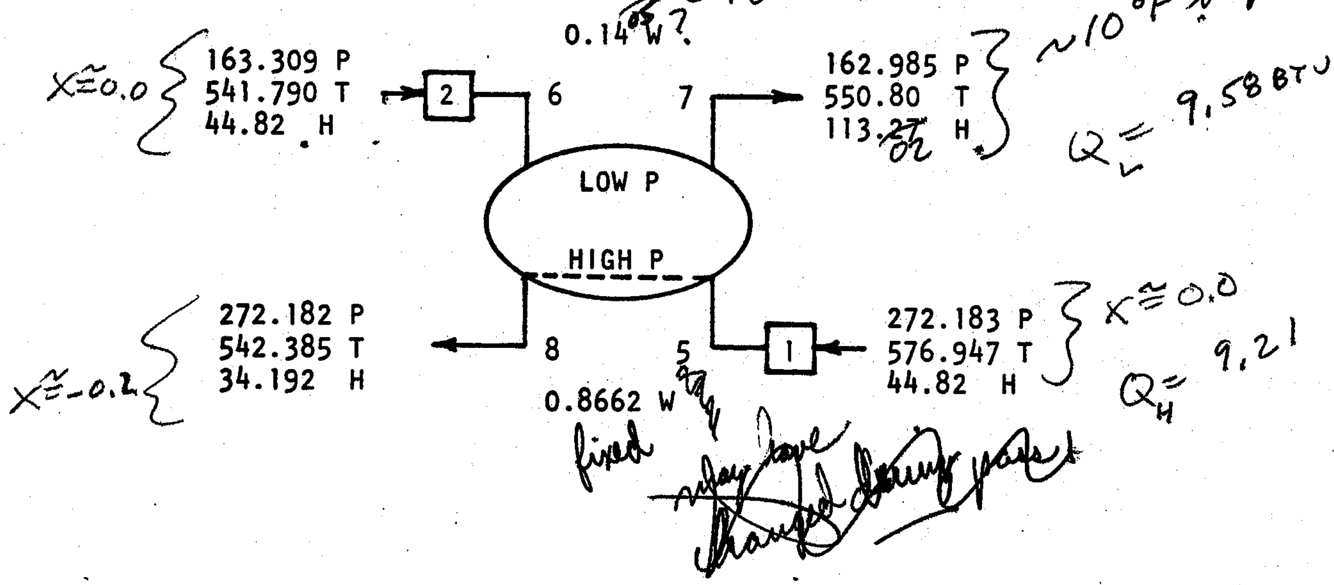


Exhibit 9.6-2: AECS Output for the Sample Case

```
*AECS*  EXAMPLE CASE FOR INTERCOOLER                                   PAGE       7
   1    CASE NRCLR                                                     DATE 09/...

TIME P      102.00

SVT
(    1)    1

EVT
(    1)    3

PASS       1

S.V.
(    1) 1.40000E-01

E.V.
(    1) 1.22132E+00

W
(    1) 8.66200E-01 (    2) 1.40000E-01

P
(    5) 2.72183E+02 (    6) 1.63309E+02 (    7) 1.62985E+02 (    8) 2.72182E+02

T
(    5) 5.76947E+02 (    6) 5.41790E+02 (    7) 5.52011E+02 (    8) 5.42385E+02

H
(    5) 4.48200E+01 (    6) 4.48200E+01 (    7) 1.13266E+02 (    8) 3.41943E+01
*AECS*  EXAMPLE CASE FOR INTERCOOLER                                   PAGE       8
   1    CASE NRCLR                                                     DATE 09/06/81

TIME E      103.89

FLOW RATE(S)-LB/MIN

(    1)      .87 (    2)      .14

PRESSURE(S)-PSI

(    5)   272.18 (    6)   163.31 (    7)   162.98 (    8)   272.18

TEMPERATURE(S)-DEG R

(    5)   576.95 (    6)   541.79 (    7)   550.80 (    8)   542.38

HUMIDITY(S)/ENTHALPY(S)-LBW/LBA / BTU/LB

(    5) 44.8200 (    6) 44.8200 (    7)113.0200 (    8) 34.1923

STATE VARIABLE TYPE(S)
(    1)    1

STATE VARIABLE(S)
(    1) 1.40545E-01

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

```
ERROR      BLE(S)
(   1)     9774E-03

SOLUTION CONVERGED IN       6 TRY(S)

     0 ERROR(S) DETECTED

CASE END
```

10. Subroutine QBOILR (Refrigerant Boiler with Given Heat Rate)

10.1. Subroutine Description

The QBOILR subroutine simulates a heat exchanger with refrigerant evaporating on one side and a known uniform heat input on the other side. The source of heat could be an electronic component or the flame of a burning fuel. However, if a fired boiler is being simulated, a re-appraisal of the heat-transfer correlations would be advisable.

RINLET 103

10.2. Prior Simulation Method

ROUTLET 106

QBOILR is a new routine; however, it is similar to the BOILER routine. The 1972 BOILER routine was based on heat transfer from a single-phase fluid to an evaporating refrigerant. The 1976 replacement for BOILER modified the model so that dehumidification could be inlcuded in the source (non-refrigerant) side. However, neither BOILER routine could simulate the cold plate or an electronic component. Therefore, the QBOILR routine was added. The previous BOILER models required the specification of the heat-transfer coefficient and pressure drop; they did not contain the computations for these values internally.

10.3. New Simulation Method

The boiler in QBOILR can be envisioned as a cold plate for an electronic component, with the cold plate consisting of two face plates enclosing a compact heat-exchanger surface. The refrigerant flows through the core, absorbing heat and evaporating. The heat input is assumed to be uniformly distributed over the cold plate.

no superheated vapor @ inlet

The refrigerant can enter the cold plate subcooled, saturated, in two phases, or as a vapor. The outlet states can be subcooled, saturated liquid, two-phase, saturated vapor, or superheated vapor. The corresponding heat-transfer coefficients and pressure drops are computed by correlation equations internal to the subroutine.

The subroutine computes the temperature and pressure of the fluid leaving the boiler and the plate temperature at the outlet (usually, the end of the superheat region). The temperature of the components mounted on the surface of the cold plate must be computed separately based on their individual heat dissipations and conductances to the cold plate.

The temperature of the cold-plate surface at the outlet can be used as a control point (generating an error variable). This temperature will become a set point; it will not be an upper limit to the surface temperature. The difference between this set point and the surface temperature computed by AECS is an error variable, which will become zero when AECS converges.

10.4. Computational Procedure

The computational procedure is presented in the form of a heavily annotated FORTRAN program listing in Exhibit 10.4-1.

The pressure-drop computation for the two-phase flow is based on the FAC, Inc., correlation of Baroczy's method, as described in Section 10.7 below and derived under this contract. The pressure-drop computation includes the momentum change between the inlet and outlet. Slip velocities and void fractions are based on correlations against the liquid-to-vapor density ratio only.

The computations are divided into five flow regions: liquid-only, subcooled boiling, saturated boiling, vaporization, and vapor-only. Branching in the computations depends on whether the next flow region occurs. Although the maximum cold-plate temperature invariably occurs at the outlet, the five regions are needed to permit computation of the pressure drop.

10.5. Program Listing

Exhibit 10.4-1, which presents the program computational procedure also is the program listing as used in AECS. However, the AECS program does not include the comment cards.

10.6. Sample Case

The sample case, as depicted in Exhibit 10.6-1, is based on having the QBOILR alone as the total system. The input data are shown in the required format for AECS input. The corresponding system output data are shown in the system schematic (Exhibit 10.6-1) as well as in the output format (Exhibit 10.6-2), starting with Page 7 of the output, the beginning of the computed data. Previous pages contain the headers and a repeat of the input data.

10.7. Technical Background

General correlations for flow boiling are not currently available. The text by L.S.Tong: Boiling Heat Transfer and Two-Phase Flow, gives some idea of the complexities involved. For example, the correlation for the critical heat flux (burnout) for water involves 24 dimensional terms. Because the terms are dimensional, they cannot be generalized to other fluids. The complexity of the boiling process itself, which involves the interaction between a fluid and randomly located, randomly activated nucleation sites on a surface, is perhaps the primary impediment to the development of a general correlation.

see p 93

Exhibit 10.4-1: Performance-Program Logic and Listing

```
      SUBROUTINE QBLRPP
      COMMON /CC/ C(400)
      EQUIVALENCE (IRCD,C(45)),(IW,C(27)),(IP,C(28)),(IT,C(29))
     *,(IH,C(30)),(SCR(1),C(151)),(GC,C(370)),(JC,C(371))
     *,(ICPP,C(88)),(IFP,C(22)),(OUT,C(7)),(IGA,C(35))
     *,(PASS,C(17)),(IEVT,C(48)),(IEV,C(49)),(ITAD,C(54))
     *,(IFB,C(55)),(ISN,C(38))
      DIMENSION SCR(30)
      INTEGER OUT,PASS
      REAL L,MU,K,JC,ME,MI,MP
      EQUIVALENCE  (SCR(1),NL),(SCR(2),NSI),(SCR(3),NSO)
     *,(SCR(4),IOP),(SCR(5),FFT),(SCR(6),COT),(SCR(7),AF)
     *,(SCR(8),Q),(SCR(9),L),(SCR(10),AH),(SCR(11),DH)
      DIMENSION MU(2),CPY(2),V(2),PR(2),T(5),TW(5),HT(5),DP(2)
     *,K(2)
      COMMON /DC/ DZ(2),D(2)
      DIMENSION ID(2)
      EQUIVALENCE (ID(1),D(1))
     *,(D(51),T(1)),(D(56),TW(1)),(D(61),HT(1))
     *,(D(71),HFG),(D(72),ST),(D(73),PT)
     *,(D(75),TIN),(D(76),W),(D(77),IRET),(D(78),CO)
     *,(D(79),FF),(D(81),VR),(D(82),DV)
     *,(D(83),SL),(D(84),HSAT),(D(86),TSAT)
     *,(D(87),X1),(D(88),X2),(D(89),TNB),(D(90),DD)
     *,(D(91),FD),(D(92),B),(D(93),EM),(D(94),RS)
C    1 COMP CODE
C    2 LEG NO
C    3 INLET STATION NO
C    4 OUTLET STATION NO
C    5 OPTION NO
C    6 FRICTION FACTOR TABLE
C    7 COLBURN FACTOR TABLE
C    8 HEAT EXCHANGER FLOW AREA
C    9 HEAT INPUT RATE IN (BTU/MIN)
C   10 HEAT EXCHANGER FLOW PATH LENGTH (FEET)
C   11 HT EXCHG/HT TRANSFER AREA INCLUDING FINS (SQUARE FEET)
C   12 HEAT EXCHANGER HYDRAULIC DIAMETER
C   13 ERROR VARIABLE OPTION
C*** ERROR-VARIABLE OPTION: 0 IF NO ERROR VARIABLE
                          ; 1 IF SUPERHEAT
C   14 ERROR VARIABLE INDEX
C   15 MAXIMUM BOILER WALL TEMPERATURE
C*** SET UP INTERNAL VARIABLES IN TERMS OF STORED ARRAY
      IRCD = IRCDB(15)
      NL=ID(IRCD+2)
      NSI=ID(IRCD+3)
      NSO=ID(IRCD+4)
      IOP=ID(IRCD+5)
      IF (ID(IRCD+13).EQ.0) GO TO 107
      TMAX=D(ID(IRCD+15))
      JEVI=ID(IRCD+14)
  107 CONTINUE
      LOCT=ID(IFB+NL)
      LOCT=ID(LOCT+3)
```

index notation of 14 (data input card)

```
      AF=D(ID(IRCD+8))
      Q=D(ID(IRCD+9))
      L=D(ID(IRCD+10))
      AH=D(ID(IRCD+11))
      DH=D(ID(IRCD+12))
C*** COMPUTE THE SATURATION PROPERTIES
      TSAT=VTS(LOCT,D(IP+NSI))
C*** COMPUTE TRANSPORT PROPERTIES BASED ON INLET CONDITIONS
      CPY(1)=VCPF(LOCT,D(IP+NSI),TSAT)
      CPY(2)=VCPV(LOCT,D(IP+NSI),TSAT)
      MU(1)=VVISCF(LOCT,D(IP+NSI),TSAT)
      MU(2)=VVISCV(LOCT,D(IP+NSI),TSAT)
      K(1)=VCONDF(LOCT,D(IP+NSI),TSAT)
      K(2)=VCONDV(LOCT,D(IP+NSI),TSAT)
      V(1)=1.0/VDL(LOCT,TSAT)
      V(2)=VSV(LOCT,D(IP+NSI),TSAT)
      HFG=VHFG(LOCT,D(IP+NSI),TSAT,V(2))
      ST=VST(LOCT,TSAT)
      PT=VDPDT(LOCT,D(IP+NSI))
      TIN=D(IT+NSI)
      W=D(IW+NL)
      DO 1 I = 1,2
    1 PR(I)=3600.*CPY(I)*MU(I)/K(I)
      IRET=-1
C*** COMPUTE THE REYNOLDS NUMBER AS THE INDEPENDENT VARIABLE
      G=W/AF/60.0
C*** BASED ON 100% LIQUID FLOW
      D(IGA+21)=G*DH/MU(1)
C*** USE TLUP FOR COLBURN FACTOR, THEN COMPUTE HEA
                                   T TRANSFER COEFF.
      CO=TLUP(ID(IRCD+7))
      HT(1)=CO*60.*G*CPY(1)/PR(1)**.67
C*** USE TLUP FOR FRICTION FACTOR
      FF=TLUP(ID(IRCD+6))
C*** COMPUTE VOLUME RATIO AND SLIP FOR LATER TWO-P
                                   HASE COMPUTATIONS
      VR=V(2)/V(1)
      DV=1.0-1.0/VR
      SL=SQRT(SQRT(VR-1.))
C*** COMPUTE PRESSURE DROP AS IF 100% LIQUID FLOW
      DP(1)=4.*FF*L*G*G*V(1)/(2.*DH*GC)
C*** REPEAT THE ABOVE COMPUTATIONS AS IF 100% VAPOR FLOW
      D(IGA+21)=G*DH/MU(2)
      CO=TLUP(ID(IRCD+7))
      HT(5)=CO*60.*G*CPY(2)/PR(2)**.67
      FF=TLUP(ID(IRCD+6))
      DP(2)=4.*FF*L*G*G*V(2)/(2.*DH*GC)
C*** DETERMINE WHICH FLUID-PHASE IS FLOWING AT THE INLET
      HSAT=VH(LOCT,D(IP+NSI),TSAT,V(2))-HFG
      TIN=D(IT+NSI)
      IF(D(IH+NSI)-HSAT)360,332,332
  332 IF(D(IH+NSI)-HSAT-HFG)333,1272,1272
C*** IN TWO-PHASE REGION
  333 XI=(D(IH+NSI)-HSAT)/HFG
```

uses "VSV"... assumes superheated vapor (actually $x=1.000$)

lbm/sec ft^2

BTU/MIN FT^2 °F

lbF/Ft^2

BTU/min ft^2 °F

$= 4f\frac{L}{D}\left(G^2 N/2g_c\right)$

$\dot m = \rho V A$

$G = \frac{\dot m}{a} = \rho V$

VSV@TSAT

$\frac{1}{2}\rho V^2 = \frac{1}{2}\rho\frac{\dot m^2}{\rho^2 A^2} = \frac{1}{2\rho}G^2 = \frac{G^2 N}{2}$

$h = k\frac{Nu}{D}$

$St = \frac{h}{\rho C_p U_\infty}$

$j = St\, Pr^{2/3} \Rightarrow h = \frac{j \rho C_p U_\infty}{PR^{2/3}}$

$h = \frac{j\, G\, C_p}{Pr^{2/3}}$

$60 \times \frac{lbm}{sec\, ft^2} \times \frac{BTU}{lbm\, °F} = \frac{BTU}{min\, ft^2\, °F}$

DP lbf/ft^2

$j = \frac{h\, Pr^{2/3}}{G\, C_p}$

Does PT need to be x144? to be lbf/ft² °F

$\frac{BTU/MIN}{FT^2 \times BTU/MIN\,°F} = °F$

eqn from p95

wow! units ok!

```
      TIN=TSAT
      GO TO 370
C*** IN LIQUID-ONLY REGION
  360 XI=0.0
  370 IF(D(IH+NSI)-HSAT)380,371,371
C*** IN TWO-PHASE REGION
  371 X1=0.0
      X2=0.0
      GO TO 750
C*** IN LIQUID-ONLY REGION
C*** COMPUTE FLUID TEMPERATURE (T) AND WALL TEMPER
                              ATURE (TW) AT OUTLET
  380 T(5)=TIN+Q/(W*CPY(1))
      TW(5)=T(5)+Q/(AH*HT(1))
C*** DETERMINE TEMPERATURE AT WHICH NUCLEATE BOILI
                              NG BEGINS (TNB)
C    AND DETERMINE IF FLUID REACHES THIS TEMPERATU
                              RE BEFORE OUTLET
      TNB=TSAT+SQRT(8.*60.*ST*Q/(K(1)*AH*PT))
      X1=(TNB-TIN)*W*CPY(1)*L/Q-W*CPY(1)*L/(HT(1)*AH)
      IF(X1)430,450,450
C*** SUBCOOLED BOILING BEGINS IMMEDIATELY AT THE INLET
  430 X1=0
      GO TO 485
  450 IF(TW(5)-TNB)460,480,480
C*** THERE IS NO BOILING WITHIN THE BOILER
  460 X1=L
      GO TO 1310
C*** COMPUTE THE TEMPERATURES AT THE END OF THE NO
                              N-BOILING REGION
  480 T(1)=TIN+Q*X1/(L*W*CPY(1))
      TW(1)=T(1)+Q/(HT(1)*AH)
C*** COMPUTE THE LENGTH OF THE SUBCOOLED-BOILING REGION
  485 X2=(TSAT-TIN)*W*CPY(1)*L/Q-X1
      IF(X2.GE.(L-X1))X2=L-X1
C*** COMPUTE THE BUBBLE DEPARTURE DIAMETER (DD) IN FEET
  490 DD=4.65E-4*SQRT(GC/GC*ST*V(1)/DV)*(VR*CPY(1)*TSAT/HFG)
     ***1.25
C*** COMPUTE THE FREQUENCY OF DEPARTURE OF THE BUBBLES, 1/SEC.
      FD=.6*SQRT(SQRT(ST*GC*GC*V(1)*DV))/DD
C*** ASSUME THE SURFACE FACTORS: B (SURFACE COEFFI
                              CIENT); EM (EXPONENT
C    RELATING THE NUMBER OF NUCLEATION SITES GO THE TEMPERATURE
C    DIFFERENCE); AND RS (RADIUS, FT., OF SMALLEST
                              NUCLEATION SITE)
      B=400.
      EM=2.0
      RS=0.0001
C*** COMPUTE THE NUMBER OF NUCLEATION SITES PER SQ. FT.
      XN=B*(JC*RS*HFG*(TNB-TSAT)/(2.*TSAT*ST*V(2)))**EM
C*** COMPUTE THE POOL-BOILING HEAT-TRANSFER COEFFICIENT
      HP=3.5*(K(1)/DD/60.)*XN*DD*DD
      HP=HP*SQRT(PR(1))*SQRT(FD*DD*DD/(V(1)*MU(1)))
      IF(IRET)500,500,980
```

WALL

(derivative) from VDPDT

~~ADD PAREN'S~~

OK units without parens

Missing parens

S/B

```
TIME P      5.00
VSCLE
     0.00000000E+00    0.00000000E+00    0.00000000E+00    0.00000000E+00  0.0000  0.0000
     0.00000000E+00    0.00000000E+00    0.00000000E+00    0.00000000E+00  0.0000  0.0000
     0.00000000E+00    0.00000000E+00    0.00000000E+00    0.00000000E+00  0.0000  0.0000
     0.00000000E+00    0.00000000E+00    0.00000000E+00    0.00000000E+00

*********WRITE 9011 FROM "QBLRPP" ***********************************
AFLOW = 0.10000E+01 QRATE = 0.60000E+02 LFLOW = 0.10000E+01 AHTRAN= 0.10000E+03
DHYD  = 0.83300E-02 TSAT  = 0.60941E+03 CPY(1)= 0.35501E+00 CPY(2)= 0.31808E+00
MU(1) = 0.13283E-03 MU(2) = 0.98607E-05 K(1)  = 0.34802E-01 K(2)  = 0.76429E-02
V(1)  = 0.16010E-01 V(2)  = 0.12500E+00 HFG V2= 0.56697E+02 ST    = 0.18837E-03
PTDPDT= 0.46127E+01 TIN   = 0.58737E+03 W     = 0.64000E+01
WRITE 9021 FROM "QBLRPP"
PR(1) = 0.48780E+01 PR(2) = 0.14774E+01 G     = 0.10667E+00 REF   = 0.66892E+01
COLBF = 0.52321E+01 HT(1) = 0.41113E+01 FFF   = 0.45177E+01 VR    = 0.78078E+01
DV    = 0.87192E+00 SL    = 0.16153E+01 DP(1) = 0.61410E-02 REV   = 0.90108E+02
COLBV = 0.10419E+00 HT(5) = 0.16330E+00 FFV   = 0.28681E+00 DP(2) = 0.30441E-02
HSAT L= 0.56039E+02 TIN   = 0.58737E+03 VHPTV2= 0.11274E+03
WRITE 9031 FROM "QBLRPP"
T(5)  = 0.61378E+03 TW(5) = 0.61392E+03 TNB   = 0.60999E+03 X1    = 0.85112E+00
WRITE 9041 FROM "QBLRPP"
X1    = 0.85112E+00 T(1)  = 0.60985E+03 TW(1) = 0.60999E+03 X2    =-0.16486E-01
DD    = 0.60197E-04 FD    = 0.22767E+04 B     = 0.40000E+03 EM    = 0.20000E+01
RS    = 0.10000E-03 XN    = 0.31952E+07
HP    = 0.16986E+01
```

$V = \dot{w}/60/\cancel{\rho}A = \dfrac{\cancel{lbm}/sec}{lbm/ft^3 \times \cancel{ft^2}} = ft/sec$

Re = 6?

```
TIME M        5.00 SEC.
CHANGE*PCHANGE                                                                 *
CHANGE*TITLE   MRFV.DATA   BASE CASE                                           *
CHANGE*TITLE   GROUND IDLE                                                     *
CHANGE*TITEND                                                                  *
CHANGE*CASEB      0  -6   1  -1  -2                                            *
CHANGE*CASEC     66000.    9999.    8888.                                      *
CHANGE*CASED     3.5                                                           *
CHANGE*CASEND                                                                  *
CHANGE*VALUES  01 60.      40.      760.     0.0000    14.7                    *
CHANGE*VALUES  06 65.      960.     100.     100.      530.                    *
CHANGE*VALUES  11 500.     14.7     580.     0.0000    5.0                     *
CHANGE*VALUES  16 0.1      0.1      0.1      0.1       0.1                     *
CHANGE*VALUES  21 520.     300.     56.88    1137.6    14.7                    *
CHANGE*VALUES  26 710.     88.                                                 *
CHANGE*VALUES  31 40.      450.     660.     80.                               *
CHANGE*VALUES  35 0.0001   1.       0.0001   0.2       0.0001                  *
CHANGE*VALUES  40 0.02     0.2      0.8                                        *
CHANGE*VALUES  43 33.      14.9     600.     0.0000                            *
CHANGE*VALUES  47 100.     100.     580.     20000.                            *
CHANGE*VALUES  51 88.      88.      88.                                        *
CHANGE*VALUES  71 1.       0.       0.       888.      888.                    *
CHANGE*PAREND                                                                  *
CHANGE*COMEND                                                                  *
CHANGE*PTAB       1   0   2   0                                                *
CHANGE*ENDCASE                                                                 *
```

```
PARAMETER TABLE      150 VALUE(S)
(   1) 6.00000E+01 (   2) 4.00000E+01 (   3) 7.60000E+02 (   4) 0.00000E+00 (   5) 1.47000E+01 (   6) 6.50000E+01
(   7) 9.60000E+02 (   8) 1.00000E+02 (   9) 1.00000E+02 (  10) 5.30000E+02 (  11) 5.00000E+02 (  12) 1.47000E+01
(  13) 5.80000E+02 (  14) 0.00000E+00 (  15) 5.00000E+00 (  16) 1.00000E-01 (  17) 1.00000E-01 (  18) 1.00000E-01
(  19) 1.00000E-01 (  20) 1.00000E-01 (  21) 5.20000E+02 (  22) 3.00000E+02 (  23) 5.68800E+01 (  24) 1.13760E+03
(  25) 1.47000E+01 (  26) 7.10000E+02 (  27) 8.80000E+01 (  28) 0.00000E+00 (  29) 0.00000E+00 (  30) 0.00000E+00
(  31) 4.00000E+01 (  32) 4.50000E+02 (  33) 6.60000E+02 (  34) 8.00000E+01 (  35) 1.00000E-04 (  36) 1.00000E+00
(  37) 1.00000E-04 (  38) 2.00000E-01 (  39) 1.00000E-04 (  40) 2.00000E-02 (  41) 2.00000E-01 (  42) 8.00000E-01
(  43) 3.30000E+01 (  44) 1.49000E+01 (  45) 6.00000E+02 (  46) 0.00000E+00 (  47) 1.00000E+02 (  48) 1.00000E+02
(  49) 5.80000E+02 (  50) 2.00000E+04 (  51) 8.80000E+01 (  52) 8.80000E+01 (  53) 8.80000E+01 (  54) 0.00000E+00
(  55) 0.00000E+00 (  56) 7.77000E+02 (  57) 7.77000E+02 (  58) 7.77000E+02 (  59) 7.77000E+02 (  60) 7.77000E+02
(  61) 7.77000E+02 (  62) 7.77000E+02 (  63) 7.77000E+02 (  64) 7.77000E+02 (  65) 7.77000E+02 (  66) 7.77000E+02
(  67) 7.77000E+02 (  68) 7.77000E+02 (  69) 7.77000E+02 (  70) 7.77000E+02 (  71) 1.00000E+00 (  72) 0.00000E+00
(  73) 0.00000E+00 (  74) 8.88000E+02 (  75) 8.88000E+02 (  76) 7.77000E+02 (  77) 7.77000E+02 (  78) 7.77000E+02
(  79) 7.77000E+02 (  80) 7.77000E+02 (  81) 7.77000E+02 (  82) 7.77000E+02 (  83) 7.77000E+02 (  84) 7.77000E+02
(  85) 7.77000E+02 (  86) 7.77000E+02 (  87) 7.77000E+02 (  88) 7.77000E+02 (  89) 7.77000E+02 (  90) 7.77000E+02
(  91) 7.77000E+02 (  92) 7.77000E+02 (  93) 7.77000E+02 (  94) 7.77000E+02 (  95) 7.77000E+02 (  96) 7.77000E+02
(  97) 7.77000E+02 (  98) 7.77000E+02 (  99) 7.77000E+02 ( 100) 0.00000E+00 ( 101) 1.00000E+00 ( 102) 2.00000E+00
( 103) 3.00000E+00 ( 104) 4.00000E+00 ( 105) 5.00000E+00 ( 106) 6.00000E+00 ( 107) 7.00000E+00 ( 108) 8.00000E+00
( 109) 9.00000E+00 ( 110) 1.00000E+01 ( 111) 1.20000E+02 ( 112) 8.88000E+02 ( 113) 4.00000E-01 ( 114) 7.77000E+02
( 115) 1.50000E+01 ( 116) 9.90000E-01 ( 117) 8.88000E+02 ( 118) 8.88000E+02 ( 119) 9.80000E-01 ( 120) 5.55000E+02
( 121) 2.50000E+00 ( 122) 2.50000E+00 ( 123) 5.00000E-01 ( 124) 4.00000E+00 ( 125) 5.00000E+01 ( 126) 2.00000E+00
( 127) 1.00000E+02 ( 128) 1.00000E+02 ( 129) 1.00000E+00 ( 130) 6.00000E+01 ( 131) 1.00000E+00 ( 132) 1.00000E+02
( 133) 8.33000E-03 ( 134) 2.50000E+00 ( 135) 2.00000E+00 ( 136) 2.00000E+00 ( 137) 1.00000E+01 ( 138) 8.00000E+01
( 139) 1.00000E+01 ( 140) 3.40000E+38 ( 141) 3.40000E+38 ( 142) 3.40000E+38 ( 143) 3.40000E+38 ( 144) 3.40000E+38
( 145) 3.40000E+38 ( 146) 3.40000E+38 ( 147) 3.40000E+38 ( 148) 3.40000E+38 ( 149) 3.40000E+38 ( 150) 3.40000E+38
```

AECS MRFV.DATA BASE CASE
2 CASE

COMPONENT(S)

1 6 8	12	16	20	24	28	32	36	40	44	48	52	56	60	64	68	72	76	80
LOOPS	329	701	704	701	708	2	-1	0	43	44	45	46	0	0	0	0	0	0
LOOPS	329	621	648	621	656	1	-3	0	47	48	49	0	0	0	0	0	0	0
LOOPS	329	401	404	505	528	3	-22	1101	31	32	33	34	0	0	0	0	0	0
																		SV N 1 T 1
																		SV N 2 T 2
																		SV N 3 T 10
SPLIT	255	401	404	409	420	413	412	1	41	0	0	0	0	0	0	0	0	0
																		SV N 4 T 5
COND	256	413	412	432	621	648	656	0	211	211	221	121	0	0	0	0	0	0
SPLIT	255	413	432	417	440	419	448	1	42	0	0	0	0	0	0	0	0	0
																		SV N 5 T 5
CVALVE	255	419	448	456	0	35	36	0	0	0	0	0	0	0	0	0	0	0
																		SV N 6 T 6
CNNCT	255	419	456	419	460	0	0	0	0	0	0	0	0	0	0	0	0	0
CNNCT	255	417	440	417	480	0	0	0	0	0	0	0	0	0	0	0	0	0
QBOILR	258	419	460	468	0	-1	-1	129	130	131	132	133	0	0	0	0	0	0
CVALVE	255	417	480	488	0	37	38	0	0	0	0	0	0	0	0	0	0	0
																		SV N 7 T 6
EVAP	256	417	488	492	701	704	708	1	311	311	0	311	134	0	0	0	0	0
CVALVE	255	417	492	496	0	39	40	0	0	0	0	0	0	0	0	0	0	0
																		SV N 8 T 6
MERGE	445	417	496	409	420	501	504	0	0	0	0	0	0	0	0	0	0	0
SHAFT	320	1	0	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VCOMP	446	501	504	512	1	0	135	0	911	116	0	0	0	0	0	0	0	0
MERGE	445	501	512	419	468	505	520	1	0	0	0	0	0	0	0	0	0	0
																		EV N 1 T 2
VCOMP	446	505	520	528	1	0	136	0	911	116	0	0	0	0	0	0	0	0
LOOPE	432	401	404	505	528	1101	0	0	0	0	0	0	0	0	0	0	0	0
																		EV N 2 T 1
																		EV N 3 T 2
																		EV N 4 T 4
SENSOR	204	417	492	5	137	0	0	0	0	0	0	0	0	0	0	0	0	0
																		EV N 5 T 5
SENSOR	204	417	496	2	138	0	0	0	0	0	0	0	0	0	0	0	0	0
																		EV N 6 T 2
SENSOR	204	501	504	1	31	0	0	0	0	0	0	0	0	0	0	0	0	0
																		EV N 7 T 1
SENSOR	204	419	468	5	139	0	0	0	0	0	0	0	0	0	0	0	0	0
																		EV N 8 T 5
LOOPE	432	701	704	701	708	0	0	0	0	0	0	0	0	0	0	0	0	0
LOOPE	432	621	648	621	656	0	0	0	0	0	0	0	0	0	0	0	0	0

```
C*** COMPUTE THE COMBINED CONVECTION/BOILING COEFFICIENT
  500 HT(2)=(HP*HP+HT(1)*HT(1))/(2.*HP)
C*** ITERATIVELY COMPUTE THE WALL TEMPERATURE IN T
                              HE SUBCOOLED REGION
      A1=HP/(TNB-TSAT)**2
      A0=2.0*(Q/(A1*AH))**2
      A1=4.0*((HT(1)/A1)**2)/3.0
      S0=SQRT(A0*A0-A1**3)
      XX=ABS((A0-S0)/(A0+S0))
      IF(XX-.0001)650,670,670
```

IF (Aφ-Sφ) 650,670,670

```
  650 U=(A0+S0)**(1./3.)
      GO TO 680
  670 U=(A0+S0)**(1./3.)+(A0-S0)**(1./3.)
```

GOTO 500?

```
  680 C=(SQRT(U)+SQRT(U-4.*(U/2.-SQRT((U/2.)**2-.75*A1))))/2.
      T(2)=TSAT
      TW(2)=TSAT+C
      TW(5)=TW(2)
       X3=0.0
C*** GO TO 1280 IF THE EXIT IS 100% LIQUID (NO NET BOILING)
      IF(X2.GE.(L-X1))GO TO 1280
C*** STARTING REGION 3: BULK BOILING
  750 XC=1.0
```

= 0 unless subcooled

LBM/MIN BTU/LBM * FT/BTU/MIN = FT

```
C*** COMPUTE THE DRYOUT POSITION
      X3=W*(CPY(1)*(TSAT-TIN)+HFG*(1.0-XI))*L/Q-X1-X2
C*** COMPUTE THE EXIT QUALITY
      XE=(Q/W-CPY(1)*(TSAT-TIN))/HFG+XI
      IF(XE-1.)830,820,820
C*** FILM BOILING OR VAPOR-ONLY HEATING OCCUR
  820 XE=1.0
      GO TO 1140
C*** COMPUTE THE CRITICAL EXIT QUALITY ABOVE WHICH
                                VAPORIZATION OCCURS
  830 XC=JC*HFG*(XE-XI)/L
      XC=1.04-1.14E-5*(D(IGA+21)*D(IGA+21)*XC)**.375
```

Ref

supposed to be Ref (see p 97) last time D(IGA+21) was calculated was p 87 for vapor

```
C*** COMPUTE THE LENGTH OF THE BULK-BOILING REGION (X3)
      X3=X3*(XC-XI)/(1.0-XI)
      IF (X3.LT.0.0) X3=0.0
      IF(X3.GT.(L-X1-X2))X3=L-X1-X2
      IF(XE.GE.XC)GO TO 1140
C*** COMPUTE THE TWO-PHASE FLOW PARAMETER
      TT=(1.0/XE-1.0)**0.9*SQRT(DP(1)/DP(2))
      X3=L-X1-X2
C*** GO TO 1090 IF XE AND TT INDICATE THE RANGE FO
                              R ELLERBROOK'S FORMULA
      IF(XE.GT.0.7.OR.TT.LT.0.01)GO TO 1090
C*** USE CHEN'S FORMULA
      F=1.0+1.88/TT**0.8
      Y=F*(G*DH/MU(1)*(1.0-XE))**0.8/10000.
      S=EXP(-Y)
C*** COMPUTE TNB AS A FIRST APPROXIMATION TO THE WALL TEMPERATURE
C     THEN GO TO 490 TO COMPUTE THE POOL-BOILING HE
                              AT-TRANSFER COEFF.
      TNB=TSAT+SQRT(.8*60.*ST*Q/(K(1)*AH*PT))
      IRET=1
```

```
      GO TO 490
C*** COMPUTE THE BULK-BOILING COEFFICIENT WITH CHEN'S FACTORS
  980 HT(3)=F*HT(1)+S*HP
C*** COMPUTE THE WALL TEMPERATURE AT THE END OF TH
                               E TWO-PHASE REGION
C    UNDER THE ASSUMPTION THAT EM IS APPROXIMATELY 2.0
      A1=HP/(TNB-TSAT)**2
      A0=Q/(AH*S*A1*2.0)
      A1=F*HT(1)/(3.0*S*A1)
      S0=SQRT(A0*A0+A1**3)
      T(3)=TSAT
      TW(3)=TSAT+(A0+S0)**(1./3.)-(S0-A0)**(1./3.)
      TW(5)=TW(3)
      T(5)=TSAT
C*** GO TO 1320 TO COMPUTE THE TWO-PHASE PRESSURE DROP
      GO TO 1320
C*** ELLERBROOK'S FORMULA FOR THE HEAT-TRANSFER COEFFICIENT
 1090 Y=2.35-ALOG(TT)*(.266+.0255*ALOG(TT))
      HT(3)=HT(5)*(Q/(AH*60.*G*HFG))**.4*EXP(Y)
      GO TO 1180
```

is q = Q/AH ?

p 96 has Q/(W/A * hfg)

```
C*** FILM BOILING OR VAPOR-ONLY HEATING OCCURS
 1140 HT(3)=HT(5)*(XE+SL/VR*(1.0-XE))**0.8
C*** FLUID AND WALL TEMPERATURES AT THE END OF THE
                                TWO-PHASE REGION
 1180 T(3)=TSAT+(Q*(X3+X2+X1)/W/L-CPY(1)*(TSAT-TIN)-HFG*(XE-XI))
     * /CPY(2)
      TW(3)=T(3)+Q/(AH*HT(3))
      T(5)=T(3)
      TW(5)=TW(3)
C*** IF VAPOR-ONLY FLOW DOES NOT OCCUR, GO TO 1320
                                TO COMPUTE DELTA P
      IF(XE.LT.1.0)GO TO 1320
C*** COMPUTE THE OUTLET TEMPERATURE FOR VAPOR-ONLY FLOW
      T(5)=(Q/W-CPY(1)*(TSAT-TIN)-HFG*(1.0-XI))/CPY(2)+TSAT
      XE=1.0
      TW(5)=T(5)+Q/(AH*HT(5))
      GO TO 1320
C*** COMPUTE OUTLET CONDITIONS FOR VAPOR-ONLY FLOW
                                FROM INLET TO OUTLET
 1272 T(5)=TIN+Q/W/CPY(2)
      TW(5)=T(5)+Q/AH/HT(5)
      XDP=DP(2)
      D(IP+NSO)=D(IP+NSI)-DP(2)
      GO TO 1475
```

Similar

144. — from p87

where is 144 ?

as for label 1470 added

```
C*** COMPUTE THE OUTLET TEMPERATURE FOR NO NET VAPOR GENERATION
 1280 T(5)= TIN+Q/(AH*CPY(1))
 1310 PB=0.0
      GO TO 1350
```

S/B W

$\frac{BTU/MIN}{FT^2 \times \frac{BTU}{lbm°F}} = lbm°F/FT^2 MIN$

```
C*** COMPUTE THE TWO-PHASE PRESSURE DROP BY FAC,IN
                               C. CORRELATION OF
C     BAROCZY'S GRAPHICAL CORRELATION
 1320 PF=0.25*ALOG10(DP(1)/DP(2))
      PB=XE**.7/1.7-(1-XE)**2.3/2.3+(1.-(1-XE)**3.3)/(3.3*2.3*XE)
C*** COMPUTE THE FRICTION PRESSURE DROP
```

```
      PB=-XE**1.65*PF/2.65+(1.0+PF)*PB
 1350 FP=DP(1)*(X1+X2)/L+(DP(1)+PB*(DP(2)-DP(1)))*X3/L
      FP=FP+DP(2)*(1.-(X1+X2+X3)/L)
      IF(XE)1382,1382,1385
C*** ADD THE MOMENTUM PRESSURE DROP
 1382 MP=0.0
      GO TO 1470
 1385 VE=XE/(XE+SL*(1.0-XE)/VR)   = VOID FRACTION @ exit
      IF(VE-1.0)1388,1386,1386
 1386 ME=VR
      GO TO 1390
 1388 ME=((1.-XE)/(1.-VE))**2*(1.-VE*(1.-SL*SL/VR))      No. NOT IN MOMENTUM TERM
 1390 IF(XI)1395,1395,1400
 1395 MI=1.0
      GO TO 1440
 1400 VI=XI/(XI+SL*(1.0-XI)/VR) - VOID FRACTION @ INLET      no factor of 2?
      IF(VI-1.0)1430,1425,1425
 1425 MI=VR                                                  "MP" units!
      GO TO 1440
 1430 MI=((1.-XI)/(1.-VI))**2*(1.-VI*(1.-SL*SL/VR))   lbm^2/sec ft^4 x ft^3/lbm / lbm ft/lbf sec^2
 1440 MP=G*G*V(1)*(ME-MI)/(GC)                                  lbf/ft^2
 1470 XDP=(FP+MP)/144.                                                  ✓
 1475 D(IP+NSO)=D(IP+NSI)-XDP
      IF (D(IP+NSO).GT.0.0) GO TO 1476
      WRITE(OUT,7655) D(IP+NSO),D(IP+NSI)
 7655 FORMAT(" *** OUTLET PRESSURE IN QBOILER WAS",E14.7,
     *  " RESET PRESSURE TO INLET VALUE",E14.7)
      XDP=0.0
      D(IP+NSO)=D(IP+NSI)      IF T(5)=TSAT, should not use "1479" method
 1476 CONTINUE
      IF(T(5)-TSAT)1478,1479,1479
 1478 D(IH+NSO)=VHLI@(LOCT,D(IP+NSI),T(5))
      D(IT+NSO)=T(5)
      GO TO 1480
 1479 VV=VSV(LOCT,D(IP+NSO),T(5))
      D(IH+NSO)=VH(LOCT,D(IP+NSO),T(5),VV)
      D(IT+NSO)=T(5)
 1480 CONTINUE
      IF (ID(IRCD+13).EQ.0) GO TO 1579
      IF (PASS.NE.1) GO TO 1577
      ID(IEVT+JEVI)=3
 1577 IF (TMAX.GE.TSAT) GO TO 1576
      WRITE(OUT,1580) TMAX,TSAT,TW(5)
 1580 FORMAT(5X,"WARNING FROM QBOILER: ERROR VARIA
                              BLE CANNONT BE "/
     *" CONTROLLED BECAUSE THE CONTROLLED WALL TEM
                              PERATURE OF",E17.7/
     *" IS LESS THAN THE SATURATION TEMPERATURE OF",E17.7/
     *" THE WALL TEMPERATURE IS",E17.7)
 1576 IF(T(5).GT.TSAT)GO TO 1578
      WRITE(OUT,1590)XE
 1590 FORMAT(5X,"WARNING FROM QBOILER: TWO PHASE F
                              LUID AT OUTLET",
     *" PROBABLY CANNOT CONTROL WALL TEMP. EXIT QU
```

```
                                  ALITY IS",E12.4)
1578 D(IEV+JEVI) = (TMAX-TW(5))/XE
1579 CONTINUE
1485 FORMAT(" OVERALL: DP,TW(5),T(5) ",3F10.3)
     IF (IFP.NE.1 .OR. ICPP.NE.0) GO TO 99
     CALL PIOP(1,NL,NSI,NSO)
     CALL LINES(2)
     WRITE(OUT,1581) ID(ISN+NSO),TW(5)
1581 FORMAT(5X,"BOILER AT STATION NO.",I4," HAS A
                                    MAXIMUM WALL ",
    * "TEMPERATURE OF",E15.5," DEGREES R")
  99 CONTINUE
     RETURN
C    QBLRPP
     END
```

In 1970, Dr. Frederick A. Costello, the author of this report, conducted an extensive literature review in the field of boiling, condensing and two-phase flow. The correlations used in the computational procedure and reported in the following pages are taken from that review. Most of the work is taken directly from the open literature; however, in some cases correlations were derived by Dr. Costello, either during the review or during the development of the QBOILR computational procedure. In many cases, as is common in the literature, the measured heat-transfer coefficients can differ from the predicted by a factor of two. Therefore, we should not expect much better behavior in the predictions of the temperature differences for the cold plate. Because most of the temperature difference will be between the electronic component and the cold plate, the predictions will seldom lead to serious errors in the computation of the component temperatures.

The temperature profile through a typical cold-plate heat exchanger is illustrated in Exhibit 10.7-1. Five flow regions are defined. These five regions could have been further divided into such categories as bubbly flow, slug flow, annular flow, mist flow, etc. These subdivisions would be necessary if greater accuracy were to be obtained. For the present, the regions were divided into non-boiling, subcooled boiling, saturated (bulk) boiling, vaporization, and vapor-only. The resulting correlations should be more convenient and yield more reliable results than the choice between 300 and 500 Btu/hr-sf-F that is used in BOILER (the predecessor of QBOILR).

The following descriptions of the underlying theory follow the order of the computational procedure. Under each heading, we have listed the reference as well as some explanation of the development of the equations. The reader can find more information in the references.

Region 1: Forced Convection of the Liquid

This is a single-phase region for which heat-exchanger data are normally available. The form used in the simulation is the same as used in published data:

St * Pr**(2/3) = j(Re) = Colburn factor, a function of the Reynolds number

where

Re = df * V * Dh / muf
   = (1 - x) * W * Dh / (muf * Aflow)
St = Hf / (df * V * cf)

and

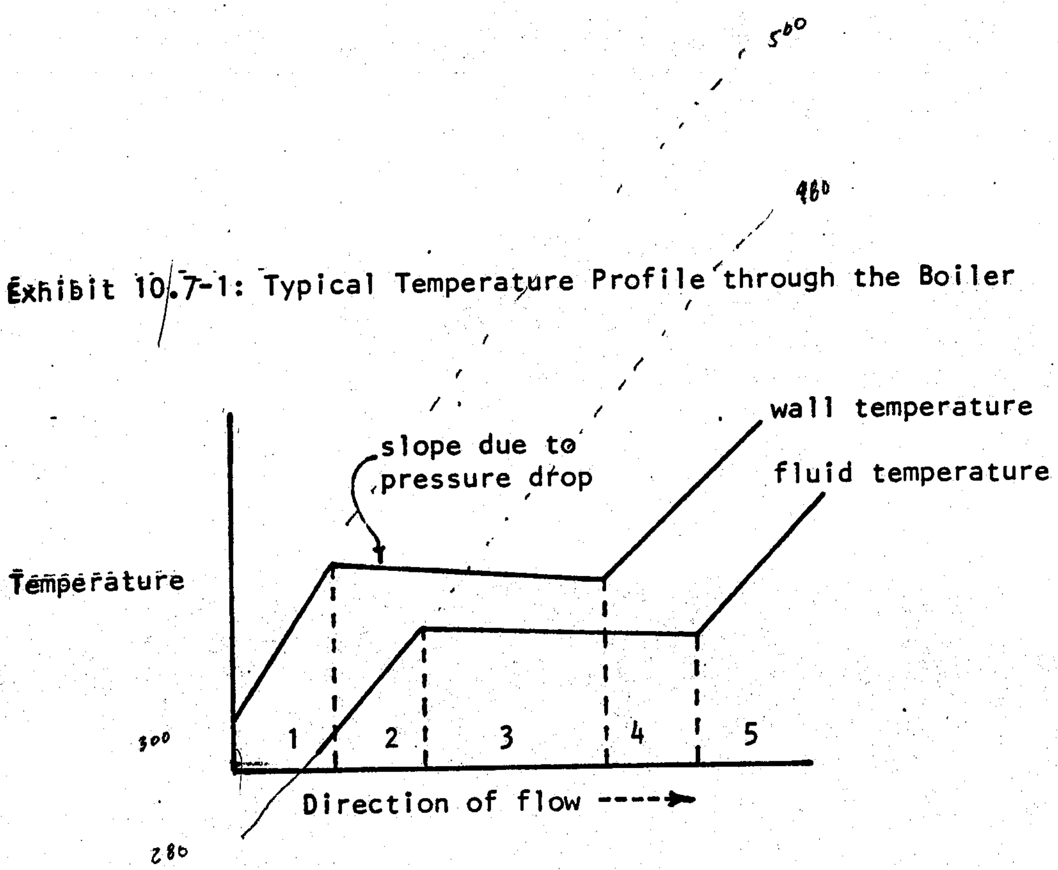
Pr = cf * muf / kf = c_p BTU/LBM °F × LBM/(SEC) FT / BTU/FT (HR) °F

3600. ✓ is in code

In these equations, St is the Stanton number; Pr, the Prandtl number; j, the Colburn number; Re, the Reynolds number; df, the density of the fluid (liquid); V, the velocity; Dh, the hydraulic diameter; muf, the

h = "Hf" see p 87

Exhibit 10.7-1: Typical Temperature Profile through the Boiler



Region	Description
1	Non-boiling, forced convection, liquid only
2	Local (sub-cooled) boiling
3	Saturated boiling
4	Forced-convection vaporization, liquid deficient
5	Non-boiling, forced convection, vapor only

dynamic viscosity of the fluid; x, the quality; W, the total mass flow rate; Aflow, the flow area; Hf, the heat-transfer coefficient; cf, the specific heat of the fluid; and kf, the thermal conductivity of the fluid. The symbol ** should be read "raised to the power of". (The fluid properties: df, muf, cf and kf, are calculated within the fluid-properties subroutines of AECS.) The Colburn factor is entered into AECS as a tabulated function of the Reynolds number. Double-logarithmic interpolation should be used. The permanent tables contain may such tabulations.

Region 2: Sub-cooled Nucleate Boiling

In the sub-cooled nucleate-boiling region, boiling occurs at the walls but the bubbles are immediately condensed in the core of the flow, because the fluid temperature is below the saturation temperature. Boiling begins at the wall if the temperature is high enough. According to Bergles and Rohsenow (American Society of Mechanical Engineers (ASME) Journal of Heat Transfer, Vol. 86C, No. 3, Pp. 365-372, Aug. 1964), with some modifications by FAC, Inc., Tnb, the wall temperature at which subcooled nucleate boiling begins, is given by:

```
Tnb = Tsat + SQRT( (8 * ST/kf) * (q / dP/dT) )
```

8. on p 88
.8 in code
"PT" in code, in fortran p 87

similar prob p 90 of code

?

where Tsat is the saturation temperature corresponding to the local pressure; ST, the surface tension; q, the heat ~~flux~~; and dP/dT is the derivative of the saturation pressure with respect to the temperature. The symbol SQRT represents the square-root function.

q = Q/AH = BTU/MW FT²

yes, "heat flux" has area included

The heat flux is computed as the root-mean-square of the heat flux that would be realized by forced convection alone and by pool boiling alone:

```
q**2 = [(Hf * (Tw - Tsat))**2] + [(Hp * (Tw - Tsat) - q)**2]
```

or

```
ht(2)
~~q/(Tw - Tsat)~~ = (Hp**2 + Hf**2) / (2 * Hp)
```

In these equations Tw is the wall temperature; and Hp, the pool-boiling heat-transfer coefficient. The other terms are defined above. Because Hp depends non-linearly on (Tw - Tsat), when q is known, a non-linear equation must be solved for Tw. The non-linear equation is of the quartic form, which can be solved directly.

dg/dF

The pool boiling heat-transfer coefficient can be computed according to the series of equations developed by Mikic and Rohsenow (ASME Journal of Heat Transfer, Vol. 91C, Pp.245f, 1969):

ve = v1/v2

v(1) * Dv = 1/df * (1 - 1/ve) = 1 - (df/dg) / df

```
Dd = 4.65E-04 * SQRT( Go * ST / (G * dfg) ) *
          (df * cf * Tsat / (dg * hfg) )**(5/4)
fd = 0.6 * (ST * Go * G * dfg / df**2)**(1/4) / Dd
Xn = B**3 * (RS * J * hfg * dg * (Tw - Tsat)/(2 * Tsat * ST))**m
Hp * Dd / kf = 3.5 * Xn * Dd**2 * SQRT(Prf * fd * df * Dd**2 / muf)
```

BTU/MW FT² °F

"B" in code, not B³
B = 400 in code and on p. 89 and on p 96

In these equations, Dd is the bubble diameter at departure from the wall; Go, 32.2 lbm/slug; G, the acceleration (of gravity); dfg, the difference between the density of the liquid and the density of the vapor at saturation; hfg, the difference between the enthalpy of the vapor and the enthalpy of the liquid at saturation; fd, the frequency of departure of the bubbles; "Xn," the number of nucleation sites per square foot of surface; B, a constant (approximately 400) that relates .0001 the interaction between the fluid and the wall materials; RS, the radius of the smallest nucleation site on the surface; J, 778 ft-lbf/Btu; Tw, the wall temperature; and "m", an exponent (approximately 2.0) that characterizes the correlation between the number of nucleation sites and the size of the sites, so is a function of the fluid/surface interaction. The other symbols were defined above.

Region 3: Saturated Boiling

In this region, the fluid temperature is at or above the saturation temperature across the entire fluid channel (but not necessarily along the channel in the flow direction). The heat-transfer coefficient is a weighted average of the forced-convection coefficient with only liquid flowing and the pool-boiling coefficient (J.C.Chen, Ind. and Eng'g Chem. Proc., Design and Dev., Vol. 5, Pp. 322f, 1966). FAC, Inc., developed the algebraic expressions for the curves presented by Chen for the weighting factors, F and S. as per Chen

Xtt = ((1 - x)/x)**0.9 * SQRT(DPf / DPg) $\approx \left(\frac{\rho_L}{\rho_V}\right)^{.5}\left(\frac{\mu_V}{\mu_L}\right)$

F = 1.0 + 1.88 / Xtt**0.8

Y = ~~F * Ref**0.8 / 10000.~~ = F * (ReF * (1-XE))**.8/10000.

S = EXP(-Y)

Htp = F * Hf + S * Hp

These equations apply if Xtt is greater than 0.01 and x is less than or equal to 0.7. In these equations, Xtt is the two-phase flow factor; DPf, the pressure drop as if the flow is totally liquid; DPg, the pressure drop as if the flow is totally vapor; Ref, the Reynolds number based on liquid properties; and Htp, the heat-transfer coefficient in two-phase flow. Because Hp depends non-linearly on (Tw-Tsat), if q is known and Tw is sought, a non-linear equation must be solved. Because the equation is cubic, it can be solved directly.

If x is greater than 0.7 or Xtt is less than 0.01, then Ellerbrook's correlation is used (National Aeronautics and Space Administration Special Publication SP-20, 1962):

Y = 2.35 - 0.266 * ALOG(Xtt) - 0.0255 * (ALOG(Xtt))**2 — coded on p90

Htp = Hg * (q / (W/Aflow * hfg))**0.4 * EXP(Y)

where ALOG is the natural-logarithm function; and Hg, the heat-transfer coefficient that would be realized if the flow were totally vapor (see below).

Region 4: Forced-Convection Vaporization

If this region mostly vapor is flowing. The flow is liquid deficient. The equations are the same as used in Region 3; however, Ellerbrook's formulas normally apply because the quality is greater than 70%.

Region 5: Vapor-Only Flow

This is a classical, single-phase flow region in which the fluid flowing is vapor. The equations are similar to those for Region 1:

```
St * Pr**(2/3) = j(Reg)        From table    (p87 Fortran)
Reg = W * Dh / (mug * Aflow)
 Pr = cg * mug / kg
 Hg = St * dg * V * cg       = j G Cp/PR^.67
```

In these equations, Reg is the Reynolds number based on vapor flow; mug, the dynamic viscosity of the vapor; cg, the specific heat of the vapor; kg, the thermal conductivity of the vapor; Hg, the heat-transfer coefficient for Region 5; and dg, the density of the vapor.

does this assume round, evenly heated vertical pipe? What about stratified horizontal flow?

Critical Heat Flux

The foregoing equations are based on nucleate boiling. If the surface temperature is too high, film boiling will occur. (Actually, the critical heat flux is a hydrodynamic effect, so it is governed by the heat flux rather than the temperature difference.) Most available correlations are dimensional and pertain to high-pressure water. A simple correlation that has proven accurate for fluorocarbons and liquid nitrogen is that given by Jones (General Electric Report TIS 63SD275, 1963):

```
                  Ref = W * Dh / (Aflow * muf)
                   Kf = J * hfg * (xo - xi) / L
778 ft lbf/BTU   xchf= 1.04 - 1.14E-05 * (Ref**2 * Kf)**0.375
```

these equations contain no input of q or wall temp. directly, but by way of (Xi - XO)

In these equations, xo is the outlet quality; xi, the inlet quality; L, the flow length; and xchf, the quality at the critical heat flux. If the quality exceeds xchf as given by these formulas, then film boiling will occur.

if XO = Xi, Kf = 0, xchf = 1.04, no film boiling

Film Boiling

Few correlations are available for the rarely encountered film-boiling regime in forced convection. The correlations are all of the same basic form. We have chosen the constants reported by Dougall in a 1963 report from the Massachusetts Institute of Technology:

```
Nu =  Htp * Dh / kg = 0.023 * Re**0.8 * Pr**0.4
```

WRONG! On the next page H_{tp}/H_G = ~ ~ (for film boiling)

Since H_G = HT(5) recieves "j" from a table, H_{tp} in the Fortran is completely unrelated to the eqn. here. It looks like a nice equation, though.

where

Re = dg * Dh * (Wg/dg + Wf/df) / (Aflow * mug)
Pr = cg * mug / kg

In these equations, Wg is the flow rate of the vapor and Wf is the flow rate of the liquid. These equations can be written in a somewhat more convenient form by taking the ratio of Htp to Hg:

jGCp/Pe   density ratio = 1/VR

Htp/Hg = (x + SL* dg / df * (1 - x))**0.8
SL= (df / dfg-1)**0.25

In these equations S is the slip (the ratio of vapor velocity to liquid velocity). There is no generally accepted correlation for S; the one presented is that used in the simulation. S=√√(VR-1)

Computation of the Pressure Drop in the Two-Phase-Flow Regions

Pressure-drop in the two-phase regions is due in part to friction and in part to momentum change. We assume that the momentum change occurs perfectly (i.e., 100% recovery in a decelerating flow). The ~~momentum~~ ΔP due to Δmomentum of the flow is given by:

volume ratio / VR = df/dg densities

"XE" S = SL = √√(VR-1) "VE"

q liquid X2

ΔP [M(x)] = (W / Aflow)**2 / (df * Go) * (((1 - x)/(1 - a))**2
* (1 - a + a * dg * S**2 / df))

label 1385 p.91 of code

where
"VE" a = x / (x + dg * S * (1 - x) / df) ⇒ VE = XE/(XE+SL*(1-XE)/VR)

a = α = V(x) = VE = VOID FRACTION

and the other symbols were defined above. When the quality, x, is zero, M is indeterminant according to the above equation; L'Hôpital's rule gives:

M = (W / Aflow)**2 / (df * Go)   for x=0.0.

this is very nice, but the logic (label 1382) sets ΔP mome = 0 if XE ≤ 0.0

The frictional pressure drop can be estimated from the graphs developed by Baroczy (1966), omitting the dimensional corrections for water. The graphs cover the range of DPf/DPg from 0.0001 to 1.0 and the range of qualities, x, from 0.001 to 1.000. FAC, Inc., modified the Baroczy graphs so the two-phase pressure drop would be obtained by interpolation between the liquid-only and vapor-only values:

DPtp = DPf + PHI * (DPg - DPf)

where PHI is obtained by re-arranging Baroczy's correlation. In this equation, DPtp is the two-phase pressure drop. Notice that PHI is 0.0 if the flow is 100% liquid and 1.0 if the flow is 100% vapor. Casting Baroczy's graphical data such that PHI is a function of x and DPf/DPg (Baroczy's two independent variables) results in irregular and somewhat unbelievable results. We have smoothed the curves and changed them slightly to obtain a more consistent pattern. We then developed an analytical expression for PHI:

"PF" code has ALOG10 = $\log_{10}(\sim)$

```
PHI = x**1.65 + ( 1. + 0.25 * ALOG(DPf/DPg) ) *
        ( x**0.7 + x * (1. - x)**1.3 - x**1.65 )
```

Because the quality changes as the flow progresses, this local value of PHI is not as useful as the average value, which can be obtained by integration. The average from x = 0 to x = x is:

```
PHIBAR(x) = x**1.65 / 2.65 + ( 1. + 0.25 * ALOG(DPf/DPg) ) *
              ( x**1.7 / 2.7 - (1. - x)**2.3 / 2.3 +
                (1. - (1. - x)**3.3) / (2.3 * 3.3 * x) -
                   x**1.65 / 2.65 )
```

The average from x = xi to x = xo can be computed from:

```
PHIAVG(xi to xo) = ( xo * PHIBAR(xo) - xi * PHIBAR(xi) )
                       / (xo - xi)
```

The two-phase frictional pressure drop is calculated, therefore, by determining first the single-phase pressure drop for 100% liquid and for 100% vapor flow. The known entering quality, xi, and the exit quality , xo, as calculated by the energy balance, can then be used to compute PHIAVG. The frictional pressure drop in the two-phase region is then computed from:

```
DPtp = DPf + PHIAVG * (DPg - DPf)
```

The total two-phase pressure drop is computed by adding to this the pressure drop due to the momentum change:

```
Total DPtp = DPtp + M(xo) - M(xi)
```

✓ increase in M ⇒ increase in ΔP

Note that the length of the two-phase region enters not only through the computation of the temperatures but also through the lengths used in computing DPf and DPg.

Figure 10.6-1: Input Cards and Flow Diagram for the Sample Case

flow varies to get $T_{max\ wall} \approx 560°R$

```
EXAMPLE CASE FOR QBOILER
QBOILR  0000   1   2   0
   0   0   0   0   0
   0.0          0.0          0.0
   0.0
26
 1  1.300       90.70       516.2      84.4    10000.
 6  .125        62.5        .008       1.0      2.0
11  .4331     88.1249       510.     109.665
16  .4331     91.2005       505.      32.22
21  .01         33.54       2.0        6.5        .03
26  560
  20   1   131000   1   2   3   4   3  -22
  40   1   13  14   0  -6  -6  21  22  23  24  25   1  26
  50   1   140000   1   7   2   7
   1   0   1   0
ASE
0
```

A_F .01 - 1.44 in^2 Q 33.54 L = 2.0 ft A_{HT} = 6.5

R-22 D_h = .36"

24 32 40 48 56 64

E.V. = yes

Tmax wall = 560.°R

use ΔP

FRIC TAB Type 32 No GA21 (Re)

COLB TAB Type 33

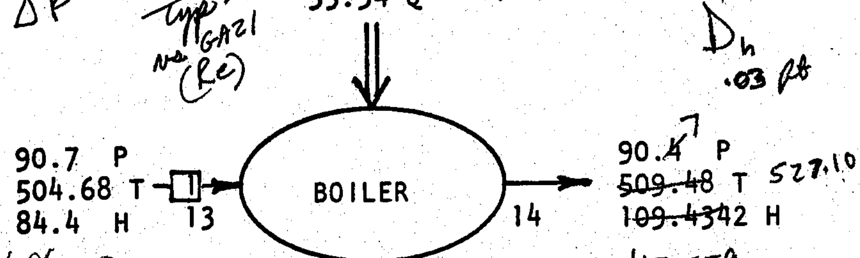
AFLOW

Q 33.54

L 2.0

AHT trans 6.5

Dh .03 ft



X ≅ .72

H_F ≈ 22 BTU/LBM

~~1.341~~ W

1.19

X ≅ 1.05

H_V ≅ 108 BTU/LBM

Exhibit 10.6-2: AECS Output for the Sample Case

```
*AECS* EXAMPLE CASE FOR QBOILER                                                  PAGE        7
    1  CASE QBOILR                                                               DATE 09/06/81

TIME P       96.33

SVT
(    1)     1

EVT
(    1)     3

PASS        1

S.V.
(    1) 1.30000E+00

E.V.
(    1) 1.50653E+01

W
(    1) 1.30000E+00

P
(   13) 9.07000E+01 (   14) 9.06980E+01

T
(   13) 5.04678E+02 (   14) 5.13834E+02

H
(   13) 8.44000E+01 (   14) 1.10195E+02

COMPONENT QBOILR EXTRAPOLATED TABLE     -6    -33 VALUE =  2.44867E-02 ARGUMENT(S)  3.94766E+02

COMPONENT QBOILR EXTRAPOLATED TABLE     -6    -32 VALUE =  1.08060E-01 ARGUMENT(S)  3.94766E+02

COMPONENT QBOILR EXTRAPOLATED TABLE     -6    -33 VALUE =  6.98646E-03 ARGUMENT(S)  7.28690E+03

COMPONENT QBOILR EXTRAPOLATED TABLE     -6    -32 VALUE =  3.25818E-02 ARGUMENT(S)  7.28690E+03

COMPONENT QBOILR

     NL        1    NSI      13    NSO      14    FT        3    FN      -22

     W     1.19    PI    90.70    PO    90.70    TI  504.68    TO  527.10    HI 84.4000   HO112.5592
    BOILER AT STATION NO.  14 HAS A MAXIMUM WALL TEMPERATURE OF      .56000E+03 DEGREES R
*AECS* EXAMPLE CASE FOR QBOILER                                                  PAGE        8
    1  CASE QBOILR                                                               DATE 09/06/81

TIME E       96.43

FLOW RATE(S)-LB/MIN

(    1)     1.19

PRESSURE(S)-PSI

(   13)    90.70 (   14)    90.70
```

```
HUMIDITY(S)/ENTHALPY(S)-LBW/LBA / BTU/LB

(  13) 84.4000 (  14)112.5592

STATE VARIABLE TYPE(S)
(    1)     1

STATE VARIABLE(S)
(    1) 1.18990E+00

ERROR VARIABLE TYPE(S)
(    1)     3

ERROR VARIABLE(S)
(    1) 2.36965E-05

SOLUTION CONVERGED IN       6 TRY(S)

     0 ERROR(S) DETECTED

CASE END
```

11. Subroutine RINLET (Refrigerant Inlet)

11.1. Subroutine Description

The RINLET (Refrigerant Inlet) subroutine does not simulate a component; instead, it permits the user to define the flow rate, pressure, temperature, and enthalpy at some point in an open-loop refrigerant system.

11.2. Prior Simulation Method

RINLET is a new subroutine --- or rather a new entry point in a previously available subroutine: INLET. INLET previously would not permit the use of a refrigerant. RINLET does.

11.3. New Simulation Method

RINLET is a new entry point in the subroutine INLET that permits the fluid to be a refrigerant. In addition, the inlet state is defined by the flow rate, pressure and enthalpy. The inlet temperature as entered by the user is overridden by the computer if the fluid is a refrigerant. The computer determines the temperature from the refrigerant-properties subroutines based on the pressure and enthalpy.

11.4. Computational Procedure

The modification to INLET to add the entry point RINLET is almost trivial (Exhibit 11.4-1). A branch is made if the fluid is a refrigerant, so the temperature can be computed as a function of pressure and enthalpy. Any refrigerant state is permissible. The branch also establishes the enthalpy as the state variable, if the user so designates it.

11.5. Program Listing

The few lines that have been modified are easily identified (Fluid Type = 3). The annotated listing is presented in Exhibit 11.4-1.

11.6. Sample Case

RINLET, like INLET, must be used in conjunction with other components. Therefore, a separate sample case is inappropriate. The reader can see examples of the use of RINLET in any of the examples presented for the other components.

```
      SUBROUTINE INLTPP
      COMMON /CC/ C(400)
      EQUIVALENCE (IRCD,C(45)), (IP,C(28)), (IT,C(
                                 29)), (IH,C(30))
     *, (IW,C(27)), (PASS,C(17)), (ISVT,C(46)), (ISV,C(47))
     *, (SCR(1),C(151)), (IFB,C(55))
      INTEGER PASS
      DIMENSION SCR(30)
      EQUIVALENCE (SCR(1),NL), (SCR(2),NS), (SCR(3),JSV)
     *, (SCR(4),NC), (SCR(5),LOCT), (SCR(6),P), (SCR(7),T)
     *, (SCR(8),TS), (SCR(9),V), (SCR(10),DSH)
      COMMON /DC/ DZ(2),D(2)
      DIMENSION ID(2)
      EQUIVALENCE (ID(1),D(1))
C     1 COMP CODE
C     2 LEG
C     3 STATION
C     4 W
C     5 P
C     6 T
C     7 H
C     8 SV W
C     9 SV P
C    10 SV T
C    11 SV H
C    12 DSH
      IENTRY=0
      GO TO 1
C*** ADD REFRIGERANT INLET AS AN ENTRY POINT
C     TO THE PREVIOUS INLET SUBROUTINE
      ENTRY RINLTPP
      IENTRY=1
    1 IRCD = IRCDB(12)
      NL = ID(IRCD+2)
      NS = ID(IRCD+3)
      IF (PASS.EQ.1) CALL FLUIDP(NL)
      LOCT = ID(IFB+NL)
      NC = ID(LOCT+1)
      LOCT = ID(LOCT+3)
      D(IW+NL) = D(ID(IRCD+4))
      D(IP+NS) = D(ID(IRCD+5))
      D(IT+NS) = D(ID(IRCD+6))
      D(IH+NS) = D(ID(IRCD+7))
    9 JSV = ID(IRCD+8)
      IF (JSV.EQ.0) GO TO 20
C*** FLOW RATE IS A STATE VARIABLE
      IF (PASS.NE.1) GO TO 12
      ID(ISVT+JSV) = 1
      D(ISV+JSV) = D(IW+NL)
   12 D(IW+NL) = D(ISV+JSV)
   20 JSV = ID(IRCD+9)
C*** PRESSURE IS A STATE VARIABLE
      IF (JSV.EQ.0) GO TO 30
      IF (PASS.NE.1) GO TO 22
```

```
      ID(ISVT+JSV) = 2
      D(ISV+JSV) = D(IP+NS)
   22 D(IP+NS) = D(ISV+JSV)
   30 JSV = ID(IRCD+10)
      IF (JSV.EQ.0) GO TO 40
C*** TEMPERATURE IS A STATE VARIABLE
      IF (PASS.NE.1) GO TO 32
      ID(ISVT+JSV) = 3
      D(ISV+JSV) = D(IT+NS)
   32 D(IT+NS) = D(ISV+JSV)
   40 JSV = ID(IRCD+11)
      IF (JSV.EQ.0) GO TO 50
C*** ENTHALPY OR HUMIDITY IS A STATE VARIABLE
      IF (PASS.NE.1) GO TO 42
      ID(ISVT+JSV) = 4
C*** IF FLUID TYPE IS 3 (REFRIGERANT), S.V. TYPE = 10 (ENTHALPY)
      IF(IENTRY.EQ.1)ID(ISVT+JSV)=10
      D(ISV+JSV) = D(IH+NS)
   42 D(IH+NS) = D(ISV+JSV)
   50 IF(NC.NE.3)GO TO 99
C*** RE-COMPUTE THE TEMPERATURE IF FLUID TYPE IS 3 (REFRIGERANT)
C     TO AVOID ATTEMPTING TO DEFINE THE FLUID STATE
                                   BY PRESSURE AND
C     TEMPERATURE WHEN THE FLUID IS IN THE TWO-PHASE REGION
      QUAL=VQUALH(LOCT,D(IP+NS),D(IH+NS))
      IF(QUAL.LT.0.0)D(IT+NS)=VTLIQ(LOCT,D(IP+NS),D(IH+NS))
      IF(QUAL.GE.0.0.AND.QUAL.LE.1.0)D(IT+NS)=VTS(LOCT,D(IP+NS))
      IF(QUAL.GT.1.0)CALL VTAV2(LOCT,D(IT+NS),V,D(
                                  IP+NS),D(IH+NS))
   99 CONTINUE
      RETURN
C     INLTPP
      END
```

12. Subroutine ROUTLT (Refrigerant Outlet)

12.1. Subroutine Description

The ROUTLT (Refrigerant Outlet) subroutine does not simulate a component; instead, it permits the user to define the flow rate, pressure, or enthalpy as an error variable at the end of an open-loop refrigerant system.

12.2. Prior Simulation Method

ROUTLT is a new subroutine --- or rather a new entry point in a previously available subroutine: OUTLET. OUTLET previously would not permit the use of a refrigerant. ROUTLT does.

12.3. Present Simulation Method

ROUTLT is a new entry point in the subroutine OUTLET that permits the fluid to be a refrigerant. In addition, the outlet flow rate, pressure and enthalpy are computed. The outlet temperature is computed from the refrigerant properties subroutines based on the pressure and enthalpy. As with OUTLET, there is no need for ROUTLT if the user does not want an error variable to be defined at the outlet. With the omission of ROUTLT, an open-loop refrigeration system will terminate at the last component. We have included ROUTLT in the sample cases just to be tidy.

12.4. Computational Procedure

The modification to OUTLET to add the entry point ROUTLT is almost trivial (Exhibit 12.4-1). A branch is made if the fluid is a refrigerant, so the temperature can be computed as a function of pressure and enthalpy. Any refrigerant state is permissible. The branch can also compute the enthalpy as an error variable, if the user so designates it.

12.5. Program Listing

The few lines that have been modified are easily identified (Fluid Type = 3). The annotated listing is presented in Exhibit 12.4-1.

12.6. Sample Case

ROUTLT, like OUTLET, must be used in conjunction with other components. Therefore, a separate sample case is inappropriate. The reader can see examples of the use of ROUTLT in any of the examples presented for the other components.

Exhibit 12.4-1: Performance-Program Logic and Listing

```
      SUBROUTINE OTLTPP
      COMMON /CC/ C(400)
      EQUIVALENCE (IRCD,C(45)), (IP,C(28)), (IW,C(
                                27)), (PASS,C(17))
     *,(IEVT,C(48)),(IEV,C(49)),(IT,C(29)),(IH,C(30)),(OUT,C(7))
     *, (SCR(1),C(151))
      INTEGER PASS,OUT
      DIMENSION SCR(30)
      EQUIVALENCE (SCR(1),NL), (SCR(2),NS), (SCR(3),JEV)
      COMMON /DC/ DZ(2),D(2)
      DIMENSION ID(2)
      EQUIVALENCE (ID(1),D(1))
C   1 COMP CODE
C   2 LEG
C   3 STATION
C   4 W
C   5 P
C   6 T
C   7 H
C   8 EV W
C   9 EV P
C  10 EV T
C  11 EV H
      IENTRY=0
      GO TO 1
C*** ENTRY POINT IF FLUID IS A REFRIGERANT
      ENTRY ROTLTPP
      IENTRY=1
    1 IRCD = IRCDB(11)
      NL = ID(IRCD+2)
      NS = ID(IRCD+3)
      JEV = ID(IRCD+8)
      W=D(IW+NL)
      P=D(IP+NS)
      T=D(IT+NS)
      H=D(IH+NS)
C*** ON FIRST PASS, SET UP THE ERROR VARIABLES
      IF (JEV.EQ.0) GO TO 20
      IF (PASS.EQ.1) ID(IEVT+JEV) = 1
      D(IEV+JEV) = D(IW+NL)-D(ID(IRCD+4))
   20 JEV = ID(IRCD+9)
      IF (JEV.EQ.0) GO TO 30
      IF (PASS.EQ.1) ID(IEVT+JEV) = 2
      D(IEV+JEV) = D(IP+NS)-D(ID(IRCD+5))
   30 JEV = ID(IRCD+10)
      IF (JEV.EQ.0) GO TO 40
      IF (PASS.EQ.1) ID(IEVT+JEV) = 3
      D(IEV+JEV) = D(IT+NS)-D(ID(IRCD+6))
   40 JEV = ID(IRCD+11)
      IF (JEV.EQ.0) GO TO 99
      IF (PASS.EQ.1) ID(IEVT+JEV) = 4
      D(IEV+JEV) = D(IH+NS)-D(ID(IRCD+7))
   99 CONTINUE
      IF(IENTRY.EQ.0)RETURN
```

```
C*** IF THE FLUID IS A REFRIGERANT, WRITE W, P, T, H
      WRITE(OUT,1000)W,P,T,H
 1000 FORMAT(" *+* W = ",F8.3," P = ",F8.3," T = "
     ,F8.3," H = ",F8.3)
      RETURN
C     OTLTPP
      END
```

13. Subroutine RPMP (Refrigerant Pump)

13.1. Subroutine Description

The RPMP routine simulates the performance of a liquid transfer pump for the refrigerant. This pump might, for example, send the refrigerant to electronic cold plates remote from the compressor and condenser.

13.2. Prior Simulation Method

RPMP is a new subroutine; however, PUMPPP, a prior subroutine, simulates oil and water pumps of both positive-displacement and centrifugal types. PUMPPP computes the hydraulic power, which it divides by the efficiency. The result is divided by the motor efficiency to obtain the electrical input.

13.3. Present Simulation Method

The RPMP routine follows the PUMP routine closely, with the hydraulic and mechanical efficiencies being input tables. However, we have added warning messages to indicate to the user when the efficiency tables have been extrapolated to values less than zero or greater than one. We then adjust the efficiencies to permit the computations to continue. A message is also printed if the fluid entering the pump is not a liquid.

13.4. Computational Procedure

The computational procedure is listed in Exhibit 13.4-1. The procedure is identical to that of PUMPPP, except for the differences in the tables and the addition of warning messages and the corresponding adjustments.

13.5. Program Listing

Exhibit 13.4-1, which presents the program computational procedure, also is the program listing as used in AECS. However, the stored AECS program does not include the comment cards.

13.6. Sample Case

The sample case, as depicted in Exhibit 13.6-1, is based on having the refrigerant pump alone as the total system. The input data are shown in the required format for AECS input. The corresponding system output data are shown in the system schematic (Exhibit 13.6-1) and in output format (Exhibit 13.6-2), starting with Page 7 of the output, the beginning of the computed data. Previous output pages contain the headers and a repeat of the input data.

Exhibit 13.4-1: Performance-Program Logic and Listing

```
      SUBROUTINE RPMPPP
      INTEGER OUT
      REAL MR,NR,MEFF,MPWR
      COMMON /CC/ C(400)
      EQUIVALENCE (IRCD,C(45)),(IW,C(27)),(IP,C(28)),(IT,C(29))
     *,(IH,C(30)),(SCR(1),C(151)),(IFB,C(55)),(ITAD,C(54))
     *,(IEV,C(49)),(IEVT,C(48))
     *, (ICPP,C(88)), (IFP,C(22)), (OUT,C(7)), (IGA,C(35))
      DIMENSION SCR(30)
      EQUIVALENCE  (SCR(1),NL),(SCR(2),NSI),(SCR(3),NSO)
     *,(SCR(4),NST),(SCR(5),TBL1),(SCR(6),TBL2),(SCR(7),TBL3)
     *, (SCR(8),QR), (SCR(9),PR), (SCR(10),RPM), (SCR(11),HP)
     *, (SCR(12),ERRV)
      COMMON /DC/ DZ(2),D(2)
      DIMENSION ID(2)
      EQUIVALENCE (ID(1),D(1))
C   1 COMP CODE
C   2 LEG NO
C   3 INLET STATION NO
C   4 OUTLET STATION NO
C   5 SHAFT NO
C   6 PRESSURE RISE TABLE NO
C   7 PUMP EFFICIENCY TABLE NO
C   8 MOTOR EFFICIENCY TABLE
C   9 FLOW RATE AT ZERO PRESSURE DIFFERENCE (QR)
C  10 PRESSURE DIFFERENCE AT ZERO FLOW RATE, PSIA (PR)
C  11 SHAFT SPEED CORRESPONDING TO QR AND PR (RPM)
C  12 RATED OUTPUT OF MOTOR (HP)
C  13 ERROR VARIABLE INDEX
C*** SETUP INTERNAL VARIABLES IN TERMS OF STORED ARRAY
      IRCD = IRCDB(13)
      NL = ID(IRCD+2)
      NSI = ID(IRCD+3)
      NSO = ID(IRCD+4)
      NST = ID(IRCD+5)
C*** ENTER MASS FLOW RATE AS INDEPENDENT VARIABLE FOR TLUP
      D(IGA+41) = D(IW+NL)
      QR = D(ID(IRCD+9))
      PR = D(ID(IRCD+10))
      NR = D(ID(IRCD+11))
      MR = D(ID(IRCD+12))
      LOCT=ID(IFB+NL)
      LOCT=ID(LOCT+3)
      Q=D(IW+NL)
      D(IP+NSO)=D(IP+NSI)
      D(IT+NSO)=D(IT+NSI)
      D(IH+NSO)=D(IH+NSI)
C*** TEST THE TEMPERATURE TO SEE IF IN LIQUID REGION
```

```
      TEMP=D(IT+NSI)
      TSAT=VTS(LOCT,D(IP+NSI))
      IF(TSAT.GT.TEMP) GO TO 390
      WRITE(OUT,380) TEMP,TSAT,D(IP+NSI)
  380 FORMAT (" *** WARNING FROM RPMPPP:  INLET TWO-PHASE, WITH T=",
     *E14.7," (TSAT=",E14.7,") AT P=",E14.7,/,
     *" USING SPECIFIC VOLUME AT SAT AT P")
      TEMP=TSAT
  390 GPM=7.4805*D(IW+NL)/VDL(LOCT,D(IT+NSI))
C*** SET UP THE SHAFT SPEED AS AN INDEPENDENT VARIABLE FOR TLUP
      D(IGA+101)=D(IGA+NST+80)
C*** SET UP THE MASS FLOW RATE AS THE SECOND INDEPENDENT VARIABLE FOR TLUP
      D(IGA+102)=0
      RPM=D(IGA+NST+80)
C*** OBTAIN THE PRESSURE RISE FROM THE TABLE
      DP=TLUP(ID(IRCD+6))
      IF(DP)570,410,410
  410 D(IP+NSO)=D(IP+NSI)+DP
      PWR=144.*DP*GPM/(7.4805*33000)
C*** OBTAIN THE EFFICIENCY FROM THE TABLE
      EFF=TLUP(ID(IRCD+7))
  412 CONTINUE
C*** WATCH FOR UNREALISTIC EFFICIENCIES.  REVISE EFFICIENCY
C    AND KEEP GOING IF EFFICIENCY IS UNREALISTIC
      IF(EFF.LE.0.OR.EFF.GE.1.0)GO TO 570
      SPWR=PWR/EFF
      HEAT=(SPWR-PWR)*42.416
      D(IGA+101)=SPWR
      MEFF=TLUP(ID(IRCD+8))
  414 CONTINUE
C*** WATCH FOR UNREALISTIC MECHANICAL EFFICIENCY.  REVISE EFFICIENCY
C    AND KEEP GOING IF EFFICIENCY IS UNREALISTIC
      IF(MEFF.LE.0.0.OR.MEFF.GE.1.0)GO TO 580
      MPWR=SPWR/MEFF
      D(IGA+NST+90)=D(IGA+NST+90)-MPWR
C*** TAKE THREE ITERATIONS ON THE SPECIFIC HEAT
      DO 500 I=1,3
      D(IT+NSO)=D(IT+NSI)+HEAT/D(IW+NL)/
     * VCPF(LOCT,D(IP+NSI),(D(IT+NSO)+D(IT+NSI))/2.)
  500 CONTINUE
      D(IH+NSO)=D(IH+NSI)+SPWR*42.416/D(IW+NL)
  560 IF (IFP.NE.1 .OR. ICPP.NE.0) GO TO 99
      CALL PIOP(I,NL,NSI,NSO)
      CALL LINES(2)
      WRITE(OUT,1401) NSI,MPWR,RPM
 1401 FORMAT(5X,"REFRIGERANT PUMP WITH INLET STATION NO.",
     *I10/"      HAS A SHAFT-POWER INPUT OF",E17.7," HP AND A SHAFT"
     * " SPEED OF",E17.7," RPM")
   99 CONTINUE
      RETURN
  570 WRITE(OUT,575) D(IW+NL),RPM,EFF
  575 FORMAT(" *** UNREALISTIC EFFICIENCY IN REFRIGERANT PUMP FOR",/,
```

```
   *" *** FLOW OF",F8.4," AND",F8.1," RPM (EFF =",F8.4,")",/,
   *" *** EFFICIENCY RESET TO BE BETWEEN 0. AND 1.")
    IF (EFF.LE.0.) EFF=0.01+EFF/1000.
    IF (EFF.GE.1.) EFF=0.99+EFF/1000.
    GO TO 412
580 WRITE(OUT,585) SPWR,MEFF
585 FORMAT(" *** UNREALISTIC MECHANICAL EFFICIENCY IN REFRIGERANT ",
   *"PUMP",/," *** WITH SHAFT POWER OF ",F10.3,"HP (MEFF=",F8.4,")",/,
   *" *** MECHANICAL EFFICIENCY RESET TO BE BETWEEN 0. AND 1.")
    IF (MEFF.LE.0) MEFF=0.01+MEFF/1000.
    IF (MEFF.GE.0) MEFF=0.99+MEFF/1000.
    GO TO 414
C   RPMPPP
```

The values used in the tables were chosen for brevity and convenience. Few pumps have the linear characteristic used. If the more realistic values presented in Appendix D had been used, the input data would have been longer and the manual checkout, more difficult.

13.7. Technical Background

The technical background for this subroutine is provided in the former discussions on the PUMPPP subroutine. However, adjustments are made to the efficiencies. If the efficiency, E, is greater than 1.0, the efficiency is re-computed according to the replacement expression:

$$E = 0.99 + E / 1000.$$

If the efficiency is less than 0.0, the efficiency is re-computed according to the replacement expression:

$$E = 0.01 + E / 1000.$$

These adjustments to the efficiencies are applied to the hydraulic and mechanical efficiencies.

The adjustments to the efficiencies are made variable (rather than setting them to constants) to minimize the chance that the solution routine, on computing the derivatives relative to the state variables, will find the derivatives to be zero. If the derivatives are zero, the Newton-Raphson solution procedure will fail the matrix check and print a message that the solution failed to converge.

Exhibit 13.6-1: Input Cards and Flow Diagram for the Sample Case

```
  ORM
  LE EXAMPLE CASE FOR RPMP
  EA      RPMP   0000    1    3    0
  B        0    0    0    0    0
  C       0.          0.          0.
  D       0.
  AM     15
  ES     01  0.1332      272.1834       577.0     44.82     0.0
  ES     06   .03        10.0           1.5        0.0     530.0
  ES     11  2000.
  ET      10    1    10000    1    2    3    4    3  -22
  NE      20    1    1    2    0   -1    5    6    7    8    9   10
  T       22    1    0   11
  P       24    1    2    3    1    1    1    1
  TLT     30    1    30000    1    2    3    4
  ID       1    8   33    0    0 1010101     2    0 1020101    2
  T     PRESSURE RISE TABLE
  V        0.0          4000.
  V        0.0          4000.
  V        0.0          0.4
  V        0.0          10.0          0.0          0.0
  ID       1    9   33    0    0 1010101     2    0 1020101    2
  T     STATIC EFFICIENCY TABLE
  V        0.0          4000.
  V        0.0          4000.
  V        0.0          0.4
  V        0.8          0.9           0.8          0.9
  ID       1   10    2    0    0 1010101     3
  T      MECHANICAL EFFICIENCY TABLE
  V        0.0          0.0           0.0002       0.8
  V        0.0004       0.9
  A2       1    0    1    0
  CASE
  JOB
```

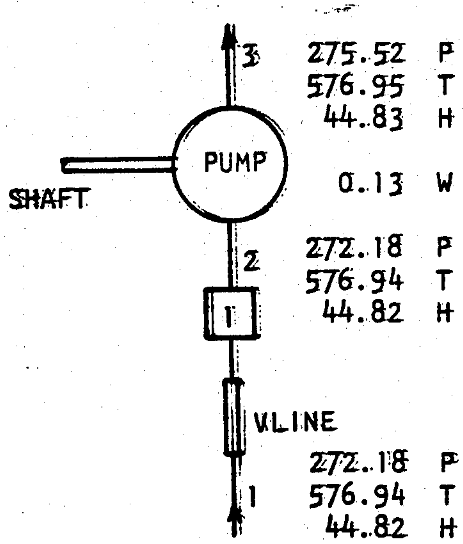


Exhibit 13.6-2: AECS Output for the Sample Case

```
TIME P      54.65

COMPONENT SHAFT

     SHAFT    1    N    2000.

COMPONENT RPMP

     NL       1    NBI      2    NBO      3    FT       3    FN      -22

     W      .13    PI  272.18    PO  275.52    TI  576.94    TO  576.95    HI 44.8200    HO 44.8306
    REFRIGERANT PUMP WITH INLET STATION NO.            2
    HAS A SHAFT-POWER INPUT OF       .2500000E-03 HP AND A SHAFT SPEED OF      .2000000E+04 RPM
*AECS* EXAMPLE CASE FOR RPMP                                                                        PAGE         8
    1  CASE    RPMP                                                                                 DATE 01/23/82

TIME E      54.66

FLOW RATE(S)-LB/MIN

(    1)     .13

PRESSURE(S)-PSI

(    1)  272.18 (    2)  272.18 (    3)  275.52

TEMPERATURE(S)-DEG R

(    1)  576.94 (    2)  576.94 (    3)  576.95

HUMIDITY(S)/ENTHALPY(S)-LBW/LBA / BTU/LB

(    1) 44.8200 (    2) 44.8200 (    3) 44.8306

     0 ERROR(S) DETECTED

CASE END
```

14. Subroutine SENSOR

14.1. Subroutine Description

The SENSOR subroutine simulates the sensing point for an unspecified controller. The controller is assumed to have the capability for maintaining the set-point value. Therefore, the iterative solution to the simulation model will continue until the sensed value equals the set point. If the system or controller does not have the capability of satisfying the control point, the iterations will not terminate and the solution procedure will fail to converge. The sensor can be applied to any fluid.

14.2. Prior Simulation Method

The previous sensor simulation model permitted the control of any one of four variables: flow rate, pressure, temperature or enthalpy (humidity, if air is the fluid). An error message was printed if any other variable were used.

14.3. New Simulation Method

The new model adds the following to the list of permitted control variables: superheat, subcooling and quality. Because these three depend on a combination of pressure, temperature and enthalpy, the logic of the sensor routine required considerable modification. In terms visible to the user, the leg and station number at which the sensor is placed must now be specified on the component card.

14.4. Computational Procedure

The computational procedure is presented in the form of a heavily annotated FORTRAN program in Exhibit 14.4-1. The only computations performed are those required to determine the superheat, quality and subcooling, based on the refrigerant-property subroutines.

14.5. Program Listing

Exhibit 14.4-1, which presents the program computational procedure, also is the program listing as used in AECS. However, the AECS program does not include the comment cards.

14.6. Sample Case

The sample case, as depicted in Exhibit 14.6-1, is based on having two sensors in a system containing an evaporator. The first senses the superheat; the second senses the air outlet temperature. The

Exhibit 14.4-1: Performance-Program Logic and Listing

```
      SUBROUTINE SENPP
      COMMON /CC/ C(400)
      EQUIVALENCE  (IRCD,C(45)),(SCR(1),C(151)),(IFB,C(55))
     *,(PASS,C(17)),(IEV,C(49)),(IEVT,C(48))
     *,(IW,C(27)),(IP,C(28)),(IT,C(29)),(IH,C(30))
      INTEGER PASS
      DIMENSION SCR(30)
      EQUIVALENCE  (SCR(1),ICT),(SCR(5),NL),(SCR(6),NS)
     *,(SCR(4),JEVI),(SCR(8),LOCT),(SCR(9),VALUE)
      COMMON /DC/ DZ(2),D(2)
      DIMENSION ID(2)
      EQUIVALENCE (ID(1),D(1))
C   1 COMP CODE
C   2 LEG NUMBER
C   3 STATION NUMBER
C   4 SENSOR CODE(1=FLOW,2=PRESSURE,3=TEMPERATURE,4=ENTHALPY,
C                  5=SUPERHEAT,6=SUBCOOLING,7=QUALITY)
C   5 CONTROL VALUE
C   6 ERROR VARIABLE TYPE
C   7 ERROR VARIABLE INDEX
      IRCD=IRCDB(7)
      NS=ID(IRCD+3)
      NL=ID(IRCD+2)
      LOCT=ID(IFB+NL)
      LOCT=ID(LOCT+3)
      ICT=ID(IRCD+4)
      GO TO (10,20,30,40,50,60,70) ICT
   10 VALUE=D(IW+NL)
C*** FLOW RATE IS BEING CONTROLLED
      GO TO 100
   20 VALUE=D(IP+NS)
C*** PRESSURE IS BEING CONTROLLED
      GO TO 100
   30 VALUE=D(IT+NS)
C*** TEMPERATURE IS BEING CONTROLLED
      GO TO 100
   40 VALUE=D(IH+NS)
C*** ENTHALPY IS BEING CONTROLLED
      GO TO 100
   50 P = D(IP+NS)
C*** COMPUTE THE SATURATION PROPERTIES FOR A REFRIGERANT
      TSAT = VTS(LOCT,P)
      TSH = D(ID(IRCD+5))
      V = VSV(LOCT,P,TSAT)
      HSAT = VH(LOCT,P,TSAT,V)
C*** COMPUTE APPROXIMATE SUPERHEAT (CORRECT AT CORRECT SUPERHEAT)
C    BY DIVIDING THE ENTHALPY DIFFERENCE BY THE SP
                              ECIFIC HEAT OF THE
C    VAPOR, THEREBY AVOIDING ZERO-SENSITIVITY ERRO
                              RS WHEN THE ITERATION
C    RESULTS IN SATURATED OR TWO-PHASE FLUID AT THE SENSED POINT
      VALUE = (D(IH+NS)-HSAT)/VCPV(LOCT,P,TSAT+0.5*TSH)
C*** SUPERHEAT IS BEING CONTROLLED
      GO TO 100
```

```
   60 P = D(IP+NS)
      TSAT = VTS(LOCT,P)
      TSC = D(ID(IRCD+3))
      HLIQ = VHLIQ(LOCT,P,TSAT)
C*** COMPUTE APPROXIMATE SUBCOOLING VIA THE ENTHAL
                             PY DIFFERENCE, AS WAS
C    DONE FOR THE SUPERHEAT
      VALUE = (HLIQ-D(IH+NS))/VCPF(LOCT,P,TSAT-0.5*TSC)
C*** SUBCOOLING IS BEING CONTROLLED
      GO TO 100
   70 VALUE=VQUALH(LOCT,D(IP+NS),D(IH+NS))
C*** QUALITY IS BEING CONTROLLED
  100 JEVI=ID(IRCD+7)
      IF(PASS.NE.1) GO TO 110
      ID(IEVT+JEVI)=ID(IRCD+6)
  110 D(IEV+JEVI)=VALUE-D(ID(IRCD+5))
C*** D(IEV+JEVI) IS THE VALUE OF THE CONTROL ERROR
                              (ERROR VARIABLE)
C    THIS ERROR WILL BECOME ZERO AS THE SYSTEM SOL
                             UTION IS OBTAINED
      RETURN
C     SENPP
      END
```

corresponding set points are 5 degrees of superheat and an air outlet temperature of 510 R, as indicated by the values of the parameters. The input data are shown in the required format for AECS input. The corresponding system output data are shown in the system schematic (Exhibit 14.6-1) as well as in the output format (Exhibit 14.6-2), starting on Page 7 of the output, the beginning of the computed data. Previous output pages contain the headers and a repeat of the input data.

14.7. Technical Background

The subroutine takes the user-specified value of the controller set point and computes the difference between this set point and the value obtained in solving the system performance. The difference is an error variable, which becomes zero as the iterative solution is obtained to the system performance. If the system is incapable of meeting the set point, the iterative solution will not converge.

Exhibit 14.6-1: Input Cards and Flow Diagram for the Sample Case

```
 FORM
 LE    EXAMPLE CASE FOR SENSOR ON AIR AND REFRIGERANT STATIONS
 SEA     SENSOR   0000     2     4     1
 ASEB       0     0     0     0     0
 ASEC       0.0              0.0         0.0
 ASED       0.0
 ARAM    20
 ALUES    1     2.100    14.7000    540.00     0.014       5.0000
 ALUES    6     1.395    14.6000    510.00     0.0075      0.0001
 ALUES   11     1.0000   91.2005    505.00    76.40        0.0
 ALUES   16     0.4331   88.1249    510.00   109.665       0.0
 LET        10    1   311000     1    2    3    4    2   -1
 INLET      20    2   181000    11   12   13   14    3  -22
 VAP        30    2   18   19    1   31   30    0    1    2    5    3   10
 OUTLT      40    2   190000    16   17   18   19
 UTLET      50    1   300000     6    7    8    9
 ENSOR      60    2   19     5    5
 ENSOR      70    1   30     3    8
 ABID        1    1    2    0    0   410101    2
 ABT         AIR SIDE PRESS DROP T=1 RN=1 (IND VAR = AIR FLOW)
 ABV          0.0         0.0           5.0          0.1
 ABID        2    5    2    0    0   410101    2
 ABT         AIR SIDE BYPASS FACTOR T=5 RN=2 (IND VAR = AIR FLOW)
 ABV          0.0         0.0           5.0          0.3
 ABID        3    2    2    0    0   420101    2
 ABT         REFRIG SIDE PRESS DROP T=1 RN=3 (IND VAR = )
 V            0.0         0.0           1.0          1.00
 B           1    0    1    0
 DCASE
 ENDJOB
```

5° superhea

Type 5 = superhe

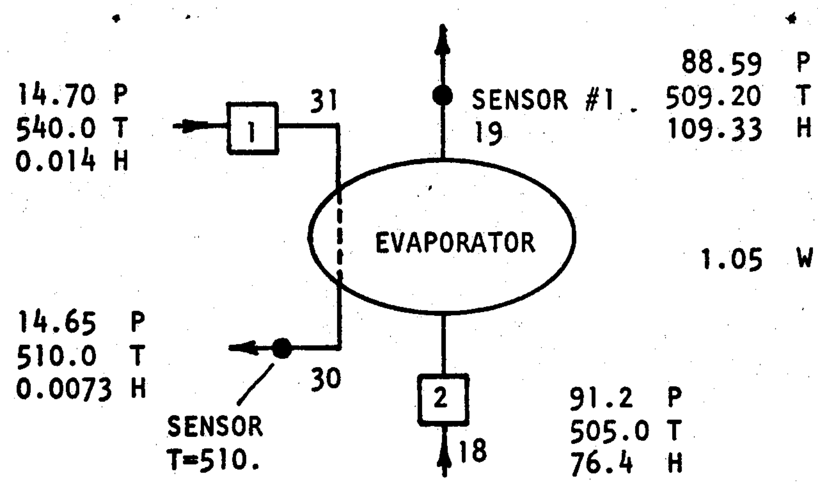


Exhibit 14.6-2: AECS Output for the Sample Case

```
THE FOLLOWING LISTING IS FOR FILE   SENSOR

TIME E      179.56

FLOW RATE(S)-LB/MIN

(    1)     2.38 (    2)     1.05

PRESSURE(S)-PSI

(   18)    91.20 (   19)    88.59 (   30)    14.65 (   31)    14.70

TEMPERATURE(S)-DEG R

(   18)   505.00 (   19)   509.20 (   30)   510.00 (   31)   540.00

HUMIDITY(S)/ENTHALPY(S)-LBW/LBA / BTU/LB

(   18) 76.4000 (   19)109.3347 (   30)    .0073 (   31)    .0140

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

STATE VARIABLE(S)
(    1) 2.38096E+00 (    2) 1.04608E+00

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

ERROR VARIABLE(S)
(    1) 1.63069E-04 (    2) 0.

SOLUTION CONVERGED IN       6 TRY(S)

     0 ERROR(S) DETECTED

CASE END
```

15. Subroutine SEPAR (Refrigerant Liquid/Vapor Separator)

15.1. Subroutine Description

The SEPAR subroutine simulates a refrigerant liquid/vapor separator in which a two-phase fluid enters, the vapor flows out the first exit leg, and the liquid flows out the second exit leg. The separator would typically be used after an expansion valve in a refrigeration system, with the vapor being sent to the middle stage of a two-stage compressor or to the pocket of a pocket-feed Roots compressor. The liquid would be sent to the evaporator, possibly through another expansion valve.

15.2. Prior Simulation Method

SEPAR is a new subroutine. It is similar in function to WSEP; however, WSEP separates liquid and air whereas SEPAR separates two phases of the same fluid.

15.3. Present Simulation Method

The liquid/vapor separation is assumed to be perfect, with no pressure drop occurring in the component. The user will want to add VLINE components as appropriate to simulate the pressure drop.

With no pressure drop, the simulation is relatively simple. The fraction of the flow leaving the vapor port is equal to the quality of the incoming flow. The enthalpy of the vapor leaving is equal to the enthalpy of the saturated vapor at the inlet pressure. The enthalpy of the liquid leaving is equal to the enthalpy of saturated liquid at the inlet pressure.

15.4. Computational Procedure

The computational procedure is presented in the form of a heavily annotated FORTRAN program listing (Exhibit 15.4-1).

The outlet pressures are set equal to the inlet pressure. The enthalpy of the outlet liquid is equal to the saturated-liquid enthalpy; the enthalpy of the outlet vapor is equal to the saturated-vapor enthalpy. The fraction of the flow leaving as vapor is equal to the quality of the incoming flow.

15.5. Program Listing

Exhibit 15.4-1, which presents the program computational procedure, is also the program listing as used in AECS. However, the AECS program does not include the comment cards.

Exhibit 15.4-1: Performance Program Logic and Listing

```
      SUBROUTINE SEPARPP
C*** THIS SUBROUTINE SIMULATES THE PERFORMANCE OF A LIQUID/VAPR
C    SEPARATOR WITH INLET FLUID IN ANY STATE; PURE VAPOR LEAVING
C    LEG OUT 1  AND PURE SATURATED LIQUID LEAVING LEG OUT 2
      COMMON /CC/C(400)
      EQUIVALENCE (IRCD,C(45)),(IW,C(27)),(IP,C(28)),(IT,C(29)),
     *(IH,C(30)),(ISV,C(47)),(PASS,C(17)),(ISVT,C(46)),
     * (SCR(1),C(151)),(IFB,C(55)),(OUT,C(7))
      INTEGER PASS,OUT
      DIMENSION SCR(30)
      EQUIVALENCE (SCR(1),NLI),(SCR(2),NSI),(SCR(3),NLOG),
     *   (SCR(4),NSOG),(SCR(5),NLOF),(SCR(6),NSOF),(SCR(7),TS),
     *   (SCR(8),VG),(SCR(9),HG),(SCR(10),HFG)
      COMMON /DC/DZ(2),D(2)
      DIMENSION ID(2)
      EQUIVALENCE (ID(1),D(1))
C    1 COMP CODE
C    2 LEG IN WITH ANY QUALITY
C    3 STATION IN
C    4 LEG OUT 1 WITH SATURATED VAPOR ONLY
C    5 STATION OUT 1
C    6 LEG OUT 2 WITH SATURATED LIQUID ONLY
C    7 STATION OUT 2
C*** SET UP THE INTERNAL VARIABLES IN TERMS OF THE STORED ARRAY
      IRCD=IRCDB(7)
      NLI=ID(IRCD+2)
      NSI=ID(IRCD+3)
      NLOG=ID(IRCD+4)
      NSOG=ID(IRCD+5)
      NLOF=ID(IRCD+6)
      NSOF=ID(IRCD+7)
      LOCT=ID(IFB+NLI)
      LOCT=ID(LOCT+3)
C*** G REPRESENTS THE GASEOUS STATE; F, THE FLUID STATE
C    COMPUTE THE SATURATION PROPERTIES
      TS=VTS(LOCT,D(IP+NSI))
      VG=VSV(LOCT,D(IP+NSI),TS)
      HG=VH(LOCT,D(IP+NSI),TS,VG)
      HFG=VHFG(LOCT,D(IP+NSI),TS,VG)
C*** SET THE OUTLET STATES BASED ON PERFECT SEPARATION INTO
C    SATURATED LIQUID AND SATURATED VAPOR
      D(IP+NSOG)=D(IP+NSI)
      D(IP+NSOF)=D(IP+NSI)
      D(IT+NSOG)=TS
      D(IT+NSOF)=TS
      D(IH+NSOG)=HG
      D(IH+NSOF)=HG-HFG
C***THE TOTAL ENERGY CONVECTED OUT EQUALS THAT CONVECTED IN
      D(IW+NLOG)=D(IW+NLI)*(D(IH+NSI)-HG+HFG)/HFG
      D(IW+NLOF)=D(IW+NLI)-D(IW+NLOG)
C***CHECK FOR UNREASONABLE FLOW SPLIT
      IF (D(IW+NLOF).LT.0.0.OR.D(IW+NLOG).LT.0.0) GO TO 50
   40 CONTINUE
      IF (IFP.NE.1 .OR. ICPP.NE.0) GO TO 99
```

```
      CALL PIOP(1,NLI,NSI,NSOG)
      CALL LINES(2)
      WRITE (OUT,1001) D(IW+NLOF),D(IW+NLOG)
 1001 FORMAT (1H0,5X,12HIN SEPARATOR,18H   LIQUID FLOW OUT,E14.5,
     * 17H   VAPOR FLOW OUT,E14.5)
   99 CONTINUE
      RETURN
   50 QUAL=(D(IH+NSI)-HG+HFG)/HFG
      WRITE (OUT,1004) QUAL
 1004 FORMAT (1H0,5X,30HINLET QUALITY TO SEPARATOR WAS,E14.5,
     *  20H  POSSIBLY AN ERROR )
      WRITE (OUT,1002) D(IW+NLOF),D(IW+NLOG)
 1002 FORMAT (1H0,5X,36HUNREASONABLE FLOW SPLIT IN SEPARATOR
     * 16H LIQUID FLOW OUT,E14.5,19H AND VAPOR FLOW OUT,E14.5)
      WRITE (OUT,1003)
 1003 FORMAT (1H0,5X,25HNEGATIVE FLOW SET TO ZERO)
      IF (D(IW+NLOF).GT.0.0) GO TO 60
      D(IW+NLOG)=D(IW+NLI)
      D(IW+NLOF)=0.
      GO TO 40
   60 D(IW+NLOF)=D(IW+NLI)
      D(IW+NLOG)=0.
      GO TO 40
C     SEPARPP
      END
```

15.6. Sample Case

The sample case, as depicted in Exhibit 15.6-1, is based on having the separator alone as the total system. The input data are shown in the required format for AECS input. The corresponding system output data are shown in the system schematic (Exhibit 15.6-1) as well as in the output format (Exhibit 15.6-2), starting with Page 7 of the output, the beginning of the computed data. Previous output pages contain the headers and a repeat of the input data.

15.7. Technical Background

The outlet pressures are assumed to be equal to the inlet pressure, so the only computation pertains to the energy balance:

Min * Hin = Mg * Hg + Mf * Hf

where Min is the inlet flow rate; Hin, the inlet enthalpy; Mg, the vapor flow out of the separator; Hg, the enthalpy of saturated vapor at the inlet pressure; Mf, the liquid flow out of the separator; and Hf, the enthalpy of the saturated liquid at the inlet pressure. Hg and Hf are known from the refrigerant-properties subroutines. Hin is known because it is computed from an upstream component. In addition, a mass balance gives:

Min = Mg + Mf

We combine these equations to obtain the relationship between the vapor flow and the inlet flow:

Mg = Min * (Hin - Hf) / (Hg - Hf)

The ratios of enthalpies in this equation can be recognized as the expression for the quality at the inlet, Xin, so

Mg = Min * Xin

This is the key equation in this simulation.

15.6-1: Input Cards and Flow Diagram for the Sample Case

```
  EXAMPLE CASE FOR SEPARATOR
      SEPAR   0000     3    3    0
        0    0    0    0    0
       0.         0.         0.
       0.
      10
      01  0.4331     91.2005     505.0    62.3     0.0
      06 - .200      .233         1.5       0.0     530.0
       10    1   120100    1    2    3    4    3 -22
       20    1   12    2   24    3   13
       40    2   241000    6    2    3    4
       50    3   130000    7    2    3    4
        1    0    1    0
  ASE
  B
```

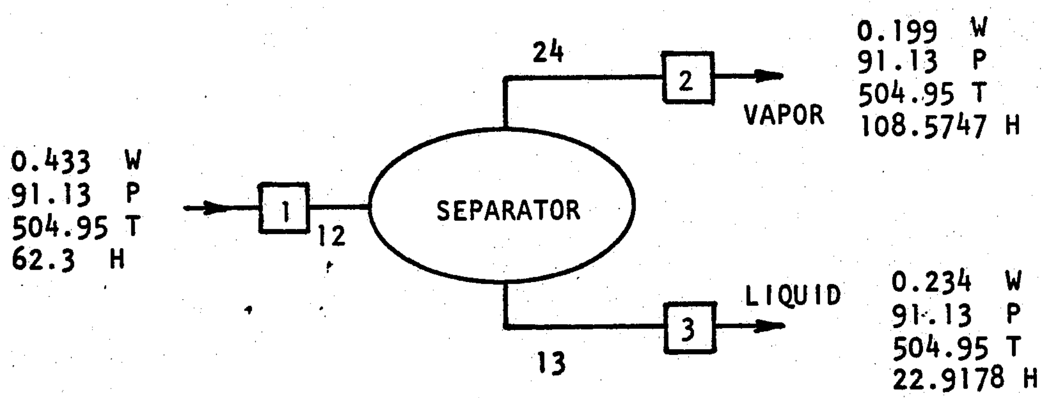


Exhibit 15.6-2: AECS Output for the Sample Case

```
PERMANE   TABLE    PIAD      1                                      PAGE      7
*AECS     MPLE CASE FOR SEPARATOR                                   DATE 09/06/81
   1      SEPAR

 TIME P        82.50

 SVT
 (    1)     2

 EVT
 (    1)     1

 PASS        1

 S.V.
 (    1) 9.12005E+01

 E.V.
 (    1)-9.20991E-04

 W
 (    1) 4.33100E-01 (    2) 1.99079E-01 (    3) 2.34021E-01

 P
 (   12) 9.12005E+01 (   24) 9.12005E+01 (   13) 9.12005E+01

 T
 (   12) 5.05000E+02 (   24) 5.05000E+02 (   13) 5.05000E+02

 H
 (   12) 6.23000E+01 (   24) 1.08579E+02 (   13) 2.29314E+01
*AECS* EXAMPLE CASE FOR SEPARATOR                                   PAGE      8
    1  CASE  SEPAR                                                  DATE 09/06/81

 TIME E        82.52

 FLOW RATE(S)-LB/MIN

 (    1)      .43 (    2)      .20 (    3)      .23

 PRESSURE(S)-PSI

 (   12)    91.13 (   13)    91.13 (   24)    91.13

 TEMPERATURE(S)-DEG R

 (   12)   504.95 (   13)   504.95 (   24)   504.95

 HUMIDITY(S)/ENTHALPY(S)-LBW/LBA / BTU/LB

 (   12) 62.3000 (   13) 22.9178 (   24)108.5747

 STATE VARIABLE TYPE(S)
 (    1)     2

 STATE VARIABLE(S)
 (    1) 9.11264E+01

 ERROR VARIABLE TYPE(S)
 (    1)     1
```

```
ERROR VARIABLE(S)
(    1)-8.74922E-04

SOLUTION CONVERGED IN       1 TRY(S)

     0 ERROR(S) DETECTED

CASE END
```

16. Subroutine SOLN (Solution Procedure)

16.1. Subroutine Description

The SOLN subroutine solves the system of equations representing the environmental-control system. The equations for each of the components are assembled by AECS according to the component cards placed ahead of SOLN. The set of equations must be solved by trial and error. SOLN lets the user select the trial-and-error procedure: either the Newton-Raphson method, which was used exclusively prior to this modification to AECS, or one of three variations in the maximum-rate-of-descent method. If the SOLN component is omitted, the prior (Newton-Raphson) solution method is used.

16.2. Prior Method

Previously only the Newton-Raphson method, in subroutine SOLN1, was available as a solution technique in AECS. This method linearizes the equations and solves the system of linear equations by Gaussian elimination. Because the equations are not linear, the solution to the linearized equations is not necessarily the solution to the non-linear equations. Therefore, the linearization is repeated after each solution to the linearized system and the solution to the new linear set is computed again, until the solution to the non-linear set is obtained.

The Newton-Raphson method frequently fails to converge. Sometimes the problem specified by the user has no solution. For example, by accident, a user might define his system with evaporators but no condensers, so there would be no heat-rejection devices. AECS will attempt to solve the problem but will fail to converge. In most problems, the absence of a physical solution is less evident. In other cases, especially with the highly non-linear refrigerant properties, the linearized solution will be physically impossible. For example, the linearized solution (an intermediate result in the process of iteratively solving the non-linear equations) can give negative absolute temperatures and negative absolute pressures. In any case, the Newton-Raphson method will not indicate the cause of the problem.

16.3. New Method

The new SOLN routine, which combines SOLN1 and a new subroutine called MRDSOLN, allows for four solution techniques: (1) Newton-Raphson; (2) MRD, a maximum-rate-of-descent procedure for minimizing the root-mean-square (RMS) error; (3) MRD1, a quasi-one-dimensional variation of MRD; and (4) MRD2, a quasi-two-dimensional variation of MRD. None of the methods can give a solution to a problem that does not have a physical solution, such as the system without a condenser, cited above. However, the MRD methods can help the user determine (1) the changes in the state variables that will bring the system closer to a solution and (2) which variables are most important in controlling the system performance. In addition, the MRD methods will permit the user to solve parts of his system, after which he can make adjustments in the remaining parts to obtain a solution that is physically realizable.

The Newton-Raphson and maximum-rate-of-descent methods are described extensively in the literature on systems engineering, optimization, and operations research. We present here a brief geometric description of each to help the user understand trends he will see in the computed results.

The Newton-Raphson method is a generalization to many dimensions of Newton's classical one-dimensional method. In Newton's method, the tangent to the curve y=f(x) is constructed at some user-selected starting point, X0. To obtain a solution to y=0 (in AECS, y is the error variable which we strive to make zero), the method extrapolates the straight tangent line to y=0, thereby replacing the exact shape of the curve, y=f(x), with a linear approximation. Where the tangent intercepts the x axis we call X1. X1 is used as a new trial solution, with a new tangent being constructed at f(X1). In some problems, the tangent is horizontal so it does not intersect the x axis, and Newton's method fails. In other, physical problems, the tangent is nearly horizontal and the intersection with the x axis occurs far from X0, yielding values of X1 that are physically impossible, such as negative absolute temperatures or pressures. The Newton-Raphson method works similarly to the Newton method, except tangent planes are used instead of tangent lines, because more dimensions are involved. Beyond two independent (state) variables, the process becomes more difficult to envision, but no more difficult to implement.

The maximum-rate-of-descent (MRD) methods are hill-climbing techniques. In the case of AECS, we climb down the hill to find the lowest point in the valley, the lowest point corresponding to the least error. The problem is trivial in one dimension, so we will describe the method in two dimensions using the function z(x,y). In AECS, z would be the root-mean-square of the error variables and x and y would be state variables. As with the Newton-Raphson method, the user defines a starting point by selecting X0 and Y0. MRD then finds the direction of the steepest descent. If z were an analytical expression, this direction would be obtained by differentiation; in AECS, small steps are taken in each state variable one at a time to approximate differentiation. A step is then taken in the direction of steepest descent to new values of x and y, which then form a new trial solution, and the process is continued. Beyond two independent (state) variables, hills become difficult to envision but the process works the same.

Several problems arise in solving problems by MRD methods. The first problem involves selecting the step size. Suppose, for example, that one independent variable were the pressure and the second, the humidity. The pressure might range from 14.7 to 100 psia, whereas the humidity might range from 0.1 to 1.0. A step of 1.0 would have little effect if taken along the pressure axis but would step beyond physical reality if taken along the humidity axis. Therefore, a scaling system is required by which all independent variables will have equal weighting. In AECS we ask the user to specify the scale factor. We suggest that the scale factor be the range in which the user expects the solution to lie. For example, if the solution to the problem should be obtained with a pressure between 14.7 and 100, the user would specify the pressure-scaling factor as (100-14.7), or 85.3. Similarly, the scaling factor for the humidity would be 0.9.

Similar scaling factors exist for the error variables. For example, one error variable could be the pressure and another, the flow rate. However, for the error variables we know that the solution will have all errors equal to zero. Therefore, we ask the user to enter scaling factors for the error variables such that a unit error in each variable has equal acceptability. For example, if the user will accept an error of 0.1 degree in temperature and 1.0 psi in pressure, then his scaling factors for the error variables should be 0.1 for temperature and 1.0 for pressure. If two different temperatures give error variables, then two scale factors would be defined. They could be the same or not.

Perhaps the most annoying problem with MRD methods is that of termination. Recognizing that the solution has been obtained, at least within the accuracy that MRD permits, can be difficult, especially if you are not sure that a physical solution exists for the problem you posed to AECS. We do provide a direction indicator that shows the cosine of the angle between each step and the previous step. We also have a built-in procedure for changing the step size. If you find the cosine is consistently negative, then the steps keep retracing themselves (exactly, if the cosine is -1.0, but only slightly if the cosine is near 0.0). The RMS error is probably near its minimum. You might want to take the MRD results and see if the Newton-Raphson method will converge from this point. If each of the error variables is small, then the MRD solution would be acceptable.

An advantage of Newton-Raphson is that you have no control over the sequence of steps. The weighting factor actually is little help because the direction of the step cannot be controlled. Everything is automatic. But the lack of control is also a disadvantage, especially if the method does not converge and the reason for not converging is not obvious --- the usual case.

The advantage of the MRD method is that you have control. You can select the step size and, to some extent via MRD1 and MRD2, the direction of the step. In addition, if you want to de-emphasize a state variable, you can enter a small scaling factor. If you want to de-emphasize an error variable, you can enter a large scaling factor. But the control is also a disadvantage. You must make decisions and you must examine the progress of the iterations toward the solution. You may also require more iterations to obtain the solution because your step size was incorrect.

In AECS we have left both the Newton-Raphson and the MRD techniques so you can attack your problem with either a controlled or an uncontrolled process. You can alternate. You can try Newton-Raphson first and hope for the best. You can try MRD when all else fails. We like being optimistic and using Newton-Raphson first. When this fails, we switch to one of the MRD techniques to study the problem and perhaps discover that the state and/or error variables were poorly chosen or that the solution requires a change in the size of one of the components. After we are confident that a solution exists, we like to obtain the final result using Newton-Raphson.

The three MRD methods available in our revision to AECS are:

- MRD: the classical method described above, in which all of the variables are changed simultaneously when the step is made. The step is in the direction of steepest descent, so the RMS error is decreased the maximum by a step in this direction (at least in the limit of an infinitesimal step). Unless overridden by a COMMON card for C(76), the solution will be limited to 26 MRD steps.
- MRD1: each state variable is changed one at a time, to find the minimum along the first axis (with respect to the first state variable), then along the second, etc., returning to the first to start again if the solution has not been obtained. Note that MRD1 does not step in the MRD direction. This technique is most useful when you are studying the effects of one variable in an attempt to discover the problems with MRD, MRD2 or Newton-Raphson. Unless overridden by COMMON cards, the solution will be limited to 3 steps in each variable (C(373) is 3) and 26 steps in the set of state variables (C(76) is 26), for a total of 78 steps in each variable.
- MRD2: state variables are changed in pairs, to find the minimum with respect to the first pair, then the second, etc. Note that MRD2 does not step in the MRD direction. This method is somewhat more flexible than MRD1, coming closer to the MRD direction. It also permits the user to plot contour maps that might help him discover what values of the state variables will most nearly give a solution. Unless overridden by COMMON cards, the solution will be limited to 3 steps per pair of variables (C(373) is 3) and 26 steps in the set of variables (C(76) is 26), for a total of 78 steps in each pair.

16.4. Computational Procedure

The computational procedure is presented in the form of a heavily annotated FORTRAN program listing. Exhibit 16.4-1 shows the modifications to SOLN1 (the previous solution subroutine); Exhibit 16.4-2, the new "component" SOLN; and Exhibit 16.4-3, the logic and listing for the MRD computations.

Exhibit 16.4-1: Revisions to the SOLN1 Subroutine

```
      SUBROUTINE SOLN1
      COMMON /CC/ C(400)
      EQUIVALENCE (IDS,C(5)), (OUT,C(7)), (CERR,C(
                         16)), (PASS,C(17))
     *, (ISVS,C(92)), (NLEG,C(25)), (NSTA,C(26)), (IGA,C(35))
     *, (ISP,C(42)), (ISVT,C(46)), (ISV,C(47)), (IEVT,C(48))
     *,(IEV,C(49)),(NSV,C(50)),(NEV,C(51)),(IFP,C(
                         22)),(MRD,C(372))
     *, (IW,C(27)), (IP,C(28)), (IT,C(29)), (IH,C(
                         30)), (IMP,C(66))
     *, (IME,C(67)), (ILN,C(37)), (ISN,C(38)), (NI
                         T,C(76)), (PF,C(77))
     *, (NWT,C(78)), (ITAD,C(54)), (SVLL(1),C(181)
                         ), (SVUL(1),C(191))
     *, (ICONV,C(79)), (IIOP,C(90)), (ERRL,C(83)), (BIG,C(31))
     *, (MRDNIT,C(373))
      INTEGER OUT, CERR, PASS
      COMMON /CCA/ CA(150)
      EQUIVALENCE (LIST(1),CA(11)),(SVSCALE(1),CA(31)),
     *(EVSCALE(1),CA(51)),(DF(1),CA(71)),(DFO(1),CA(91)),
     *(ITER,CA(111)),(RST,CA(112)),(STEP,CA(113)),(IEVS,CA(122)),
     *(ESUM,CA(114)),(DSUM,CA(115)),(SUM,CA(116)),
                         (ITBL50,CA(117)),
     *(ITBL51,CA(118)),(NORD,CA(119)),(KVAR,CA(120
                         )),(IDONE,CA(121)),
     *(IWS,CA(130)),(IPS,CA(131)),(ITS,CA(132)),(IHS,CA(133))
      DIMENSION LIST(20),DF(20),DFO(20),SVSCALE(20),EVSCALE(20)
      DIMENSION SVLL(10),SVUL(10)
      DIMENSION CD(100)
      EQUIVALENCE (CD(1),C(201))
      EQUIVALENCE (CN,CD(84))
      COMMON /DC/ DZ(2),D(2)
      DIMENSION ID(2),
      EQUIVALENCE (ID(1),D(1))
      DATA SN/5HSOLN1/
      CN=SN
      ITER = 0
      IDSS = IDS
      NUM = NSV*NSV
      IF (ISV.NE.0) GO TO 6
      CALL GDCU(NSV,4,ISP,D,ISV)
      CALL GDCU(NSV,4,ISP,D,ISVT)
      CALL GDCU(NEV,4,ISP,D,IEV)
      CALL GDCU(NEV,4,ISP,D,IEVT)
      CALL GDCU(NSV,4,ISP,D,ISVS)
      CALL GDCU(NEV,4,ISP,D,IEVS)
      CALL GDCU(NLEG,4,ISP,D,IWS)
      CALL GDCU(NSTA,4,ISP,D,IPS)
      CALL GDCU(NSTA,4,ISP,D,ITS)
      CALL GDCU(NSTA,4,ISP,D,IHS)
      CALL GDCU(NUM,4,ISP,D,IMP)
      CALL GDCU(NSV,4,ISP,D,IME)
      CALL GDCU(NSV,4,ISP,D,IEM)
C*** IF MRD WAS SELECTED, CALL THE SOLNPP COMPONENT
```

```
      IF(MRD.GT.0)CALL SOLNPP
      GO TO 7
    6 DO 51 I=1,NSV
      ID(ISV+I) = 0

      ID(ISVT+I) = 0
      ID(IEV+I) = 0
      ID(IEVT+I) = 0
      ID(ISVS+I) = 0
      ID(IEVS+I) = 0
      ID(IME+I) = 0
      ID(IEM+I) = 0
   51 CONTINUE
      DO 52 I=1,NLEG
      ID(IWS+I) = 0
   52 CONTINUE
      DO 53 I=1,NSTA
      ID(IPS+I) = 0
      ID(ITS+I) = 0
      ID(IHS+I) = 0
   53 CONTINUE
      DO 54 I=1,NUM
      ID(IMP+I) = 0
   54 CONTINUE
    7 CONTINUE
      IFP = 0
      IIOP = 0
      ICONV = -1
C*** IDONE TRACKS THE MRD SOLUTION TO SEE IF IT HAS CONVERGED
      IDONE = 1
C*** PERFORM AN INITIAL SOLUTION TO THE COMPONENTS
                                 TO CORRECT INDATA
      CALL PCOMPP
      DO 42 I=1,NSV
      IF (D(ISV+I).GT.0.0) GO TO 42
      CERR = CERR+1
      CALL LINES(2)
      WRITE (OUT,1006) CERR,I
 1006 FORMAT(6H0ERROR,I6,5X,15HSTATE VARIABLE ,I3,
                               14H INITIAL VALUE)
   42 CONTINUE
      ASSIGN 5 TO IS
      GO TO 100
    5 CONTINUE
      ASSIGN 1 TO IS
      GO TO 102
    1 CONTINUE
      IF (CERR.NE.0) GO TO 99
      IF (NIT.EQ.0) GO TO 99
C*** SET THE WEIGHTING FACTOR = 1 (CHANGED BELOW I
                               F NEWTON-RAPHSON IS USED)
      WT = 1.0
      DO 10 II=1,NIT
      IF (IDS.LT.0) IDS = 2
      IF (IDSS.LT.0 .AND. II.GT.IABS(IDSS)) IDS = 0
```

```
      IF (II.EQ.NIT) IDS = 2
      D(IGA+1) = FLOAT(PASS)
      PASS = PASS+1
       IF (ID(ITAD+NWT).NE.0) WT = TLUP(NWT)
      DO 2 I=1,NSV
      D(ISVS+I) = D(ISV+I)
    2 CONTINUE
      DO 3 I=1,NLEG
    3 D(IWS+I) = D(IW+I)
      DO 4 I=1,NSTA
      D(IPS+I) = D(IP+I)
      D(ITS+I) = D(IT+I)
    4 D(IHS+I) = D(IH+I)
      CALL PCOMPP
      DO 88 I=1,NSV
   88 D(IEVS+I)=D(IEV+I)
      ICONV = 1
C*** START THE SOLUTION PROCESS: EITHER MRD OR NEWTON RAPHSON
  300 KVAR=0
  310 KVAR=KVAR+1
      IF(KVAR.GT.NSV)GO TO 11
      J=KVAR
  312 IF(MRD.GT.0)J=LIST(KVAR)
      IIOP = J
  315 DO 12 K=1,NLEG
   12 D(IW+K) = D(IWS+K)
      DO 13 K=1,NSTA
      D(IP+K) = D(IPS+K)
      D(IT+K) = D(ITS+K)
   13 D(IH+K) = D(IHS+K)
C*** MAKE THE PERTURBATION IN THE STATE VARIABLE
      D(ISV+J) = D(ISVS+J)*PF
C*** SOLVE THE SYSTEM EQUATIONS
      CALL PCOMPP
      DSV = D(ISV+J)-D(ISVS+J)
      IF (CERR.NE.0) GO TO 99
      ASSIGN 22 TO IS
      IF (IDS.EQ.3) GO TO 101
   22 CONTINUE
      ASSIGN 21 TO IS
      IF (IDS.EQ.3) GO TO 102
   21 CONTINUE
      D(ISV+J) = D(ISVS+J)
      DO 14 K=1,NEV
C*** COMPUTE THE DERIVATIVES FROM THE RESULTS OF THE PERTURBATION
      PAR = (D(IEV+K)-D(IEVS+K))/DSV
      CALL MSTO(K,J,PAR)
      CALL MSTO(K,0,D(IEVS+K))
   14 CONTINUE
C*** BRANCH ACCORDING TO WHICH SOLUTION OPTION SELECTED
      IF(MRD.EQ.0.OR.MRD.EQ.3)GO TO 310
      IF(MRD.EQ.1)CALL MRDSOLN,RETURNS(315,330,41)
      IF(MOD(KVAR,2).EQ.0)CALL MRDSOLN,RETURNS(315,330,312)
      IF(KVAR.EQ.NSV)CALL MRDSOLN,RETURNS(315,330,312)
```

```
      D(ISV+J)=D(ISVS+J)
      GO TO 310
   11 IF(MRD.GT.0)CALL MRDSOLN,RETURNS(315,330,312)
C*** SOLVE THE SYSTEM BY THE NEWTON-RAPHSON METHOD
      IF (IDS.GE.2) CALL MPRNT(D(IMP+1),NSV,D(IME+1))
      CALL MCHK(D(IMP+1),NSV,D(IME+1))
      CALL MSOL(D(IMP+1),NSV,D(IME+1),D(IEM+1),IND)
      IF (IND.EQ.1) GO TO 41
      GO TO 40
   41 CONTINUE
      DO 16 J=1,NSV
      D(ISV+J) = D(ISVS+J) + WT*D(IMP+J)
      K = ID(ISVT+J)
      IF (D(ISV+J).LT.SVLL(K)) D(ISV+J) = SVLL(K)
      IF (D(ISV+J).GT.SVUL(K)) D(ISV+J) = SVUL(K)
   16 CONTINUE
  330 IF(IDS.LT.2)GO TO 165
      CALL LINES(2)
      WRITE(OUT,2165)
 2165 FORMAT(7H0ALTERS)
      CALL PARNTH(NSV,D(IMP+1))
C*** RECOMPUTE THE BASE POINT
  165 IIOP=0
      CALL PCOMPP
C*** BRANCH FOR EXTRA PRINTED OUTPUT
      IF (CERR.NE.0) GO TO 99
      ASSIGN 17 TO IS
      IF (IDS.GE.1) GO TO 101
   17 CONTINUE
      ASSIGN 20 TO IS
      IF (IDS.GE.1) GO TO 102
   20 CONTINUE
      ICONV = 0
      DO 15 J=1,NEV
      IF (ABS(D(IEV+J)).GT.ERRL) ICONV = ICONV+1
   15 CONTINUE
      ITER = 0
      IF (ICONV.EQ.0) GO TO 99
C*** IF NOT FINISHED GO BACK AND COMPLETE THE MRD ANALYSIS
      IF(KVAR.LT.NSV)GO TO 310
      IF(MRD.GT.0)ICONV=IDONE
      IF(IDONE.EQ.0)GO TO 99
   10 CONTINUE
   99 CONTINUE
      IDS = IDSS
      RETURN
   40 CONTINUE
      CERR = CERR+1
      CALL LINES(2)
      WRITE (OUT,1009) CERR,PASS
 1009 FORMAT(6H0ERROR,I6,5X,22HSINGULAR MATRIX - PASS,I6)
      GO TO 99
  100 CONTINUE
      CALL LINES(2)
```

```
      WRITE (OUT,1001)
 1001 FORMAT(4H0SVT)
      CALL IPRNTH(NSV,D(ISVT+1))
      CALL LINES(2)
      WRITE (OUT,1002)
 1002 FORMAT(4H0EVT)
      CALL IPRNTH(NEV,D(IEVT+1))
  101 CONTINUE
      CALL LINES(2)
      WRITE (OUT,1003) PASS
 1003 FORMAT(6H0PASS ,I6)
      CALL LINES(2)
      WRITE (OUT,1004)
 1004 FORMAT(5H0S.V.)
      CALL PARNTH(NSV,D(ISV+1))
      GO TO IS, (5,22,17)
  102 CONTINUE
      CALL LINES(2)
      WRITE (OUT,1005)
 1005 FORMAT(5H0E.V.)
      CALL PARNTH(NEV,D(IEV+1))
      CALL LINES(2)
      WRITE (OUT,1101)
 1101 FORMAT(2H0W)
      CALL PAREN(NLEG,D(ILN+1),D(IW+1))
      CALL LINES(2)
      WRITE (OUT,1102)
 1102 FORMAT(2H0P)
      CALL PAREN(NSTA,D(ISN+1),D(IP+1))
      CALL LINES(2)
      WRITE (OUT,1103)
 1103 FORMAT(2H0T)
      CALL PAREN(NSTA,D(ISN+1),D(IT+1))
      CALL LINES(2)
      WRITE (OUT,1104)
 1104 FORMAT(2H0H)
      CALL PAREN(NSTA,D(ISN+1),D(IH+1))
      GO TO IS, (1,20,21)
C     SOLN1
      END
```

Exhibit 16.4-2: Performance-Program Logic and Listing for the SOLN Component

```
      SUBROUTINE SOLNPP
      INTEGER OUT
      COMMON /CC/ C(400)
      EQUIVALENCE (OUT,C(7)),(NSV,C(50))
      COMMON /CCA/ CA(150)
      COMMON /DC/DZ(2),D(2)
      DIMENSION ID(2)
      EQUIVALENCE (ID(1),D(1))
      EQUIVALENCE (LIST(1),CA(11)),(SVSCALE(1),CA(31)),
     *(EVSCALE(1),CA(51)),(DF(1),CA(71)),(DFO(1),CA(91)),
     *(ITER,CA(111)),(RST,CA(112)),(STEP,CA(113)),
     *(ESUM,CA(114)),(DSUM,CA(115)),(SUM,CA(116)),
                          (ITBL50,CA(117)),
     *(ITBL51,CA(118)),(NORD,CA(119)),(KVAR,CA(120
                          )),(IDONE,CA(121))
      DIMENSION LIST(20),DF(20),DFO(20),SVSCALE(20),EVSCALE(20)
C   1 COMP CODE
C   2 SOLUTION OPTION
C   3 STATE VARIABLE SCALE TABLE
C   4 ERROR VARIABLE SCALE TABLE
C   5 STEP
C   6 RST
C   7 STATE VARIABLE SOLUTION ORDER
C  17 NUMBER OF STATE VARIABLE ORDERED
      IF(NORD.EQ.0.OR.NORD.EQ.NSV)GO TO 60
      J=NORD
      DO 30 I=1,NSV
      DO 40 K=1,NSV
C*** SET UP THE ORDER IN WHICH THE STATE VARIABLES ARE TO
C    BE CONSIDERED
      IF(LIST(I).EQ.K)GO TO 30
   40 CONTINUE
      J=J+1
      LIST(J)=I
   30 CONTINUE
C*** SET UP THE STATE AND ERROR VARIABLE SCALE FACTORS
   60 ITL=ITLUP(ITBL50)
      ITM=ITLUP(ITBL51)
      DO 70 I=1,NSV
      SVSCALE(I)=D(ITL+I)
      EVSCALE(I)=D(ITM+I)
   70 CONTINUE
      RETURN
C     SOLNPP
      END
```

Exhibit 16.4-3: Program Logic and Listing for the MRD Subroutine

```
      SUBROUTINE MRDSOLN,RETURNS(M1,M2,M3)
      COMMON /CC/ C(400)
      EQUIVALENCE (IDS,C(5)),(OUT,C(7)),(CERR,C(16
                         )),(PASS,C(17)),
     *(ISVS,C(92)),(NLEG,C(25)),(NSTA,C(26)),(IGA,
                         C(35)),(MRDNIT,C(373))
     *,(ISP,C(42)),(ISVT,C(46)),(ISV,C(47)),(IEVT,C(48))
     *,(IEV,C(49)),(NSV,C(50)),(NEV,C(51)),(IFP,C(
                         22)),(MRD,C(372))
     *, (IW,C(27)), (IP,C(28)), (IT,C(29)), (IH,C(
                         30)), (IMP,C(66))
     *, (IME,C(67)), (ILN,C(37)), (ISN,C(38)), (NI
                         T,C(76)), (PF,C(77))
     *, (NWT,C(78)), (ITAD,C(54)), (SVLL(1),C(181)
                         ), (SVUL(1),C(191))
     *, (ICONV,C(79)), (IIOP,C(90)), (ERRL,C(83)), (BIG,C(31))
      INTEGER OUT, CERR, PASS
      COMMON /CCA/ CA(150)
      EQUIVALENCE (LIST(1),CA(11)),(SVSCALE(1),CA(31)),
     *(EVSCALE(1),CA(51)),(DF(1),CA(71)),(DFO(1),CA(91)),
     *(ITER,CA(111)),(RST,CA(112)),(STEP,CA(113)),(IEVS,CA(122)),
     *(ESUM,CA(114)),(DSUM,CA(115)),(SUM,CA(116)),
                         (ITBL50,CA(117)),
     *(ITBL51,CA(118)),(NORD,CA(119)),(KVAR,CA(120
                         )),(IDONE,CA(121)),
     *(IWS,CA(130)),(IPS,CA(131)),(ITS,CA(132)),(IHS,CA(133))
      DIMENSION LIST(20),DF(20),DFO(20),SVSCALE(20),EVSCALE(20)
      DIMENSION SVLL(10),SVUL(10)
      DIMENSION CD(100)
      EQUIVALENCE (CD(1),C(201))
      EQUIVALENCE (CN,CD(84))
      COMMON /DC/ DZ(2),D(2)
      DIMENSION ID(2)
      EQUIVALENCE (ID(1),D(1))
      IEND=KVAR
      IF(IEND.GT.NSV)IEND=NSV
C*** INITIALIZE AND SELECT THE PATH FOR THE GIVEN MRD OPTION
      ITER=ITER+1
      IBEGIN = 1
      IF(MRD.EQ.1)IBEGIN=IEND
      IF(MRD.EQ.2)IBEGIN=KVAR-1
      IDONE=0
C**** WRITE THE VALUES OFTHE SCALED STATE VARIABLES
      WRITE(OUT,390) (D(ISV+LIST(J))/SVSCALE(LIST(J)),J=1,NSV)
  390 FORMAT(" VALUES OF THE SCALED STATE VARIABLES",/,1X,5E18.7)
C*** WRITE THE VALUES OF THE SCALED ERROR VARIABLES
      WRITE(OUT,396) (-D(IME+LIST(J))/EVSCALE(LIST(J)),J=1,NEV)
  396 FORMAT(" VALUES OF THE SCALED ERROR VARIABLES",/,1X,5E18.7)
      DO 5 J=1,NSV
    5 DF(J)=0.0
C*** COMPUTE THE SUM OF THE SQUARES OF THE RRORS
      ESUM=0.0
      DSUM=0.0
      SUM=0.0
```

```
      DO 20 J=1,NEV
      XX = (D(IME+J)**2)/(EVSCALE(J)**2).
      IF(XX.GT.1.0)IDONE=IDONE+1
   20 ESUM = ESUM + XX
      WRITE(OUT,2031) SQRT(ESUM/NEV)
 2031 FORMAT("  ROOT-MEAN-SQUARE OF THE SCALED ERRORS = ",
     *  E15.7)
C*** COMPUTE DERIVATIVES OF ERROR VARIABLES W.R.T.
                                    STATE VARIABLES
      DO 35 L=IBEGIN,IEND
      J=LIST(L)
      DO 30 K=1,NSV
      I=IMP+(J-1)*NSV
   30 DF(J)=DF(J)+2.*SVSCALE(J)*D(IME+K)*D(I+K)/EVSCALE(K)**2
C*** COMPUTE THE SUM OF THE SQUARES OF THE DERIVATIVES
   35 SUM=SUM+DF(J)**2
C     IF(IDS.LT.2)GO TO 35
      CALL LINES(4)
      WRITE(OUT,300)
  300 FORMAT("0",10X,"DERIVATIVE OF SCALED E.V. WITH RESPECT ",
     * "TO SCALED S.V.")
      WRITE(OUT,305)
  305 FORMAT("0  S.V.     E.V.:",5X,"1",13X,"2",13X
                          ,"3",13X,"4",13X,"5")
      DO 31 L=1,NSV
      I=IMP+(LIST(L)-1)*NSV
      DO 31 II = 1,NEV,5
      JJ=II+4
      IF(JJ.GT.NEV)JJ=NEV
      CALL LINES(1)
      WRITE(OUT,310)LIST(L),II,(D(I+KK)*SVSCALE(LI
                          ST(L))/EVSCALE(KK),
     * KK=II,JJ)
  310 FORMAT(" ",I4,4X,I4,5E14.7)          LIST(L),II,(YY(KK),KK=II,JJ)
   31 CONTINUE
      SDF=SQRT(SUM)
C*** COMPUTE AND SAVE DERIVATIVES DIVIDED BY SQRT
                                   OF SUM OF THEIR SQUARES
      DO 40 L=IBEGIN,IEND
      J=LIST(L)
      DF(J)=DF(J)/SDF
C*** COMPUTE THE DIRECTION COSINE RELATIVE TO THE PREVIOUS STEP
      DSUM=DSUM+DFO(J)*DF(J)
   40 DFO(J)=DF(J)
C*** COMPUTE THE NEW STEP SIZE
      STEP=STEP*RST**DSUM
C*** COMPUTE THE NEW VALUES OF THE STATE VARIABLES
      DO 80 I=IBEGIN,IEND
      J=LIST(I)
      D(ISV+J)=D(ISVS+J)+STEP*SVSCALE(J)*DF(J)
      IF(MRD.NE.3)D(ISVS+J)=D(ISV+J)
      IF(MRD.NE.3) D(IEVS+J)=D(IEV+J)
      K=ID(ISVT+J)
C*** CORRECT THE NEW VALUES SO THEY ARE WITHIN THE
```

```
                                   PERMISSIBLE LIMIS
      IF(D(ISV+J)-SVLL(K))55,55,60
   55 CALL LINES(3)
      WRITE(OUT,100)
  100 FORMAT("0*** WARNING FROM MRD SOLUTION")
      WRITE(OUT,110)J,SVLL(K),D(ISV+J)
  110 FORMAT(" STATE VARIABLE ",I5,"  RESET TO ",E
                                  12.4,"  FROM ",E15.6)
      D(ISV+J)=SVLL(K)
      GO TO 80
   60 IF(D(ISV+J)-SVUL(K))80,80,65
   65 CALL LINES(3)
      WRITE(OUT,100)
      WRITE(OUT,110)J,SVUL(K),D(ISV+J)
      D(ISV+J)=SVUL(K)
   80 CONTINUE
      WRITE(OUT,2032)ITER,STEP,DSUM,(LIST(J),DF(LIST(J)),J=1,NSV)
 2032 FORMAT(" MRD TRIAL NUMBER:",I2,/," SOLN STEP
                                   SIZE = ",E15.7,
     * " DIRECTION COSINE = ",E15.7,/," DERIVATIVES OF THE ",
     * "RMS ERROR WITH RESPECT TO THE SCALED STATE VARIABLES",/,
     * " S.V. NO.      DERIVATIVES",/, 20(I10, E16.7,/))
C*** DEPENDING ON WHICH OPTION IS INVOKED, UPDATE THE STORED BASE
C    POINT OF THE SOLN1 SOLUTION
      IF(MRD.EQ.3)RETURN M2
      DO 2 I=1,NSV
      D(ISVS+I) = D(ISV+I)
    2 CONTINUE
      DO 3 I=1,NLEG
    3 D(IWS+I) = D(IW+I)
      DO 4 I=1,NSTA
      D(IPS+I) = D(IP+I)
      D(ITS+I) = D(IT+I)
    4 D(IHS+I) = D(IH+I)
C*** SOLVE THE SYSTEM EQUATIONS FOR MRD METHODS
      CALL PCOMPP
      DO 88 I=1,NSV
   88 D(IEVS+I)=D(IEV+I)
      IF(ITER.GE.MRDNIT)RETURN M2
      IF(MRD.EQ.1.AND.ITER.EQ.1)RETURN M1
      IF(IDONE.EQ.0)RETURN M2
      IF(MRD.EQ.1)RETURN M1
      IF(MOD(KVAR,2).NE.0)RETURN M3
      KVAR=KVAR-1
      RETURN M3
C     MRDSOLN
```

skipped line

16.5. Program Listing

Exhibits 16.4-1 to 16.4-3, which present the program computational procedure, also are the program listings as used in AECS, except that the comment cards are omitted in the AECS program to conserve computer storage space.

16.6. Sample Case

The sample case, as depicted in Exhibit 4.6-1 (the COP sample case), is based on having a simple refrigeration system, consisting of a compressor, condenser, expansion valve, and an evaporator. The input data are shown in Exhibit 4.6-1 in the required format for AECS, when the solution is to be obtained by the Newton-Raphson procedure (the same computations and the same result will be obtained if SOLN is omitted, because the solution procedure defaults to Newton-Raphson). The output data for the Newton-Raphson technique are shown in Exhibit 4.6-2, starting with Page 7 of the output, the beginning of the computed data. Previous pages contain the headers and a repeat of the input data.

The input data for the MRD2 solution procedure are shown in Exhibit 16.6-1. Note that the state and error variables are numbered sequentially as they are encountered in passing down the component cards. For the example, the first state variable is AK, the CVALVE flow factor. Therefore, AK is state-variable number 1 (see also the last page of the output sheets). The second state variable encountered is the air flow rate through the evaporator, so this flow rate is state variable number 2. The two error variables are at LOOPE: pressure (error variable number 1) and enthalpy (error variable number 2). The state and error variable numbering systems can be used to specify the order in which the MRD procedures search for the minimum error (see the SOLN component card).

The output from the MRD2 method is shown in Exhibit 16.6-2. The progression of the solution is illustrated graphically in Appendix B for the MRD2 and MRD1 methods. The results for MRD would be same as for MRD2 in this two-state-variable case. Although all of the solution techniques were applied to this case, the Newton-Raphson is definitely superior because there is definitely a solution.

16.7. Technical Background

In AECS, the set of error variables, Ei, are functions of the set of state variables, Sj. AECS solves the problem of finding the Sj's that make each of the Ei's zero.

When AECS uses the Newton-Raphson method, it starts with an initial set of state variables, Sj. It then takes 0.1% perturbations in each of the Sj's and observes the changes in the Ei's. The ratio of the changes is treated as a partial derivative, dEi/dSj. These partial derivatives form the matrix seen referenced in the listing. By the

Newton-Raphson linearization procedure, the Taylor series is used such that

```
Ei(Sj') = Ei(Sj) + SUM ( dEi/dSj * (Sj' - Sj) )
                    j
```

Because we want the errors, Ei(Sj'), to be zero, we select the Sj' as the solution to the system of equations:

```
SUM ( dEi/dSj * (Sj' - Sj) ) = - Ei(Sj)
 j
```

The Sj' then are used as a new set of "initial" state variables and the process is repeated until the errors are acceptably small.

In the MRD method, the step direction is obtained by differentiating the root-mean-square of the error variables, Ei(Sj'). The MRD method maximizes the change in the RMS value of the Ei, subject to the constraint that the step size, STEP, is specified. STEP is given by:

```
STEP = SQRT(  SUM( ((Sj' - Sj)/Wsj)**2 )  ) / NSV  )
               j
```

where NSV is the number of state variables. NSV is introduced so STEP can be interpreted as the fractional distance across the diagonal of the space of state variables. The RMS error is given by:

```
RMS  = SQRT(  SUM( (Ei/Wei)**2 ) / NEV  )
               i
```

In these equations, Wsj represents the weighting factor for state-variable j and Wei, for error-variable i. Note that the weighting factors make the sums dimensionless.

The change in RMS for a infinitesimal change in the Sj's is obtained by differentiating RMS with respect to the Sj's:

```
RMS * dRMS/dSj = SUM( Ei * dEi/dSj / Wei**2 ) / NEV
                  i
```

Then a Taylor-series expansion yields

```
RMS' = RMS + SUM( dRMS/dSj * (Sj' - Sj) )
              j
```

This equation for RMS' is next differentiated with respect to Sj'-Sj, subject to the constraint that STEP is fixed. Lagrange multipliers can make this process relatively simple. The result is that the Sj' should be chosen from the formula:

```
Sj' = Sj - STEP * Wsj**2 * dRMS/dSj / SS
```

where

```
SS = SQRT(   SUM(  (Wsj * dRMS/dSj)**2  )   )
              j
```

In the AECS version of the MRD methods, the step size is adjusted automatically according to the direction of two successive steps. The cosine of the angle between successive steps is given by:

```
     DSUM = SUM( (Sj'' - Sj')*(Sj' - Sj) / Wsj**2 )
             j
```

and the new step size is computed from

```
     STEP = STEP * RST**DSUM
```

where RST is an input parameter, normally equal to 1.5.

This same theory, although derived for the multi-dimensional MRD procedure, can be applied in one dimension or in sequence in many dimensions. For example, it can be applied first with two of the Sj's and then with another two, etc., as needed for MRD2. Therefore, the foregoing gives the complete theory on which SOLN is based.

Exhibit 16.6-1: Input Cards for the Sample Case

```
PERFORM
TITLE   REFRIGERANT TEST CASE - MRD2
CASEA    R22-01   0000    3    9    0
CASEB       0    0    0    0    0
CASEC       0.0           0.0          0.0
CASED       0.0
PARAM    22
VALUES    1      0.43      92.0       519.7       111.20     10000.
VALUES    6      3.26      0.85        4.0        14.7       540.0
VALUES   11       0.0     0.001        1.0       1119.0        1.8
VALUES   16      14.7     540.0       0.015       11.0        0.01
VALUES   21      0.05      1.5
LOOPS       10   1    1    1    5    3 -220000    1    2    3    4
SHAFT       20   1    0    5
VCOMP       30   1    1    2    1    0    6    1   72    7    0
INLET       40   2  210000   8    9   10   11    2   -1
COND        50   1    2    3    2   21   22    0    1    2    3   12
CVALVE      60   1    3    4    0   13   14
INLET       70   3  311000  15   16   17   18    2   -1
EVAP        80   1    4    5    3   31   32    0    4    5   19    6   20    0
LOOPE       90   1    1    1    50101
COP        100   1    1    4    1
SOLN       110   2    1    2   21   22    1    2
TABID       72   6   33    0    0  280001    2    0 101 101    2
TABT       VCOMP: EFFICIENCY = F(FLOW RATE,SHAFT SPEED)
TABV       0.0        1.0
TABV       0.0          11.0
TABV       1000.        11000.
TABV        0.85       0.85        0.85        0.85
TABID        1    1    2    0    0  410001    2
TABT       AIR SIDE PRESS DROP T=1 RN=1 (IND.VAR.=AIR FLOW)
TABV          0.0          0.0         30.0        1.0
TABID        2    5    2    0    0  410001    2
TABT       AIR SIDE EFFECTIVENESS T=5 RN=2 (IND.VAR.=AIR FLOW)
TABV          0.0          1.0         30.0        0.5
TABID        3    1    2    0    0  420001    2
TABT       REFRIG SIDE PRESS DROP T=1 RN=3 (IND.VAR.=REFRIG FLOW)
TABV          0.0          0.0          2.0        6.0
TABID        4    1    2    0    0  410001    2
TABT       AIR SIDE PRESS DROP T=1 RN=1 (IND VAR = AIR FLOW)
TABV         0.0        0.0          5.0         0.1
TABID        5    5    2    0    0  410001    2
TABT       AIR SIDE BYPASS FACTOR T=5 RN=2 (IND VAR = AIR FLOW)
TABV         0.0        0.0          5.0         0.3
TABID        6    2    2    0    0  420001    2
TABT       REFRIG SIDE PRESS DROP T=1 RN=3 (IND VAR = )
TABV         0.0        0.0          1.0        10.0
TABID        1   50   -1    0    0   00000    2
TABT       SCALE FACTORS FOR STATE VARIABLES
TABV       40.          1.0
TABID        2   51   -1    0    0   00000    2
TABT       SCALE FACTORS FOR ERROR VARIABLES
TABV         0.1        0.1
ENDCASE
ENDJOB
```

Exhibit 16.6-2: AECS Output for the Sample Case Solved with MRD2

```
THE FOLLOWING LISTING IS FOR FILE   MRD2 EXAMPLE


PASS       1

S.V.
(    1) 1.11900E+03 (    2) 1.80000E+00

E.V.
(    1) 6.91362E-01 (    2) 1.12942E+01

W
(    1) 4.30000E-01 (    2) 4.00000E+00 (    3) 1.80000E+00

P
(    1) 9.20000E+01 (    5) 9.13086E+01 (    2) 2.99920E+02 (   21) 1.47000E+01 (    3) 2.99774E+02 (   22) 1.45667E+01
(    4) 9.28708E+01 (   31) 1.47000E+01 (   32) 1.46640E+01

T
(    1) 5.19883E+02 (    5) 5.06065E+02 (    2) 6.45909E+02 (   21) 5.40000E+02 (    3) 5.44285E+02 (   22) 5.83541E+02
(    4) 5.06065E+02 (   31) 5.40000E+02 (   32) 5.09730E+02

H
(    1) 1.11200E+02 (    5) 9.99058E+01 (    2) 1.26804E+02 (   21) 0.            (    3) 3.48313E+01 (   22) 0.
(    4) 3.48313E+01 (   31) 1.50000E-02 (   32) 7.36521E-03
VALUES OF THE SCALED STATE VARIABLES
      .2797500E+02      .1800000E+01
VALUES OF THE SCALED ERROR VARIABLES
      .6913617E+01      .1129420E+03
 ROOT-MEAN-SQUARE OF THE SCALED ERRORS =     .8001154E+02

          DERIVATIVE OF SCALED E.V. WITH RESPECT TO SCALED S.V.

  S.V.    E.V.:     1             2             3             4             5
   1        1   .7633967E+02 -.8742862E+02
   2        1   .3760735E+01 -.3179829E+03
MRD TRIAL NUMBER: 1
SOLN STEP SIZE =     .5000000E-01 DIRECTION COSINE =    0.
DERIVATIVES OF THE RMS ERROR WITH RESPECT TO THE SCALED STATE VARIABLES
S.V. NO.      DERIVATIVES
     1        .2520328E+00
     2        .9677187E+00

VALUES OF THE SCALED STATE VARIABLES
      .2798760E+02      .1848386E+01
VALUES OF THE SCALED ERROR VARIABLES
      .8057043E+01      .9648276E+02
 ROOT-MEAN-SQUARE OF THE SCALED ERRORS =     .6846108E+02

          DERIVATIVE OF SCALED E.V. WITH RESPECT TO SCALED S.V.

  S.V.    E.V.:     1             2             3             4             5
   1        1   .7637788E+02 -.8947296E+02
   2        1   .3729781E+01 -.3161763E+03
```

```
MRD TRIAL NUMBER: 2
SOLN STEP SIZE =     .7499991E-01 DIRECTION COSINE =     .9999970E+00
DERIVATIVES OF THE RMS ERROR WITH RESPECT TO THE SCALED STATE VARIABLES
S.V. NO.     DERIVATIVES
       1    .2544146E+00
       2    .9670952E+00

VALUES OF THE SCALED STATE VARIABLES
     .2800668E+02      .1920918E+01
VALUES OF THE SCALED ERROR VARIABLES
     .9784027E+01      .7190828E+02
 ROOT-MEAN-SQUARE OF THE SCALED ERRORS =     .5131534E+02

          DERIVATIVE OF SCALED E.V. WITH RESPECT TO SCALED S.V.

  S.V.     E.V.:     1              2              3              4              5
   1         1  .7643748E+02 -.9250759E+02
   2         1  .3692022E+01 -.3134608E+03
MRD TRIAL NUMBER: 3
SOLN STEP SIZE =     .1124999E+00 DIRECTION COSINE =     .9999998E+00
DERIVATIVES OF THE RMS ERROR WITH RESPECT TO THE SCALED STATE VARIABLES
S.V. NO.     DERIVATIVES
       1    .2537701E+00
       2    .9672646E+00

VALUES OF THE SCALED STATE VARIABLES
     .2803523E+02      .2029735E+01
VALUES OF THE SCALED ERROR VARIABLES
     .1236731E+02      .3531068E+02
 ROOT-MEAN-SQUARE OF THE SCALED ERRORS =     .2645557E+02

          DERIVATIVE OF SCALED E.V. WITH RESPECT TO SCALED S.V.

  S.V.     E.V.:     1              2              3              4              5
   1         1  .7653588E+02 -.9699378E+02
   2         1  .3663495E+01 -.3093490E+03
MRD TRIAL NUMBER: 1
SOLN STEP SIZE =     .1687135E+00 DIRECTION COSINE =     .9994698E+00
DERIVATIVES OF THE RMS ERROR WITH RESPECT TO THE SCALED STATE VARIABLES
S.V. NO.     DERIVATIVES
       1    .2221407E+00
       2    .9750146E+00

VALUES OF THE SCALED STATE VARIABLES
     .2807271E+02      .2194233E+01
VALUES OF THE SCALED ERROR VARIABLES
     .1530667E+02     -.1881072E+02
 ROOT-MEAN-SQUARE OF THE SCALED ERRORS =     .1714843E+02
```



```
          DERIVATIVE OF SCALED E.V. WITH RESPECT TO SCALED S.V.

  S.V.     E.V.:     1              2              3              4              5
```

```
  1        1  .7535606E+02 -.1036327E+03
  2        1 0.            -.3028266E+03
MRD TRIAL NUMBER: 2
SOLN STEP SIZE =     .1141994E+00 DIRECTION COSINE =    -.9624903E+00
DERIVATIVES OF THE RMS ERROR WITH RESPECT TO THE SCALED STATE VARIABLES
S.V. NO.      DERIVATIVES
        1    -.4783454E+00
        2    -.8781718E+00

VALUES OF THE SCALED STATE VARIABLES
      .2801808E+02       .2093947E+01
VALUES OF THE SCALED ERROR VARIABLES
      .1119070E+02       .1725337E+02
 ROOT-MEAN-SQUARE OF THE SCALED ERRORS =     .1454150E+02

          DERIVATIVE OF SCALED E.V. WITH RESPECT TO SCALED S.V.

  S.V.     E.V.:     1             2             3             4             5
   1        1  .7534447E+02 -.9965431E+02
   2        1 0.            -.3055153E+03
MRD TRIAL NUMBER: 3
SOLN STEP SIZE =     .7785854E-01 DIRECTION COSINE =    -.9447229E+00
DERIVATIVES OF THE RMS ERROR WITH RESPECT TO THE SCALED STATE VARIABLES
S.V. NO.      DERIVATIVES
        1     .1639779E+00
        2     .9864640E+00

VALUES OF THE SCALED STATE VARIABLES
      .2803085E+02       .2170751E+01
VALUES OF THE SCALED ERROR VARIABLES
      .1215261E+02      -.7384242E+01
 ROOT-MEAN-SQUARE OF THE SCALED ERRORS =     .1005517E+02

          DERIVATIVE OF SCALED E.V. WITH RESPECT TO SCALED S.V.

  S.V.     E.V.:     1             2             3             4             5
   1        1  .7534716E+02 -.1027520E+03
   2        1 0.            -.3022905E+03
MRD TRIAL NUMBER: 1
SOLN STEP SIZE =     .5432770E-01 DIRECTION COSINE =    -.8875223E+00
DERIVATIVES OF THE RMS ERROR WITH RESPECT TO THE SCALED STATE VARIABLES
S.V. NO.      DERIVATIVES
        1    -.6000619E+00
        2    -.7999536E+00

VALUES OF THE SCALED STATE VARIABLES
      .2799825E+02       .2127292E+01
VALUES OF THE SCALED ERROR VARIABLES
      .9696498E+01       .9095412E+01
 ROOT-MEAN-SQUARE OF THE SCALED ERRORS =     .9400760E+01

          DERIVATIVE OF SCALED E.V. WITH RESPECT TO SCALED S.V.

  S.V.     E.V.:     1             2             3             4             5
   1        1  .7534030E+02 -.1010427E+03
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  2       1 0.               -.3030860E+03
MRD TRIAL NUMBER: 2
SOLN STEP SIZE =    .3866131E-01 DIRECTION COSINE =   -.8390237E+00
DERIVATIVES OF THE RMS ERROR WITH RESPECT TO THE SCALED STATE VARIABLES
S.V. NO.      DERIVATIVES
        1     .6821546E-01
        2     .9976706E+00

VALUES OF THE SCALED STATE VARIABLES
      .2800089E+02       .2165863E+01
VALUES OF THE SCALED ERROR VARIABLES
      .9895186E+01      -.2831531E+01
 ROOT-MEAN-SQUARE OF THE SCALED ERRORS =     .7277784E+01

          DERIVATIVE OF SCALED E.V. WITH RESPECT TO SCALED S.V.

  S.V.     E.V.:     1             2             3             4             5
   1        1  .7534085E+02 -.1026011E+03
   2        1 0.              -.3013193E+03
MRD TRIAL NUMBER: 3
SOLN STEP SIZE =    .2926327E-01 DIRECTION COSINE =   -.6868814E+00
DERIVATIVES OF THE RMS ERROR WITH RESPECT TO THE SCALED STATE VARIABLES
S.V. NO.      DERIVATIVES
        1    -.7719325E+00
        2    -.6357045E+00

VALUES OF THE SCALED STATE VARIABLES
      .2797830E+02       .2147260E+01
VALUES OF THE SCALED ERROR VARIABLES
      .8193411E+01       .5084802E+01
 ROOT-MEAN-SQUARE OF THE SCALED ERRORS =     .6818621E+01

          DERIVATIVE OF SCALED E.V. WITH RESPECT TO SCALED S.V.

  S.V.     E.V.:     1             2             3             4             5
   1        1  .7533612E+02 -.1018837E+03
   2        1 0.              -.3013079E+03
MRI TRIAL NUMBER: 1
SOLN STEP SIZE =    .2308860E-01 DIRECTION COSINE =   -.5844988E+00
DERIVATIVES OF THE RMS ERROR WITH RESPECT TO THE SCALED STATE VARIABLES
S.V. NO.      DERIVATIVES
        1    -.6461357E-01
        2     .9979104E+00

VALUES OF THE SCALED STATE VARIABLES
      .2797681E+02       .2170300E+01
VALUES OF THE SCALED ERROR VARIABLES
      .8081026E+01      -.1692369E+01
 ROOT-MEAN-SQUARE OF THE SCALED ERRORS =     .5838112E+01

          DERIVATIVE OF SCALED E.V. WITH RESPECT TO SCALED S.V.

  S.V.     E.V.:     1             2             3             4             5
   1        1  .7533581E+02 -.1028179E+03
   2        1 0.              -.3001317E+03
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MRD TRIAL NUMBER: 2
SOLN STEP SIZE =    .1893617E-01 DIRECTION COSINE =   -.4889820E+00
DERIVATIVES OF THE RMS ERROR WITH RESPECT TO THE SCALED STATE VARIABLES
S.V. NO.      DERIVATIVES
        1   -.8388762E+00
        2   -.5443222E+00

VALUES OF THE SCALED STATE VARIABLES
      .2796092E+02      .2159993E+01
VALUES OF THE SCALED ERROR VARIABLES
      .6884381E+01      .3031519E+01
 ROOT-MEAN-SQUARE OF THE SCALED ERRORS =    .5319061E+01

          DERIVATIVE OF SCALED E.V. WITH RESPECT TO SCALED S.V.

  S.V.    E.V.:     1            2            3            4            5
   1        1  .7533250E+02 -.1024264E+03
   2        1 0.            -.2999884E+03
MRD TRIAL NUMBER: 3
SOLN STEP SIZE =    .1647438E-01 DIRECTION COSINE =   -.3434766E+00
DERIVATIVES OF THE RMS ERROR WITH RESPECT TO THE SCALED STATE VARIABLES
S.V. NO.      DERIVATIVES
        1   -.2230719E+00
        2    .9748020E+00

VALUES OF THE SCALED STATE VARIABLES
      .2795725E+02      .2176052E+01
VALUES OF THE SCALED ERROR VARIABLES
      .6607549E+01     -.1401791E+01
 ROOT-MEAN-SQUARE OF THE SCALED ERRORS =    .4776228E+01

          DERIVATIVE OF SCALED E.V. WITH RESPECT TO SCALED S.V.

  S.V.    E.V.:     1            2            3            4            5
   1        1  .7533174E+02 -.1030809E+03
   2        1 0.            -.2990641E+03
MRD TRIAL NUMBER: 1
SOLN STEP SIZE =    .1431781E-01 DIRECTION COSINE =   -.3460274E+00
DERIVATIVES OF THE RMS ERROR WITH RESPECT TO THE SCALED STATE VARIABLES
S.V. NO.      DERIVATIVES
        1   -.8373940E+00
        2   -.5465997E+00

VALUES OF THE SCALED STATE VARIABLES
      .2794526E+02      .2168226E+01
VALUES OF THE SCALED ERROR VARIABLES
      .5704397E+01      .2173102E+01
 ROOT-MEAN-SQUARE OF THE SCALED ERRORS =    .4316394E+01

          DERIVATIVE OF SCALED E.V. WITH RESPECT TO SCALED S.V.

  S.V.    E.V.:     1            2            3            4            5
   1        1  .7532925E+02 -.1027839E+03
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   2       1 0.              -.2989578E+03
MRD TRIAL NUMBER: 2
SOLN STEP SIZE =    .1284634E-01 DIRECTION COSINE =   -.2674581E+00
DERIVATIVES OF THE RMS ERROR WITH RESPECT TO THE SCALED STATE VARIABLES
S.V. NO.     DERIVATIVES
       1   -.3027190E+00
       2    .9530799E+00

VALUES OF THE SCALED STATE VARIABLES
      .2794137E+02      .2180470E+01
VALUES OF THE SCALED ERROR VARIABLES
      .5411467E+01     -.1082512E+01
 ROOT-MEAN-SQUARE OF THE SCALED ERRORS =    .3902295E+01

          DERIVATIVE OF SCALED E.V. WITH RESPECT TO SCALED S.V.

  S.V.    E.V.:     1             2             3             4             5
   1        1  .7532844E+02 -.1032843E+03
   2        1 0.              -.2982105E+03
MRD TRIAL NUMBER: 3
SOLN STEP SIZE =    .1162702E-01 DIRECTION COSINE =   -.2459595E+00
DERIVATIVES OF THE RMS ERROR WITH RESPECT TO THE SCALED STATE VARIABLES
S.V. NO.     DERIVATIVES
       1   -.8493447E+00
       2   -.5278385E+00

VALUES OF THE SCALED STATE VARIABLES
      .2793149E+02      .2174333E+01

VALUES OF THE SCALED ERROR VARIABLES
      .4667611E+01      .1766712E+01
 ROOT-MEAN-SQUARE OF THE SCALED ERRORS =    .3529013E+01

          DERIVATIVE OF SCALED E.V. WITH RESPECT TO SCALED S.V.

  S.V.    E.V.:     1             2             3             4             5
   1        1  .7532640E+02 -.1030524E+03
   2        1 0.              -.2981077E+03
MRD TRIAL NUMBER: 1
SOLN STEP SIZE =    .1053946E-01 DIRECTION COSINE =   -.2422036E+00
DERIVATIVES OF THE RMS ERROR WITH RESPECT TO THE SCALED STATE VARIABLES
S.V. NO.     DERIVATIVES
       1   -.3064080E+00
       2    .9519003E+00

VALUES OF THE SCALED STATE VARIABLES
      .2792826E+02      .2184365E+01
VALUES OF THE SCALED ERROR VARIABLES
      .4424365E+01     -.8879783E+00
 ROOT-MEAN-SQUARE OF THE SCALED ERRORS =    .3190886E+01

          DERIVATIVE OF SCALED E.V. WITH RESPECT TO SCALED S.V.

  S.V.    E.V.:     1             2             3             4             5
   1        1  .7532574E+02 -.1034623E+03
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  2        1 0.             -.2974946E+03
MRD TRIAL NUMBER: 2
SOLN STEP SIZE =    .9553894E-02 DIRECTION COSINE =   -.2421351E+00
DERIVATIVES OF THE RMS ERROR WITH RESPECT TO THE SCALED STATE VARIABLES
S.V. NO.     DERIVATIVES
       1   -.8493820E+00
       2   -.5277785E+00

VALUES OF THE SCALED STATE VARIABLES
     .2792015E+02      .2179323E+01
VALUES OF THE SCALED ERROR VARIABLES
     .3813133E+01      .1451139E+01
 ROOT-MEAN-SQUARE OF THE SCALED ERRORS =    .2884943E+01

        DERIVATIVE OF SCALED E.V. WITH RESPECT TO SCALED S.V.

 S.V.    E.V.:     1            2            3            4            5
  1        1  .7532406E+02 -.1032720E+03
  2        1 0.             -.2974098E+03
MRD TRIAL NUMBER: 3
SOLN STEP SIZE =    .8649305E-02 DIRECTION COSINE =   -.2453229E+00
DERIVATIVES OF THE RMS ERROR WITH RESPECT TO THE SCALED STATE VARIABLES
S.V. NO.     DERIVATIVES
       1   -.3032775E+00
       2    .9529023E+00

VALUES OF THE SCALED STATE VARIABLES
     .2791753E+02      .2187565E+01
VALUES OF THE SCALED ERROR VARIABLES
     .3615556E+01     -.7270625E+00
 ROOT-MEAN-SQUARE OF THE SCALED ERRORS =    .2607764E+01

        DERIVATIVE OF SCALED E.V. WITH RESPECT TO SCALED S.V.

 S.V.    E.V.:     1            2            3            4            5
  1        1  .7532352E+02 -.1036085E+03
  2        1 0.             -.2969080E+03
MRD TRIAL NUMBER: 1
SOLN STEP SIZE =    .7831374E-02 DIRECTION COSINE =   -.2450051E+00
DERIVATIVES OF THE RMS ERROR WITH RESPECT TO THE SCALED STATE VARIABLES
S.V. NO.     DERIVATIVES
       1   -.8495550E+00
       2   -.5275001E+00

VALUES OF THE SCALED STATE VARIABLES
     .2791087E+02      .2183434E+01
VALUES OF THE SCALED ERROR VARIABLES
     .3114439E+01      .1188511E+01
 ROOT-MEAN-SQUARE OF THE SCALED ERRORS =    .2357147E+01

        DERIVATIVE OF SCALED E.V. WITH RESPECT TO SCALED S.V.

 S.V.    E.V.:     1            2            3            4            5
  1        1  .7532215E+02 -.1034528E+03
  2        1 0.             -.2968382E+03
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MRD TRIAL NUMBER: 2
SOLN STEP SIZE =     .7086116E-02 DIRECTION COSINE =   -.2466318E+00
DERIVATIVES OF THE RMS ERROR WITH RESPECT TO THE SCALED STATE VARIABLES
S.V. NO.      DERIVATIVES
        1   -.3016780E+00
        2    .9534099E+00

VALUES OF THE SCALED STATE VARIABLES
      .2790873E+02       .2190190E+01
VALUES OF THE SCALED ERROR VARIABLES
      .2953427E+01      -.5943916E+00
 ROOT-MEAN-SQUARE OF THE SCALED ERRORS =     .2130262E+01

          DERIVATIVE OF SCALED E.V. WITH RESPECT TO SCALED S.V.

  S.V.    E.V.:     1             2             3             4             5
   1        1  .7532171E+02 -.1037285E+03
   2        1 0.            -.2964278E+03
MRD TRIAL NUMBER: 3
SOLN STEP SIZE =     .6413157E-02 DIRECTION COSINE =   -.2461020E+00
DERIVATIVES OF THE RMS ERROR WITH RESPECT TO THE SCALED STATE VARIABLES
S.V. NO.      DERIVATIVES
        1   -.8498432E+00
        2   -.5270356E+00

VALUES OF THE SCALED STATE VARIABLES
      .2790328E+02       .2186810E+01
VALUES OF THE SCALED ERROR VARIABLES
      .2542929E+01       .9727185E+00
 ROOT-MEAN-SQUARE OF THE SCALED ERRORS =     .1925184E+01

          DERIVATIVE OF SCALED E.V. WITH RESPECT TO SCALED S.V.

  S.V.    E.V.:     1             2             3             4             5
   1        1  .7532059E+02 -.1036011E+03
   2        1 0.            -.2963703E+03
MRD TRIAL NUMBER: 1
SOLN STEP SIZE =     .5800807E-02 DIRECTION COSINE =   -.2475049E+00
DERIVATIVES OF THE RMS ERROR WITH RESPECT TO THE SCALED STATE VARIABLES
S.V. NO.      DERIVATIVES
        1   -.3002974E+00
        2    .9538456E+00

VALUES OF THE SCALED STATE VARIABLES
      .2790154E+02       .2192343E+01
VALUES OF THE SCALED ERROR VARIABLES
      .2411728E+01      -.4857767E+00
 ROOT-MEAN-SQUARE OF THE SCALED ERRORS =     .1739600E+01

          DERIVATIVE OF SCALED E.V. WITH RESPECT TO SCALED S.V.

  S.V.    E.V.:     1             2             3             4             5
   1        1  .7532024E+02 -.1038269E+03
   2        1 0.            -.2960349E+03
MRD TRIAL NUMBER: 2
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SOLN STEP SIZE =     .5247724E-02 DIRECTION COSINE =    -.2471297E+00
DERIVATIVES OF THE RMS ERROR WITH RESPECT TO THE SCALED STATE VARIABLES
S.V. NO.        DERIVATIVES
         1    -.8500474E+00
         2    -.5267065E+00

VALUES OF THE SCALED STATE VARIABLES
      .2789708E+02       .2189579E+01
VALUES OF THE SCALED ERROR VARIABLES
      .2075754E+01       .7955681E+00
 ROOT-MEAN-SQUARE OF THE SCALED ERRORS =     .1571891E+01
*AECS*  REFRIGERANT TEST CASE
    1  CASE R22-01


          DERIVATIVE OF SCALED E.V. WITH RESPECT TO SCALED S.V.

  S.V.     E.V.:     1             2             3             4             5
   1        1  .7531932E+02 -.1037228E+03
   2        1 0.            -.2959876E+03
MRD TRIAL NUMBER: 3
SOLN STEP SIZE =     .4745146E-02 DIRECTION COSINE =    -.2482882E+00
DERIVATIVES OF THE RMS ERROR WITH RESPECT TO THE SCALED STATE VARIABLES
S.V. NO.        DERIVATIVES
         1    -.2991566E+00
         2     .9542040E+00

VALUES OF THE SCALED STATE VARIABLES
      .2789566E+02       .2194107E+01
VALUES OF THE SCALED ERROR VARIABLES
      .1960039E+01      -.3960307E+00
 ROOT-MEAN-SQUARE OF THE SCALED ERRORS =     .1420176E+01

          DERIVATIVE OF SCALED E.V. WITH RESPECT TO SCALED S.V.

  S.V.     E.V.:     1             2             3             4             5
   1        1  .7531903E+02 -.1039075E+03
   2        1 0.            -.2957135E+03
MRD TRIAL NUMBER: 1
SOLN STEP SIZE =     .4291248E-02 DIRECTION COSINE =    -.2479737E+00
DERIVATIVES OF THE RMS ERROR WITH RESPECT TO THE SCALED STATE VARIABLES
S.V. NO.        DERIVATIVES
         1    -.8502182E+00
         2    -.5264304E+00

VALUES OF THE SCALED STATE VARIABLES
      .2789201E+02       .2191848E+01
VALUES OF THE SCALED ERROR VARIABLES
      .1694050E+01       .6503080E+00
 ROOT-MEAN-SQUARE OF THE SCALED ERRORS =     .1283103E+01

          DERIVATIVE OF SCALED E.V. WITH RESPECT TO SCALED S.V.

  S.V.     E.V.:     1             2             3             4             5
   1        1  .7531828E+02 -.1038225E+03
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  2       1 0.             -.2954740E+03
MRD TRIAL NUMBER: 2
SOLN STEP SIZE =     .3879280E-02 DIRECTION COSINE =    -.2489192E+00
DERIVATIVES OF THE RMS ERROR WITH RESPECT TO THE SCALED STATE VARIABLES
S.V. NO.      DERIVATIVES
        1    -.2982250E+00
        2     .9544956E+00

VALUES OF THE SCALED STATE VARIABLES
      .2789086E+02       .2195550E+01
VALUES OF THE SCALED ERROR VARIABLES
      .1606917E+01      -.3240577E+00
 ROOT-MEAN-SQUARE OF THE SCALED ERRORS =     .1159137E+01

          DERIVATIVE OF SCALED E.V. WITH RESPECT TO SCALED S.V.

  S.V.     E.V.:     1             2             3             4             5
   1         1  .7531805E+02 -.1039735E+03
   2         1 0.            -.2954509E+03
MRD TRIAL NUMBER: 3
SOLN STEP SIZE =     .3507228E-02 DIRECTION COSINE =    -.2486612E+00
DERIVATIVES OF THE RMS ERROR WITH RESPECT TO THE SCALED STATE VARIABLES
S.V. NO.      DERIVATIVES
        1    -.8503585E+00
        2    -.5262039E+00

VALUES OF THE SCALED STATE VARIABLES
      .2788787E+02       .2193705E+01
VALUES OF THE SCALED ERROR VARIABLES
      .1382298E+01       .5313247E+00
 ROOT-MEAN-SQUARE OF THE SCALED ERRORS =     .1047152E+01

          DERIVATIVE OF SCALED E.V. WITH RESPECT TO SCALED S.V.

  S.V.     E.V.:     1             2             3             4             5
   1         1  .7531744E+02 -.1039040E+03
   2         1 0.            -.2954192E+03
MRD TRIAL NUMBER: 1
SOLN STEP SIZE =     .3169864E-02 DIRECTION COSINE =    -.2494353E+00
DERIVATIVES OF THE RMS ERROR WITH RESPECT TO THE SCALED STATE VARIABLES
S.V. NO.      DERIVATIVES
        1    -.2974619E+00
        2     .9547337E+00

VALUES OF THE SCALED STATE VARIABLES
      .2788693E+02       .2196731E+01
VALUES OF THE SCALED ERROR VARIABLES
      .1311283E+01      -.2645549E+00
 ROOT-MEAN-SQUARE OF THE SCALED ERRORS =     .9458997E+00

          DERIVATIVE OF SCALED E.V. WITH RESPECT TO SCALED S.V.

  S.V.     E.V.:     1             2             3             4             5
   1         1  .7531724E+02 -.1040274E+03
   2         1 0.            -.2952364E+03
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MRD TRIAL NUMBER: 2
SOLN STEP SIZE =     .2865197E-02 DIRECTION COSINE =    -.2492240E+00
DERIVATIVES OF THE RMS ERROR WITH RESPECT TO THE SCALED STATE VARIABLES
S.V. NO.      DERIVATIVES
        1   -.8504733E+00
        2   -.5260183E+00

VALUES OF THE SCALED STATE VARIABLES
      .2788449E+02       .2195224E+01
VALUES OF THE SCALED ERROR VARIABLES
      .1127760E+01       .4339468E+00
 ROOT-MEAN-SQUARE OF THE SCALED ERRORS =      .8544447E+00

          DERIVATIVE OF SCALED E.V. WITH RESPECT TO SCALED S.V.

  S.V.    E.V.:     1             2             3             4             5
   1        1  .7531675E+02 -.1039707E+03
   2        1 0.               -.2952104E+03
MRD TRIAL NUMBER: 3
SOLN STEP SIZE =     .2589148E-02 DIRECTION COSINE =    -.2498570E+00
DERIVATIVES OF THE RMS ERROR WITH RESPECT TO THE SCALED STATE VARIABLES
S.V. NO.      DERIVATIVES
        1   -.2968377E+00
        2    .9549279E+00

VALUES OF THE SCALED STATE VARIABLES
      .2788373E+02       .2197696E+01
VALUES OF THE SCALED ERROR VARIABLES
      .1069877E+01      -.2159277E+00
 ROOT-MEAN-SQUARE OF THE SCALED ERRORS =      .7717709E+00

          DERIVATIVE OF SCALED E.V. WITH RESPECT TO SCALED S.V.

  S.V.    E.V.:     1             2             3             4             5
   1        1  .7531659E+02 -.1040715E+03
   2        1 0.               -.2950612E+03
MRD TRIAL NUMBER: 1
SOLN STEP SIZE =     .2339859E-02 DIRECTION COSINE =    -.2496839E+00
DERIVATIVES OF THE RMS ERROR WITH RESPECT TO THE SCALED STATE VARIABLES
S.V. NO.      DERIVATIVES
        1   -.8505673E+00
        2   -.5258663E+00

VALUES OF THE SCALED STATE VARIABLES
      .2788174E+02       .2196466E+01
VALUES OF THE SCALED ERROR VARIABLES
      .9199870E+00       .3543062E+00
 ROOT-MEAN-SQUARE OF THE SCALED ERRORS =      .6971043E+00

          DERIVATIVE OF SCALED E.V. WITH RESPECT TO SCALED S.V.

  S.V.    E.V.:     1             2             3             4             5
   1        1  .7531618E+02 -.1040252E+03
   2        1 0.               -.2950399E+03
MRD TRIAL NUMBER: 2
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B.. N     IZE =    .21141.9E-02 DIRECTION COSINE =    -.2502...
DERIVAT...S OF THE RMS ERROR WITH RESPECT TO THE SCALED STATE VARIABLES
S.V. NO.      DERIVATIVES
       1    -.2963275E+00
       2     .9550864E+00

COMPONENT SHAFT

     SHAFT     1    N    10000.
*AECS*  REFRIGERANT TEST CASE
    1  CASE R22-01

COMPONENT VCOMP

     NL         1   NSI       1   NSO       2   FT        3   FN      -22

     W        .43   PI    92.00   PO   299.92   TI   519.88   TO   645.91   HI111.2000   HO126.8038

     NL********     NSI       3   NSO       2   FT        0   FN        0

     W       0.00   PI     2.20   PO   299.92   TI    14.66   TO   645.91   HI510.9221   HO126.8038

     SHAFT      1   PR   3.2600   EFF   .8500   HP     -.19
COMPONENT COND

     NL         1   NSI       2   NSO       3   FT        3   FN      -22

     W        .43   PI   299.92   PO   299.77   TI   645.91   TO   544.29   HI126.8038   HO 34.8313

     NL         2   NSI      21   NSO      22   FT        2   FN       -1

     W       4.00   PI    14.70   PO    14.57   TI   540.00   TO   583.54   HI   0.0000  HO   0.0000

     EFF    .8824   Q     39.55
COMPONENT CVALVE

     NL         1   NSI       3   NSO       4   FT        3   FN      -22

     W        .43   PI   299.77   PO    93.57   TI   544.29   TO   506.50   HI 34.8313   HO 34.8313

     K   1.115244E+03
COMPONENT EVAP

     NL         1   NSI       4   NSO       5   FT        3   FN      -22

     W        .43   PI    93.57   PO    91.91   TI   506.50   TO   520.48   HI 34.8313   HO111.2176

     NL         3   NSI      31   NSO      32   FT        2   FN       -1

     W       2.20   PI    14.70   PO    14.66   TI   540.00   TO   510.92   HI    .0150   HO    .0077
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      BYPASS FACTOR  .1319   Q    32.85

COEFFICIENT OF PERFORMANCE = 4.895
EVAPORATOR STATIONS           4
VAPOR COMPRESSOR STATIONS   1
*AECS*  REFRIGERANT TEST CASE
    1  CASE R22-01

TIME E      34.95

FLOW RATE(S)-LB/MIN

(   1)     .43 (   2)    4.00 (   3)    2.20

PRESSURE(S)-PSI

(   1)   92.00 (   2)  299.92 (   3)  299.77 (   4)   93.57 (   5)   91.91 (  21)   14.70
(  22)   14.57 (  31)   14.70 (  32)   14.66

TEMPERATURE(S)-DEG R

(   1)  519.88 (   2)  645.91 (   3)  544.29 (   4)  506.50 (   5)  520.48 (  21)  540.00
(  22)  583.54 (  31)  540.00 (  32)  510.92

HUMIDITY(S)/ENTHALPY(S)-LBW/LBA / BTU/LB

(   1)111.2000 (   2)126.8038 (   3) 34.8313 (   4) 34.8313 (   5)111.2176 (  21)  0.0000
(  22)  0.0000 (  31)   .0150 (  32)   .0077

STATE VARIABLE TYPE(S)
(   1)    6 (   2)    1

STATE VARIABLE(S)
(   1) 1.11524E+03 (   2) 2.19849E+00

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

ERROR VARIABLE(S)
(   1) 8.72805E-02 (   2)-1.76205E-02

SOLUTION CONVERGED IN     11 TRY(S)

     0 ERROR(S) DETECTED

CASE END
```

CVALVE

AIR FLOW IN EVAR

92-Poutevap-

(Hout evap -111.2)=.0176

17. Subroutine VCOMP (Refrigerant Vapor Compressor)

17.1. Subroutine Description

The VCOMP subroutine simulates a refrigerant compressor, with saturated or superheated vapor entering at a relatively low pressure and leaving at a relatively high pressure. The leaving refrigerant is assumed to be saturated or superheated vapor. The simulation is applicable to dynamic (turbomachines) and positive-displacement compressors, including Roots-type compressors and Roots-type compressors with pocket feed.

17.2. Prior Simulation Method

The previous simulation method was restricted to compressors other than the Roots type. Therefore, the ideal compressor was assumed to be isentropic. As in the present simulation method, the compressor was assumed to be adiabatic.

17.3. New Simulation Method

The new simulation method adds an input option in which the Roots type of compressor can be selected, either with or without pocket feed. The performance of the conventional Roots compressor is based on the leg flow rate and the pressure ratio, which is obtained either as a state variable or as a tabulated input based on the flow rate and the shaft speed. If a Roots compressor with pocket feed is used, an iterative solution to the governing equations gives the inlet and pocket flows, as well as the outlet pressure, temperature and enthalpy.

17.4. Computational Procedure

The computational procedure is presented in the form of a heavily annotated FORTRAN program in Exhibit 17.4-1. The procedure used for the conventional compressors is based on the usual isentropic efficiency, which is entered as a table by the user, with the independent variables being the volumetric flow rate and the shaft speed. No changes have been made in this part of the simulation. Note that if the pressure ratio is selected as a state variable, the compressor flow rate is assumed to exactly match the leg flow rate; the flow/pressure characteristics of the compressor are not used.

Whereas for the conventional compressor, the work is based on the isentropic ideal, for the Roots compressor the work is based on the ideal of the product of the displacement and the pressure difference. The thermodynamic ideals for the two types of compressors are inherently different. In the Roots compressor, the low-pressure vapor is suddenly exposed to the high-pressure exit, so much entropy is generated. Although the Roots compressor is, therefore, inherently less efficient than the conventional compressor, its simplicity gives

Exhibit 17.4-1: Performance-Program Logic and Listing

```
      SUBROUTINE VCMPPP
      COMMON /CC/ C(400)
      EQUIVALENCE (IRCD,C(45)),(IW,C(27)),(IP,C(28)),(IT,C(29))
     *,(IH,C(30)),(SCR(1),C(151)),(IFB,C(55)),(IGA,C(35))
     *,(PASS,C(17)),(ISVT,C(46)),(ISV,C(47)),(IFP,C(22))
     *,(ICPP,C(88)),(OUT,C(7)),(QJC,C(371)),(IEV,C
                          (49)),(IEVT,C(48))
      DIMENSION SCR(30)
      INTEGER OUT,PASS
      EQUIVALENCE (SCR(1),NLI),(SCR(2),NSI),(SCR(3
                          ),NSO),(SCR(4),NST)
     *,(SCR(5),IOP),(SCR(6),PR),(SCR(9),EFF),(SCR(10),JSVI)
     *,(SCR(11),KT),(SCR(12),IDISP),(SCR(13),NSP),(SCR(14),NLP)
     *,(SCR(15),NLO),(SCR(16),FH),(SCR(17),T),(SCR(18),HP)
     *,(SCR(19),WT),(SCR(20),PS),(SCR(21),TS),(SCR(22),HS)
     *,(SCR(23),VP),(SCR(24),PI),(SCR(25),TI),(SCR(26),HI)
     *,(SCR(27),PO),(SCR(28),VO),(SCR(29),HO)
      EQUIVALENCE (SCR(30),I1)
      COMMON /DC/ DZ(2),D(2)
      DIMENSION ID(2)
      EQUIVALENCE (ID(1),D(1))
      EQUIVALENCE
     * (D(43),H1),(D(44),T1),(D(45),V1),(D(46),V2)
     *,(D(47),T2T),(D(48),ITERATE)
     *,(D(49),X2),(D(50),X1),(D(51),EV),(D(52),DR)
     *,(D(53),DI),(D(54),DL),(D(55),WI),(D(56),WS)
C    1 COMP CODE
C    2 LEG NO FOR INLET
C    3 INLET STATION NO
C    4 OUTLET STATION NO
C    5 SHAFT NO
C    6 STATE VARIABLE OPTION (0 IF NO STATE VARIABLE)
C    7 PRESSURE RATIO
C    8 PRESSURE RATIO TABLE NO
C    9 EFFICIENCY TABLE NO
C   10 MECHANICAL EFFICIENCY
C   11 STATE VARIABLE INDEX
C   12 COMPRESSOR-TYPE OPTION
C*** IF ROOTS TYPE COMPRESSOR, INSERT ADDITIONAL DATA
C   13 DISPLACEMENT IN CUBIC FEET
C*** INSERT A NEW STATION IDENTIFICATION FOR POCKET FEED
C   14 POCKET-FEED INLET STATION
C   15 POCKET-FEED LEG NO
C   16 LEG NO OF OUTLET
C   17 FRACTION OF LEAKAGE FLOW TO POCKET
C*** THIS SUBROUTINE DETERMINES THE OUTLET P,T,H A
                          ND, IF POCKET FEED,
C    THE POCKET-FEED PRESSURE TO GIVE THE CORRECT
                          INLET FLOW RATIOS
      IRCD = IRCDB(18)
C*** SET UP THE INTERNAL VARIABLES IN TERMS OF THE STORED ARRAY
      NLI = ID(IRCD+2)
      IOP=ID(IRCD+6)
      KT=ID(IRCD+12)
```

```
C*** IF POSITIVE DISPLACEMENT, INCLUDE THE DISPLACEMENT
      IF (KT.NE.0) DISP=D(ID(IRCD+13))  .
      IF (KT.NE.2) GO TO 5
C*** IF A ROOTS COMPRESSOR WITH POCKET FEED, ADD FOUR PARAMETERS
      FH=D(ID(IRCD+17))
      NLO=ID(IRCD+16)
      NLP=ID(IRCD+15)
      NSP=ID(IRCD+14)
    5 NST=ID(IRCD+5)
      LOCT = ID(IFB+NLI)
      NSI=ID(IRCD+3)
      NSO=ID(IRCD+4)
      LOCT = ID(LOCT+3)
      D(IGA+41) = D(IW+NLI)
      JSVI = ID(IRCD+ 11)
      JEVI = ID(IRCD + 18)
      NPA = NST + 90
      EFF=D(ID(IRCD+10))
      NSA=NST+80
      ITERATE=0
C*** SHAFT SPEED AS OBTAINED FROM SHAFT
C    AND RPM IS A TLUP PARAMETER.
      D(IGA+101)=D(IGA+NSA)
      RPM=D(IGA+NSA)
C*** VOLUMETRIC FLOW RATE FOR USE IN COMPRESSOR CH
                                ARACTERISTIC (TLUP)
      V = VSV(LOCT,D(IP+NSI),D(IT+NSI) )
      D(IGA+28) = D(IW+NLI) * V
      I1 = ID(IRCD+7)
C*** SET UP THE STATE VARIABLE, THE PRESSURE RATIO, IF IOP=1
      IF(IOP-1) 9,10,8
C*** PRESSURE RATIO AS A FUNCTION OF INLET CFM AND RPM
C*** SYSTEM WILL NOT CONVERGE IF D(PR)/D(FLOW)=0 OR INFINITY
    8 PR=TLUP(ID(IRCD+8))
      IF(PR.LT.1.0)PR=1.0+PR/1000.
      IF(PR.GT.1000.)PR=1000.+PR/1000.
      GO TO 12
    9 PR=D(I1)
      GO TO 12
   10 IF(PASS.NE.1) GO TO 11
      ID(ISVT+JSVI) = 8
      D(ISV+JSVI) = D(I1)
C*** WITH PR A STATE VARIABLE, THE FLOW MAP IS NOT USED.  THE
C    COMPRESSOR CHARACTERISTIC IS ASSUMED TO BE SUCH THAT THE
C    FLOW CAN BE DELIVERED AT THE VALUE OF THE PRE
                                SSURE RATIO USED
   11 PR=D(ISV+JSVI)
C*** ETA IS THE COMPRESSOR EFFICIENCY AS A FUNCTIO
                                N OF FLOW AND RPM
   12 ETA=TLUP(ID(IRCD+9))
      IF(ETA.LE.0.) ETA=0.01+ETA/1000.
      IF(ETA.GE.1.) ETA=1.+ETA/1000.
      D(IP+NSO)=PR*D(IP+NSI)
      IF(KT-1) 64,57,22
```

```
C*** ROOTS COMPRESSOR WITH POCKET FEED
C    VARY PS TO GET INLET FLOW VALUES CORRECT
C    THEN PS WILL NOT AGREE WITH D(IP+NSP), ERROR VAR RESULTS
  22 D(IW+NLO)=D(IW+NLI)+D(IW+NLP)
     DEVHI= - D(IW+NLP)/D(IW+NLI)
     DEVLOW=1. + DEVHI
     PLOW=D(IP+NSI)
     PHI=D(IP+NSO)
     WT=D(IW+NLP)
     WO=D(IW+NLO)
     PS=D(IP+NSP)
     TS=D(IT+NSP)
     HS=D(IH+NSP)
     VP=VSV(LOCT,PS,TS)
     PI=D(IP+NSI)
     TI=D(IT+NSI)
     HI=D(IH+NSI)
     PO=D(IP+NSO)
     DISP1=DISP
     EV1=D(IW+NLI)*V/(DISP*RPM)
C*** IF VOLUMETRIC EFFICIENCY IS GT 0.99, RESET IT
     IF(EV1.LT.0.99) GO TO 21
     DISPL1=D(IW+NLI)*V/RPM
     EV1=1.
     WRITE(OUT,1003) EV1,DISP1
1003 FORMAT(1H0,5X,43HWARNING IN VCMPPP: VOLUMETR
                         IC EFFICIENCY IS,
    * E15.7,/,5X,47H AS COMPUTED FROM RPM AND FLOW.",
    * /," DISPLACEMENT IS TEMPORARILY RESET TO ",
                         E14.7," SO V.E.=1.0")
C*** AS A FIRST APPROXIMATION WE LET
  21 H1=HI
     T1T=TI
     T2T=TS
     V1=V
     V2=VP
     H2=HS
     W=RPM*DISP1*(PO-PI)*0.185053/ETA
     HO=HI+W/D(IW+NLI)
     CALL VTAV2(LOCT,TOUT,VO,PO,HO)
C*** BEGIN THE ITERATIONS
     EV=1.-(1.-EV1)/EV1*D(IW+NLI)/D(IW+NLO)
     X1=FH*(1.-EV)/(2.-EV)
     X2=(1.-FH)*(1.-EV)/(2.-EV)
  30 V1=HI/(H1/V1-X2*(HO-HI)/V2)
C*** NEWTON-RAPHSON METHOD  T1 AND H1 VS P1, V1
  31 V1T=VSV(LOCT,PI,T1T)
     DV=VSV(LOCT,PI,T1T+1.)-V1T
     T1=T1T*(V1/V1T)**(V1T/(T1T*DV))
     IF(ABS(T1-T1T).LT.0.05) GO TO 311
     T1T=T1
     GO TO 31
 311 H1=VH(LOCT,PI,T1,V1)
     DDEN=(H2/V2-H1/V1-0.185053*(PS-PI)-X1*(HO-HS)/V1)
```

```
     *      /(HS+X1*(HO-HS))
      V2=1./(1./V1+DDEN)
      HO=V2*(2.-EV)*(W/(RPM*DISP1)+(1./V1-X2/V2)*H
                                I+(DDEN-X1/V2)*HS)
C*** NEWTON-RAPHSON METHOD FOR T2, H2 VS PS, V2
   32 V2T=VSV(LOCT,PS,T2T)
      DV=VSV(LOCT,PS,T2T+1.)-V2T
      T2=T2T*(V2/V2T)**(V2T/(T2T*DV))
      IF(ABS(T2-T2T).LT.0.05) GO TO 33
      T2T=T2
      GO TO 32
   33 H2=VH(LOCT,PS,T2,V2)
      CALL VTAV2(LOCT,TOUT,VO,PO,HO)
      WO=RPM*DISP1/(V2*(2.-EV))
      WI=RPM*DISP1/V1-X2*WO
      WO=WO/(2.-EV)
      WS=WO-WI
C*** FLOW RATE MUST BALANCE WITHIN 0.1%
      IF (ABS(WS-WT)/D(IW+NLO).LT.0.001) GO TO 36
      WT=WS
      GO TO 30
   36 WS=WO-WI
      IF (WS.GE.0..AND.WI.GE.0.) GO TO 38
      WRITE (OUT,1002) WI,WS,WO
 1002 FORMAT (1H0,5X,42HIN ROOTS VCMPPP, ONE FLOW
                                WAS NEGATIVE BUT,
     * 14H RESET TO ZERO,/,10X,15HINLET FLOW WAS ,E14.7,/,10X,
     * 15HPOCKET FLOW WAS,E14.7,/,10X,15HOUTLET FLOW WAS,E14.7,/)
      IF (WI.LT.0.) GO TO 37
      WS=0.
      WI=WO
      GO TO 38
C*** WE CANNOT LET THE MAIN INLET FLOW BE ZERO
   37 WI=0.001*WO
      WS=.999*WO — W
   38 CONTINUE
 7698 D(IT+NSO)=TOUT
      D(IH+NSO)=HO
C*** IN ITERATING FOR THE POCKET PRESSURE, WE CONV
                                ERGE ON THE RATIO
C     OF THE FLOW RATES (POCKET TO MAIN) MATCHING THE RATIO OF THE
C     LEG FLOWS.  WE CANNOT MATCH THE INDIVIDUAL FL
                                OWS IF PR IS GIVEN,
C     BECAUSE THE COMPRESSOR SIZE IS NOT GIVEN IN THAT CASE
      DEV=-WS/WI+D(IW+NLP)/D(IW+NLI)
C*** POCKET PRESSURE HAS CONVERGED IF THE DEVIATION LT 0.01%
      IF (ABS(DEV).LT.0.0001) GO TO 39
C*** USE STRADDLING PROCEDURE TO GET CONVERGENCE
      IF (DEV.GT.0.) GO TO 41
      PHI=PS
      DEVHI=DEV
      GO TO 42
   41 PLOW=PS
      DEVLOW=DEV
```

```
   42 ITERATE=ITERATE+1
      PS=PLOW-(PHI-PLOW)*(DEVLOW)/(DEVHI-DEVLOW)
      IF(ITERATE-300)21,21,43
   43 WRITE(OUT,1089)
 1089 FORMAT(" *** EXCEEDED 300 ITERATION LIMIT IN VCOMP"/
     *" *** THE SPECIFIED INLET FLOW DID NOT MATCH THE"/
     *" *** OUTLET FLOW AS A FRACTION. WHERE:"/
     *" *** FRAC = (SPECFLOW - FLOWIN) / OUTFLOW")
      WRITE(OUT,1090)D(IW+NLI),WI,D(IW+NLO),PR
 1090 FORMAT(" *** FLOW SPEC = ",E14.7," IN = ",E1
                           4.7," OUT = ",E14.7,/,
     * " CONTINUING AS IF FLOWS BALANCE, WITH PR = ",E14.7)
   39 IF(PASS.NE.1) GO TO 55
      ID(IEVT+JEVI)=2
   55 D(IEV+JEVI)=PS-D(IP+NSP)
      HP=-.02356*(D(IW+NLO)*D(IH+NSO)-D(IW+NLI)*D(IH+NSI)-
     * D(IW+NLP)*D(IH+NSP))/EFF
      GO TO 67
C*** CONVENTIONAL ROOTS COMPRESSOR
   57 WORK=RPM*DISP*(PO-PI)*144./QJC/ETA
      D(IH+NSO)=D(IH+NSI)+WORK/D(IW+NLI)
      GO TO 66
C*** ISENTROPIC COMPRESSION FOR IDEAL COMPRESSOR
   64 S = VS(LOCT,D(IT+NSI),V )
      CALL VTAV1(LOCT,T,V,D(IP+NSO),S )
      H = VH(LOCT,D(IP+NSO),T,V )
      D(IH+NSO) = D(IH+NSI) +  (H - D(IH+NSI))/ ETA
      CALL VTAV2(LOCT,D(IT+NSO),V,D(IP+NSO),D(IH+NSO) )
   66 HP = -0.02356 * D(IW+NLI)*(D(IH+NSO) - D(IH+NSI))/EFF
   67 D(IGA+NPA) = D(IGA+NPA) + HP
      IF(IFP.NE.1. OR. ICPP.NE.0) GO TO 99
      CALL PIOP(1,NLI,NSI,NSO)
      CALL PIOP(2,NLP,NSP,NSO)
      CALL LINES(2)
      WRITE(OUT,1001) NST,PR,ETA,HP
 1001 FORMAT(1H0,5X,6HSHAFT ,I4,3X,2HPR,F8.4,3X,3HEFF,F7.4,3X,
     * 2HHP,F8.2 )
   99 CONTINUE
      RETURN
C     VCMPPP
      END
```

it a mechanical appeal. There are no valves to fail or leak. In addition, the pocket-feed Roots compressor has the apparent advantage of requiring a smaller volume for a given refrigeration effect.

In the Roots compressor with pocket feed, the relationship for the work is quite complicated, even if ideal gases are used. The pocket-feed vapor is added suddenly to the low-pressure vapor inside the compressor, generating entropy in the process (a high-pressure vapor is being admitted to a constant-volume container). The constant-volume container also receives vapor leaking past the tip and face seals from the discharge port. The pressure in the pocket is assumed to rise to the pocket-feed pressure. The resultant mixture is then suddenly compressed by exposure to the discharge vapor, with this process generating additional entropy.

17.5. Program Listing

Exhibit 17.4-1, which presents the computational procedure, also is the program listing as used in AECS, with the exception that the comment cards have been removed from the AECS listing to conserve computer storage space.

17.6. Sample Case

The sample case for the VCOMP subroutine uses a Roots compressor with pocket feed. There are no other components in the system. The input data are shown in AECS format in Exhibit 17.6-1. The diagram in this exhibit illustrates the system; however, the values in the diagram are the solution values, whereas the parameter values in the input format are the initial guesses. The output data are shown in Exhibit 17.6-2. Some of the output has been omitted for brevity.

The values used in the input tables were chosen for brevity and convenience. Few compressors have the linear charactertistic used. If the more realistic values presented in Appendix D had been used, the input data would have been longer and the manual checkout, more difficult.

17.7. Technical Background

The theory of the conventional compressors with the isentropic ideal is treated in most undergraduate text books in engineering thermodynamics. The theory for the conventional Roots compressor is contained in some of the texts on internal combustion engines (e.g., Edward F. Obert: Internal Combustion Engines. Third Edition: Scranton, Pa.: International Textbook Company (1968)).

The theory for the Roots compressor with pocket feed was developed for perfect gases by the hardware developer, Calspan Advanced Technology Center. The theory is described in: Roger Weatherston and George Duryea: "A Multi-Effect Two-Stage Roots Compressor for Aircraft Cooling Applications" (Wright-Patterson Air Force Base, Ohio, Technical Report AFWAL-TR-80-3135 (1980)). We revised this theory for fluids other than perfect gases. The theory involves three steps:

a. The inlet vapor from the evaporator enters the Roots compressor at the inlet pressure (the inlet pressure loss is neglected);
b. After the lobe of the compressor seals the space between the lobes from the inlet, vapor at an intermediate pressure is admitted to this space. Typically, this vapor would come from a liquid/vapor separator from which the vapor is extracted for admission to the "pocket" between the lobes. The pocket pressure rises to the intermediate pressure.
c. As the rotor continues to turn, it seals the pocket from the intermediate pressure and opens the pocket to the high exhaust pressure, thereby completing the transfer from the low and intermediate pressures to the high pressure.

The analysis includes leakage past the tips of the lobes and across the face of the rotor into both the pocket and the inlet of the compressor. Mechanical losses are included via the mechanical efficiency.

When options 0 or 1 are chosen, as was done in the prior version of AECS, the flow-vs.-head characteristic of the compressor is ignored. Instead, the simulation model assumes that the pressure ratio can be attained at whatever flow rate AECS computes for the system. Therefore, the results of the simulation give the flow-vs.-head charateristic that would be required of a compressor to meet the system needs.

Options 0 and 1 pose a new problem for the Roots compressor with pocket feed. Instead of a single inlet flow, there are two flows: the low-pressure inlet and the pocket inlet. Therefore, some modification of the prior version of AECS was required. The following modification was made: the Roots simulation with pocket feed requires, in its internal iteration scheme, that the ratio of the pocket flow to the low-pressure flow match the ratio of the corresponding system flow rates computed by AECS. The pocket pressure is adjusted to the match the ratios. The difference between the pocket pressure as computed for the system and as required to match the flow ratio is the error variable generated by VCOMPP; this error will be minimized in the solution process by the selection of the state variables. The thermodynamics of the compressor are then faithfully simulated. If such matching were not required, unrealistic flow ratios would be tolerated by AECS.

Exhibit 17.6-1: Input Cards and Flow Diagram for the Sample Case

```
PERFORM
TITLE EXAMPLE CASE FOR COMPRESSOR WITH ROOTS POCKET OPTION
CASEA    VCOMP   0000    3   4   0
CASEB      0   0   0   0   0
CASEC      0.0            0.0          0.0
CASED      0.0
PARAM    15
VALUES    1  1.0        158.5674     595.45     122.026     1140.
VALUES    6  1.74          .85       .000369       .9
VALUES   11  0.04       200.0000     600.00      121.100
RINLET     20   1   30100   1   2   3   4   3 -22
RINLET     22   3   50000  11  12  13  14   3 -22
SHAFT      30   1   0   5
VCOMP      40   1   3   9   1   0   6  71  72   7   2   8   5   3   2   9
ROUTLT     70   2   90000   1   2   3   4
TABID      71   4  33   0   0  280101   2   0 101 101   2
TABT       VCOMP: PRESSURE RATIO = F(FLOW RATE,SHAFT SPEED)
TABV       0.0         1.0
TABV       0.0          11.0
TABV       1000.       11000.
TABV       2.0         1.0         20.0         1.0
TABID      72   6  33   0   0  280101   2   0 101 101   2
TABT       VCOMP: EFFICIENCY = F(FLOW RATE,SHAFT SPEED)
TABV       0.0         1.0
TABV       0.0          11.0
TABV       1000.        11000.
TABV        0.85        0.85         0.85         0.85
PTAB        1   0   1   0
ENDCASE
ENDJOB
```

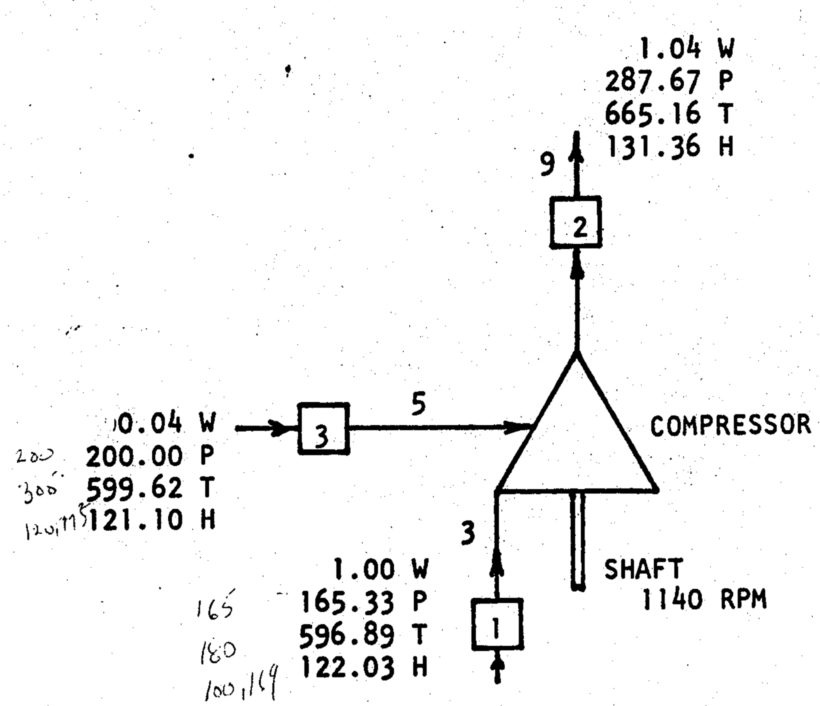


Exhibit 17.6-2: AECS Output for the Sample Case

```
   T OPTION                                              PAGE       7
  ASE VCOMP                                                                              DATE 09/06/81
 TIME P       23.09

 SVT
 (   1)     2

 EVT
 (   1)     2

 PASS        1

 S.V.
 (   1) 1.58567E+02

 E.V.
 (   1)-2.48482E+01

 W
 (   1) 1.00000E+00 (   3) 4.00000E-02 (   2) 1.04000E+00

 P
 (   3) 1.58567E+02 (   5) 2.00000E+02 (   9) 2.75907E+02 (   0) 0.

 T
 (   3) 5.95449E+02 (   5) 5.99623E+02 (   9) 6.65363E+02 (   0) 0.

 H
 (   3) 1.22026E+02 (   5) 1.21100E+02 (   9) 1.31792E+02 (   0) 0.
 COMPONENT SHAFT

      SHAFT     1    N      1140.

 COMPONENT VCOMP

      NL         1   NSI       3   NSO       9   FT       3   FN      -22

      W       1.00   PI  165.33   PO  287.68   TI  596.89   TO  665.16   HI122.0260   HO131.3652

      NL         3   NSI       5   NSO       9   FT       3   FN      -22

      W        .04   PI  200.00   PO  287.68   TI  599.62   TO  665.16   HI121.1000   HO131.3652

      SHAFT     1    PR  1.7400   EFF  .8500   HP    -.27
*AECS* EXAMPLE CASE FOR COMPRESSOR WITH ROOTS POCKET OPTION                                PAGE        8
    1  CASE VCOMP                                                                          DATE 09/06/81

 TIME E      33.66

 FLOW RATE(S)-LB/MIN

 (   1)     1.00 (   2)     1.04 (   3)      .04

 PRESSURE(S)-PSI

 (   3)   165.33 (   5)   200.00 (   9)   287.68 (   0)     0.00

 TEMPERATURE(S)-DEG R
```

```
(   -   96.89 (    5)  599.62 (    9)  665.16 (    0)    0.00
HUMIDITY(S)/ENTHALPY(S)-LBW/LBA / BTU/LB

(    3)122.0260 (    5)121.1000 (    9)131.3652 (    0)  0.0000

STATE VARIABLE TYPE(S)
(    1)     2

STATE VARIABLE(S)
(    1) 1.65332E+02

ERROR VARIABLE TYPE(S)
(    1)     2

ERROR VARIABLE(S)
(    1) 0.

SOLUTION CONVERGED IN       6 TRY(S)

     0 ERROR(S) DETECTED

CASE END
```

18. Subroutine VLINE (Refrigerant Line)

18.1. Subroutine Description

The VLINE routine simulates a refrigerant line in which liquid only, vapor only or two phases are flowing. Heat transfer to and from a constant-temperature environment is included. Friction and momentum pressure drops are computed. Fittings are included with either an equivalent-length or velocity-head-factor specification. The line is assumed to have a circular cross-section.

18.2. Prior Simulation Method

Previously, VLINE obtained the pressure drop from a user-supplied table. There were no computations associated with the flow processes, except for those performed by the user in developing the input table.

18.3. New Simulation Method

The pressure drop is computed from the theory discussed under QBOILR. Heat exchange to or from the line is based on the input values of the heat-transfer coefficient and the surrounding temperature. The refrigerant temperature is taken to be that at the inlet to the line. The line is presumably insulated, so the heat-transfer coefficient will depend almost exclusively on the thickness of the insulation, so no correction is made for longitudinal changes in the heat-transfer coefficient between the refrigerant and the wall of the line. The exit quality is computed from the heat exchange with the surroundings and an energy balance on the refrigerant.

With the known inlet and exit qualities, the pressure drop due to momentum change can be computed as was done for QBOILR. The frictional pressure drop is also computed in the same manner as for QBOILR, with the path length being taken as the sum of the physical length and the equivalent length of the fittings. If a velocity-head factor (K-factor) characterizes some or all of the fittings, the pressure drop associated with the K-factor is computed first for liquid-only flow, then for vapor-only flow. The two-phase K-factor effect is computed as the weighted average of the two single-phase pressure drops, with the weighting factor being the same as used in computing the friction pressure drop. ← from Baroczy? as in QBOILR ?

yes

The theory may not be applicable if there is significant condensation in the line, because flooding could occur. However, most lines will be insulated enough or short enough that only minor condensation will be experienced. Whether condensation is small or not, the subroutine will return with apparently reasonable values.

18.4. Computational Procedure

The computational procedure is presented in the form of a heavily annotated FORTRAN program in Exhibit 18.4-1.

The simplifying assumption is made in computing the frictional pressure drop that the average rate of pressure decrease (dp/dz) is equal to the average between the rate of pressure decrease at the inlet and the rate of pressure decrease at the outlet. The computational procedure could be improved if the transition zones between single- and two-phase flows were calculated; however, the heat exchange between the surroundings and the refrigerant is usually so small that the inlet and outlet pressure gradients differ little, so use of the arithmetic average will incur little error.

i.e., if ΔP is high, use more than one VLINE (or if lots of phase-changing)

18.5. Program Listing

Exhibit 18.4-1, which presents the program computational procedure, also is the program listing as used in AECS. However, the AECS program does not include the comment cards.

18.6. Sample Case

The sample case for VLINE was performed for vapor entering the line. The input data are shown in AECS form in Exhibit 18.6-1 in keeping with the schematic shown in the same exhibit. However, the exhibit shows the outlet state corresponding to the solution, which was computed by AECS and is shown in Exhibit 18.6-2.

18.7. Technical Background

The theory for the pressure drop in the line is taken from Baroczy, with Baroczy's data being recast in the more convenient, interpolation formula derived under this contract. The algebraic approximation to Baroczy's data was also derived under this contract.

The heat exchange with the surroundings is characterized by a heat-transfer coefficient between the refrigerant and the surroundings, with the area being the internal area of the line. The relevant theory is given in any text on heat transfer. Because the line will be insulated, at least in most cases, the heat-transfer coefficient is approximately equal to the thermal conductivity of the insulation divided by its thickness, with the result being expressed in Btu/hr-sf-F.

Exhibit 18.4-1: Performance-Program Logic and Listing

```
      SUBROUTINE VLNEPP
      REAL K,L,LE,LI,M,MI,MO
      COMMON /CC/ C(400)
      EQUIVALENCE (IRCD,C(45)),(IW,C(27)),(IP,C(28)),(IT,C(29))
     *,(IH,C(30)),(SCR(1),C(151)),(IFB,C(55)),(IGA,C(35))
     *,(OUT,C(7))
      EQUIVALENCE (SCR(1),NL),(SCR(2),NSI),(SCR(3)
                             ,NSO),(SCR(4),ISIG)
     *,(SCR(5),LOCT),(SCR(6),UAPDL),(SCR(7),DH),(SCR(8),L)
     *,(SCR(9),K),(SCR(10),LE),(SCR(11),TS)
      DIMENSION SCR(30)
      INTEGER PASS,OUT
      COMMON /DC/ DZ(2),D(2)
      DIMENSION ID(2)
      EQUIVALENCE (ID(1),D(1))
C    1 COMP CODE
C    2 LEG NO
C    3 INLET STATION NO
C    4 OUTLET STATION NO
C    5 TABLE/EQUATION OPTION
C    6 FRICTION FACTOR TABLE NO
C    7 HEAT LOSS FACTOR (UAPDL) IN BTU/HR-F DIVIDED     BTU (ft^2-hr-oF)
                              BY PI*DH*LENGTH (ft^2)
C    8 HYDRAULIC DIAMETER IN FEET (DH)
C    9 LINE LENGTH IN FEET (L)
C   10 VELOCITY HEAD LOSS COEFFICIENT (K)
C   11 EQUIVALENT-LENGTH LOSS COEFFICIENT (LE)
C   12 SOURCE/SINK TEMPERATURE RANKINE (TS)
C*** THE FOLLOWING FUNCTION COMPUTES THE AVERAGE T
                              WO-PHASE FRICTION LOSS
C    BASED ON A SMALL CHANGE IN QUALITY (X)
      P(X,PB)=-PB*X**1.65+(1+PB)*(X**.7+X*(1.-X)**1.3)
C*** THE FOLLOWING FUNCTION COMPUTES THE VOID FRACTION
      VV(X)=X/(X+SL*(1.-X)/VR)
C*** THE FOLLOWING FUNCTION COMPUTES THE MOMENTUM OF THE FLOW
      M(X)=((1.-X)/(1.-V))**2*(1.-V*(1-SL*SL/VR))
C*** SET UP INTERNAL VARIABLES IN TERMS OF THE STORED ARRAY
      IRCD = IRCDB(12)
      NL = ID(IRCD+2)
      NSI = ID(IRCD+3)
      NSO = ID(IRCD+4)
      LOCT = ID(IFB+NL)
      LOCT = ID(LOCT+3)
      UAPDL=D(ID(IRCD+7))
      DH=D(ID(IRCD+8))
      L=D(ID(IRCD+9))
      K=D(ID(IRCD+10))
      LE=D(ID(IRCD+11))
      TS=D(ID(IRCD+12))
      W=D(IW+NL)
      PI=D(IP+NSI)
      TI=D(IT+NSI)
      HIN=D(IH+NSI)
C*** COMPUTE THE SATURATION DENSITIES
```

$\frac{W}{A} D = \frac{W}{\pi D^2/4} D = W/(\pi D/4)$

lbm/sec ft — units of ~~G~~/μ should be lbm/sec ft

```
      VF=1.0/VDL(LOCT,TI)
      VG=VSV(LOCT,PI,TI)
C*** COMPUTE THE REYNOLDS NUMBER FOR LIQUID-ONLY FLOWING
      GD=W/(60.*3.14159*DH/4.)
      D(IGA+21)=GD/VVISCF(LOCT,PI,TI)
C*** AND LOOK UP THE FRICTION FACTOR
      F=TLUP(ID(IRCD+6))
C*** COMPUTE THE INLET PRESSURE DROP RATE AS IF LIQUID-ONLY FLOWS
      LI=(4.*F*(L+LE)/DH+K)*VF*GD**2/(2*32.2)
C*** REPEAT FOR VAPOR-ONLY FLOWING
      D(IGA+21)=GD/VVISCV(LOCT,PI,TI)
      F=TLUP(ID(IRCD+6))
C*** COMPUTE THE INLET PRESSURE DROP RATE AS IF VAPOR-ONLY FLOWS
      GI=(4.*F*(L+LE)/DH+K)*VG*GD**2/(2*32.2)
C*** COMPUTE THE TWO-PHASE-FLOW PARAMETERS: DENSIT
                          Y RATIO, PRESSURE-DROP
C    RATIO, SLIP AND QUALITY:
      VR=VG/VF
      PB=.25*.4343*ALOG(LI/GI)
      IF(PB.LT.-1.)PB=-1.
      SL=SQRT(SQRT(VR-1.))
      X=VQUALH(LOCT,PI,HIN)
      IF(X)380,380,390
C*** LIQUID-ONLY IS FLOWING (SINGLE PHASE)
  380 DI=LI
      MI=1.
      GO TO 460
  390 IF(X-1.)400,395,395
C*** VAPOR-ONLY IS FLOWING (SINGLE PHASE)
  395 DI=GI
      MI=VR
      GO TO 460
C*** TWO-PHASE FLOW
C    FIRST COMPUTE THE FRICTION LOSS
  400 DI=LI+P(X,PB)*(GI-LI)
C*** NEXT COMPUTE THE MOMENTUM LOSS (OR GAIN)
      V=VV(X)
      MI=M(X)
C*** COMPUTE THE HEAT LOSS (OR GAIN) FROM THE LINE
  460 QQ=UAPDL*3.14159*DH*L*(TS-TI)
      HOUT=HIN+QQ/(W*60.)
C*** COMPUTE THE OUTLET QUALITY AND DETERMINE FLOW CONDITIONS
      X=VQUALH(LOCT,PI,HOUT)
      IF(X)510,510,520
C*** LIQUID-ONLY IS FLOWING AT THE OUTLET
  510 DO=LI
      MO=1
      GO TO 560
  520 IF(X.LT.1.)GO TO 521
C*** VAPOR-ONLY IS FLOWING AT THE OUTLET
      DO=GI
      MO=VR
      GO TO 560
C*** THE FLOW IS TWO-PHASE AT THE OUTLET
```

change to G^2 where $G = \frac{GD}{DH}$

change to G^2

$= \frac{ft^3}{lbm} \times \frac{lbm^2}{sec\ ft^4} / 64.4 \frac{ft\ lbm}{lbf\ sec^2} = \frac{lbf}{ft^2}$

area of line ⇒ implies UAPDL is per ft² (BTU/hr ft² °F) not (BTU/min ft-of-line °F)

lbm/hr ⇒ implies QQ is in BTU/hr (and UAPDL in BTU/ft² hr °F)

uses inlet gas ~~density~~ specific volume (VG) (Re), F also mistake! reverse the two (p91 for QBOILR has DP=(ME-MI)* ...

should be "G**2" where G=GD/DH

MISTAKE !!

```
C     COMPUTE THE FRICTION AND THEN THE MOMENTUM LOSS
  521 DO=LI+P(X,PB)*(GI-LI)
      V=VV(X)
      MO=M(X)
C***  COMBINE THE FOREGOING TO OBTAIN THE OUTLET PRESSURE
  560 POUT=PI-((DI+DO)/2+(MI-MO)*GD**2*VF/(32.2))/144.
C***  CHECK FOR NEGATIVE ABSOLUTE (IMPOSSIBLE) PRESSURES
      IF(POUT)570,570,580
  570 WRITE(OUT,2200)
 2200 FORMAT(" *** PRESSURE OUT OF VLINE WAS UNREALISTIC ***")
      WRITE(OUT,2201)POUT,PI
 2201 FORMAT(" *** OUTLET PRESSURE ",1PE12.5," WAS
                                SET TO INLET PRESSURE

     * ",1PE12.5)
      POUT=PI
  580 D(IP+NSO)=POUT
  590 D(IH+NSO)=HOUT
      D(IW+NL)=W
      D(IT+NSO)=TI
      IF (IFP.NE.1 .OR. ICPP.NE.0) GO TO 99
      CALL PIOP(1,NL,NSI,NSO)
      CALL LINES(2)
      WRITE(OUT,591) NSI,NSO,(POUT-PI),D(IW+NL)*(D
                               (IH+NSI)-D(IH+NSO))
  591 FORMAT(5X,"VAPOR LINE FROM STATION",I10,"TO STATION",I10,
     *"HAS A PRESSURE DROP OF",E17.7,"PSI AND A HE
                               AT LOSS OF",E17.7,

     *"BTU/MIN")
   99 CONTINUE
      RETURN
C     VLNEPP
      END
```

label 560:
DI + DO have units of lbf/ft² already, only need (DI + DO)/2 /144., not all other factors
Compare p 87 and p 91, ΔP for QBOILR, which looks good.

Exhibit 18.6-1: Input Cards and Flow Diagram for the Sample Case

```
PERFORM
TITLE TEST OF RINLET,ROTLET,WITH ALL NEW THRU VLINE ONLY.
TITLE R-22 REFRIGERANT
CASEA      R 22  0000    1    2    0
CASEB        0    0    0    0    0
CASEC      0.          0.          0.
CASED      0.
PARAM   10
VALUES  01   0.4331       85.1276       534.0   114.072     0.0
VALUES  06     .03        10.0           1.5       0.0     530.0
RINLET     10    1    10000    1    2    3    4    3  -22
VLINE      20    1    1    2    0   -1    5    6    7    8    9   10
ROUTLT     30    1    20000    1    2    3    4
PTAB        1    0    1    0
ENDCASE
ENDJOB

NDJOB
E
```

.36"

D_h

L (ft)

Kt

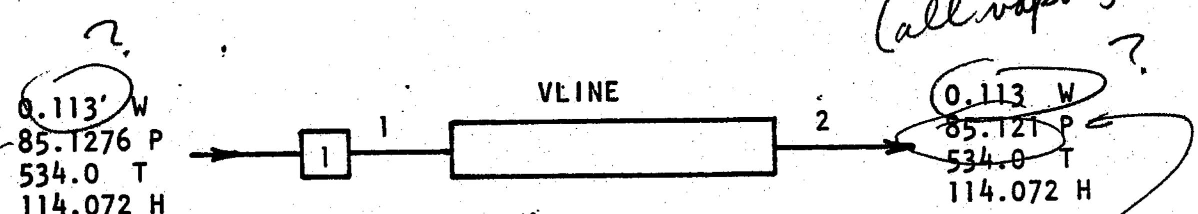
Lequiv

UA

TAMB

no heat transfer used

friction table



printout says 85.13 at in ~~&~~ out

Exhibit 18.6-2: AECS Output for the Sample Case

```
*AECS* TEB                                  PAGE      7                       DATE 09/06/81
    1  CASE   R 22

TIME P       73.33                                                            PAGE        8
*AECS* TEST OF RINLET,ROTLET,WITH ALL NEW THRU VLINE ONLY.                    DATE 09/06/81
    1  CASE    R 22

TIME E       73.33

FLOW RATE(S)-LB/MIN

(    1)     .43

PRESSURE(S)-PSI

(    1)   85.13 (    2)   85.13

TEMPERATURE(S)-DEG R

(    1)  534.00 (    2)  534.00

HUMIDITY(S)/ENTHALPY(S)-LBW/LBA / BTU/LB

(    1)114.0720 (    2)114.0720

     0 ERROR(S) DETECTED

CASE END
CA
```

19. Subroutine XPAND (Refrigerant Expander).

19.1. Subroutine Description

The XPAND routine simulates a positive-displacement or dynamic (turbomachine) expander for extracting work from a high-pressure refrigerant. The inlet side would normally contain a high pressure, moderately high-temperature refrigerant, which would expand to a low pressure, low temperature by passing through the expander. The expander might be a piston expander, a Roots blower, a turbine, or any other type of expander. The expander would normally be used after the refrigerant provides sensible cooling as a vapor. It might also be used after recovering waste heat.

19.2. Prior Simulation Method

XPAND is a new routine. It is similar to the air turbine, except that the exhaust can be in the two-phase region.

19.3. New Simulation Method

The expander in XPAND can be either a positive displacement or dynamic expander. In either case, the machine is characterized by two tabulated parameters: the relationship between the pressure difference across the machine and the flow rate; and the relationship between the flow rate and the adiabatic efficiency. For the positive-displacement expander, the pressure-flow-rate relationship is usually called the volumetric efficiency. For the dynamic expander, it is usually called the flow-head curve. The adiabatic efficiency in both cases is defined as the ratio of the enthalpy change from inlet to outlet to the enthalpy change if the expansion process were isentropic. The shaft speed is a parameter of both tables.

Three computational options are available with the expander model: (1) the pressure ratio, shaft speed and flow rate can be fixed (Option 0), in which case the subroutine ignores the pressure-flow-rate table (which must be entered in any case) and assumes that the expander has the requisite characteristics; (2) the flow rate and shaft speed are gvien (Option 1), in which case the pressure ratio is obtained from the pressure-flow-rate table; or (3) the flow rate and pressure ratio are given (Option 2), in which case the shaft speed required to meet this given combination is computed and the difference between this shaft speed and the shaft speed from the SHAFT component becomes an error variable. If Option 2 is selected, the expander computations involve an iteration for the shaft speed because the pressure-flow-rate table has pressure ratio rather than shaft speed as the dependent variable. A brief iteration is required to determine the power output, because the outlet velocity correction depends on the outlet density. All of these iterations are performed internal to the XPAND subroutine.

19.4. Computational Procedure

The computational procedure is presented in the form of a heavily annotated FORTRAN listing in Exhibit 19.4-1. Perhaps the only unusual feature of the computations is the straddling procedure used for determining the shaft speed from the pressure-flow-rate table, given the flow rate and pressure ratio (Option 2).

19.5. Program Listing

Exhibit 19.4-1, which presents the program computational procedure, also is the program listing as used in AECS. However, the AECS program does not include the comment cards.

19.6. Sample Case

The sample case of the expander is that of a positive-displacement device (Exhibit 19.6-1). The data are shown in the AECS input format, along with a diagram of the system being simulated: a system with an expander alone. The output data, the solution to the problem posed, is presented in AECS format in Exhibit 19.6-2 and in the schematic in Exhibit 19.6-1.

The values used in the tables were chosen for brevity and convenience. Few expanders have the linear characteristic used. If the more realistic values presented in Appendix D had been used, the input data would have been longer and the manual checkout, more difficult.

19.7. Technical Background

The technical background for the expander is similar to that for the air turbine used in the air cycle. Expansion into the two-phase region is similar to the expansion process found in any thermodynamics text that illustrates the analysis of steam turbines. The one variation from the textbook analysis is the incorporation of the correction for the exit velocity.

The isentropic expansion process gives the static enthalpy of the exit stream. The total enthalpy is the sum of the static enthalpy and the velocity head:

```
Htotal = Hstatic + V**2/(2*GC*J)
```

Therefore, the subroutine obtains Hstatic from the usual textbook analysis for an isentropic expansion, then adds to this the velocity term. To compute the velocity, the exit area is obtained from the input data (exit area = A0*D**2) and the exit specific volume is obtained from the known pressure and static enthalpy as determined at first by the isentropic expansion process. Note that the efficiency is assumed to be equal to the ratio of the total enthalpy change to the isentropic static enthalpy change:

Exhibit 19.4-1: Performance-Program Logic and Listing

```
      SUBROUTINE XPANDPP
      REAL K,N,N1,J,MEFF,N0
      INTEGER OUT,PASS
      COMMON /CC/ C(400)
      COMMON /DC/ DZ(2), D(2)
      DIMENSION ID(2)
      DIMENSION SCR(30)
      EQUIVALENCE (IRCD,C(45)),(IW,C(27)),(IP,C(28)),(IT,C(29)),
     *(IH,C(30)),(SCR(1),C(151)),(ICPP,C(88)),(OUT,C(7)),(IEVT,C(48)),
     *(IFP,C(22)),(IGA,C(35)),(ILN,C(37)),(PASS,C(17)),(IFB,C(55)),
     *(CERR,C(16)),(IIOP,C(90)),(GC,C(370)),(J,C(371)),(IEV,C(49)),
     *(ITAD,C(54)),(ITN,C(39))
      EQUIVALENCE (NL,SCR(2)),(NSI,SCR(3)),(NSO,SCR(4)),(NST,SCR(5)),
     *(IOPT,SCR(6)),(PR,SCR(7)),(FLO,SCR(8)),(EF,SCR(9)),(ME,SCR(10)),
     *(D3,SCR(11)),(AO,SCR(12)),(Z,SCR(13)),(KN,SCR(14)),(ITER,SCR(30))
      EQUIVALENCE (ID(1),D(1))
C   1 COMP CODE
C   2 LEG NUMBER
C   3 STATION IN
C   4 STATION OUT
C   5 SHAFT NUMBER
C   6 OPTION
C   7 PRESSURE RATIO
C   8 FLOW FACTOR TABLE
C   9 EFFICIENCY TABLE
C  10 MECHANICAL EFFICIENCY
C  11 DISPLACEMENT PER REVOLUTION
C  12 OUTLET AREA RATIO .
C  13 OPTION 0-DIMENSIONED 1-DIMENSIONLESS TABLES
C  14 EXPONENT IN PRESSURE NORMALIZING EQUATION
      IRCD=IRCDB(15)
C  15 ERROR VARIABLE INDEX
C*** SET UP THE INTERNAL VARIABLES IN TERMS OF THE STORED ARRAY
      NL=ID(IRCD+2)
      NSI=ID(IRCD+3)
      NSO=ID(IRCD+4)
      NST=ID(IRCD+5)
      IOPT=ID(IRCD+6)
      PR=D(ID(IRCD+7))
      MEFF=D(ID(IRCD+10))
      D3=D(ID(IRCD+11))
      AO=D(ID(IRCD+12))
      Z=ID(IRCD+13)
      KN=D(ID(IRCD+14))
      JEVI=ID(IRCD+15)
      LOCT=ID(IFB+NL)
      LOCT=ID(LOCT+3)
      QUAL=VQUALH(LOCT,D(IP+NSI),D(IH+NSI))
```

```
      ITER=0
      N=D(IGA+NST+80)
      FR=D(IW+NL)
      IF(QUAL)55,55,60
C*** IF PURE LIQUID ENTERS THE EXPANDER, SET OUTLET = INLET
  55  WRITE(OUT,111)
 111  FORMAT(" PURE LIQUID IS ENTERING THE EXPANDER")
      D(IP+NSO)=D(IP+NSI)
      D(IT+NSO)=D(IT+NSI)
      D(IH+NSO)=D(IH+NSI)
      RETURN
  60  IF(QUAL-1.0)65,100,100
C*** TWO PHASE FLOW ENTERING THE EXPANDER
  65  VI=1.0/VDL(LOCT,D(IT+NSI))+QUAL*(VSV(LOCT,D(IP+NSI),D(IT+NSI))
     * - 1.0/VDL(LOCT,D(IT+NSI)))
      HFG=VHFG(LOCT,D(IP+NSI),D(IT+NSI),VI)
      SSAT=VS(LOCT,D(IT+NSI),VI)
      SI=SSAT-(1.0 - QUAL) * HFG/D(IT+NSI)
      GO TO 200
C*** PURE VAPOR ENTERING THE EXPANDER
 100  VI=VSV(LOCT,D(IP+NSI),D(IT+NSI))
      SI=VS(LOCT,D(IT+NSI),VI)
C*** COMPUTE THE SPEED OF SOUND BASED ON THE VAPOR
 200  AI=VSOS(LOCT,D(IP+NSI),D(IT+NSI))*60.
  310  DM=D3**(1./3.)
      DN=N
  320  IF(IOPT-1)550,770,960
C*** PRESSURE RATIO AND FLOW RATE ARE FIXED; SHAFT SPEED IS KNOWN
  550 D(IP+NSO)=PR*(D(IP+NSI))
      QX=FR*VI
      GO TO 620
  610  FR=QX/VI
C*** USE TLUP FOR EFFICIENCY AS A FUNCTION OF CFM AND RPM
  620 D(IGA+101)=QX
      D(IGA+102)=DN
      EF=TLUP(ID(IRCD+9))
C*** DETERMINE THE OUTLET CONDITIONS BASED ON ISENTROPIC EXPANSION
      TSAT=VTS(LOCT,D(IP+NSO))
      VSAT=VSV(LOCT,D(IP+NSO),TSAT)
      SSAT=VS(LOCT,TSAT,VSAT)
      HSAT=VH(LOCT,D(IP+NSO),TSAT,VSAT)
      HFG=VHFG(LOCT,D(IP+NSO),TSAT,VSAT)
      SFG=HFG/TSAT
      QUAL=((SI-SSAT)/SFG) + 1.0
      IF(QUAL.GE.1.0) GO TO 650
      VO=(1.0/VDL(LOCT,TSAT))+QUAL*(VSAT-1.0/VDL(LOCT,TSAT))
      HX=HSAT-(1.0-QUAL)*HFG
      GO TO 660
  650 CALL VTAV1(LOCT,D(IT+NSO),VO,D(IP+NSO),SI)
      HX = VH(LOCT,D(IP+NSO),D(IT+NSO),VO)
C*** COMPUTE THE OUTLET CONDITIONS BASED ON THE EXPANDER EFFICIENCY
  660  HT=HX
```

```
 670 D(IH+NSO)=D(IH+NSI)-EF*(D(IH+NSI)-HX)-(FR*VO/(DM*DM*AO*60))**2/
    * (2.*GC*J)
      HSAT=VH(LOCT,D(IP+NSO),TSAT,VSAT)
      QUAL=1.0+(D(IH+NSO)-HSAT)/HFG
      IF(QUAL.GE.1.0)GO TO 500
      D(IT+NSO)=TSAT
      VO= 1.0/VDL(LOCT,D(IT+NSO))+QUAL*((VSAT)-1./VDL(LOCT,D(IT+NSO)))
      GO TO 600
 500  CALL VTAV2(LOCT,D(IT+NSO),VO,D(IP+NSO),D(IH+NSO))
 600  CONTINUE
C*** ITERATE ON THE OUTLET-VELOCITY CORRECTION
 700  IF(ABS((D(IH+NSO)-HT)/(D(IH+NSO)-D(IH+NSI))).LT..0001)GO TO 710
      HT=D(IH+NSO)
      GO TO 670
 710  FR=QX/VI
C*** COMPUTE THE POWER OUTPUT, W
      W=FR*EF*(D(IH+NSI)-HX)
      D(IGA+NST+90)=D(IGA+NST+90)+W*778./33000.
      IF(IOPT.EQ.2)GO TO 750
      GO TO 1130
 750  CONTINUE
      IF(PASS.NE.1)GO TO 752
      ID(IEVT+JEVI)=7
 752  D(IEV+JEVI)=(DN-D(NST+80+IGA))/(DN+D(NST+80+IGA))
 760  GO TO 1130
C*** RPM AND CFM ARE KNOWN.  USE STRADDLING PROCEDURE TO GET PRESSURE
C    RATIO FROM TLUP OF CFM AS A FUNCTION OF RPM AND PRESSURE RATIO
 770  QX=FR*VI
      I=1
      JD=1
      KY=0
      JN=ID(IRCD+8)
      IAD=ID(ITAD+JN)
      NX=ID(IAD+4)
      IX=ID(IAD+8)
      IND=0
      D(IGA+102)=DN
      NZ=ID(IAD+7)
      IZ=ID(IAD+9)
C*** TEST TO SEE IF THE HIGHEST FLOW RATE IS HIGHER THAN THE
C    LEG FLOW RATE (AT ZERO PRESSURE DROP)
      D(IGA+101)=0.0
      Q9=TLUP(JN)
      IF(Q9.GT.QX)GO TO 780
      WRITE(OUT,3130)
      GO TO 1140
 780  IF(ID(IAD+1).EQ.3)GO TO 785
      IF(ID(IAD+1).EQ.33)GO TO 781
      WRITE(OUT,3133)
3133  FORMAT(" ***WRONG TABLE FOR XPANDR.  MUST BE 3 DIMENSIONAL")
      CERR = CERR + 1
      RETURN
```

```
C*** START THE SCAN FOR THE STRADDLING POINTS.  FIND THE INDEX (IX) OF
C    THE LOWEST PRESSURE RATIO IN THE TABLE
  781 CALL MDISSR(N,D(IZ),I,NZ,JD,NPX,KY,IND)
      IX = IX + (NX * NPX)
  785 IENDX = IX + NX - 1
C*** SCAN THE VALUES OF THE PRESSURE RATIOS FORTHE ONE THAT GIVES A
C    FLOW JUST BELOW THE LEG FLOW (QX)
      DO 800 I=IX,IENDX
      D(IGA+101)=D(I)
      YVAL=TLUP(JN)
      IF(YVAL.GT.QX)GO TO 790
C*** SET UP THE STRADDLE BETWEEN (P1,Q1) AND (P2,Q2).  NOTE THAT Q IS
C    ASSUME TO DECREASE AS THE PR (P) INCREASES.
      Q1=YVAL
      P1=D(I)
      P9=D(I-1)
      IF(I.GT.IX)GO TO 810
      P9=0.0
      GO TO 810
  790 Q9=YVAL
  800 CONTINUE
      WRITE(OUT,3130)
 3130 FORMAT(" *** NO BRACKET IN TABLE FOR QX")
      GO TO 1140
  810 P9MP1=P9-P1
      P1HLD=P1
  830  IF(Q9-Q1)832,1140,832
C*** INTERPOLATE LINEARLY BETWEEN THE STRADDLE POINTS TO DETERMINE BY
C    ITERATION THE CORRECT PRESSURE RATIO
  832  PX=P1+(QX-Q1)*(P9-P1)/(Q9-Q1)
       IF(PX.GT.1.0)GO TO 1140
  840 D(IGA+101)=PX
      Q0=TLUP(ID(IRCD+8))
  855  IF(ABS((QX-Q0)/QX).LT..0001)GO TO 920
  860  IF(QX-Q0)870,870,885
  870  P9=PX
      Q9 = Q0
      GO TO 900
  885  P1=PX
  887  Q1=Q0
  900 ITER=ITER + 1
      IF(ITER-100)832,832,1140
C*** AT 920 THE SOLUTION HAS BEEN FOUND, SO RETURN TO 620 TO
C    DETERMINE THE OUTLET CONDITIONS.
  920  D(IP+NSO)=D(IP+NSI)*PX
  930  GO TO 610
C*** PRESSURE RATIO AND LEG FLOW ARE KNOWN.  DETERMINE THE SHAFT SPEED
C    REQUIRED TO GIVE THESE.  USE NEWTON'S METHOD WITH A PERTURBATION
C    INSTEAD OF DIFFERENTIATION.
  960  PX=PR
  990 QX=FR*VI
 1000 D(IGA+101)=PX
```

```
      D(IGA+102)=DN
      Q0=TLUP(ID(IRCD+8))
 1010  XX=ABS((Q0-QX)/QX)
 1015  IF(XX-.0001)1090,1090,1020
 1020  DN1=1.001*DN
      D(IGA+102)=DN1
      Q1=TLUP(ID(IRCD+8))
 1050  IF(Q1-Q0)1052,1140,1052
 1052  DN=DN+(DN1-DN)*(QX-Q0)/(Q1-Q0)
      IF(DN.LE.0.0.OR.DN.GT.1.E+20)GO TO 1140
      ITER=ITER+1
      IF(ITER-100)1000,1000,1140
 1070  GO TO 1000
C*** ITERATION IS COMPLETE, SO GO TO 610 TO DETERMINE THE REMAINDER
C    OF THE OUTLET CONDITIONS.
 1090 D(IP+NSO)=D(IP+NSI)*PX
 1120  GO TO 610
 1140  WRITE(OUT,1142)
 1142  FORMAT(" SOLUTION IS PHYSICALLY IMPOSSIBLE")
 1150  WRITE(OUT,1152)QX
 1152  FORMAT(" VOLUME FLOW RATE, IN CFM, WAS",F9.2)
 1160  WRITE(OUT,1162)PX
 1162  FORMAT(" PRESSURE RATIO WAS",F9.2)
      WRITE(OUT,1170) N
 1170 FORMAT(" RPM WAS",F9.2)
      D(IP+NSO)=D(IP+NSI)
      D(IT+NSO)=D(IT+NSI)
      D(IH+NSO)=D(IH+NSI)
 1130 IF (IFP.NE.1 .OR. ICPP.EQ.0 ) GO TO 99
      CALL PIOP(1,NL,NSI,NSO)
      CALL LINES(2)
      WRITE(OUT,1173) W
 1173 FORMAT(5X,"EXPANDER OUTPUT =",E17.7,"BTU/MIN")
   99 CONTINUE
 2000  RETURN
C     XPANDPP
```

$$Efficiency = (Hinlet - Hstatic-V**2/(2*GC*J))/(Hinlet-HX)$$

where HX is the enthalpy evaluated at the inlet entropy and the exit pressure. With this definition, the exit static enthalpy must be computed iteratively, because the exit velocity, V, depends on the exiting-vapor specific volume, which depends on the exit static enthalpy. This iteration is incorporated in the computational procedure presented in Exhibit 19.4-1.

Exhibit 19.6-1: Input Cards and Flow Diagram for the Sample Case

```
PERFORM
TITLE EXAMPLE CASE FOR EXPANDER
CASEA    XPAND    0000    1    2    0
CASEB       0    0    0    0    0
CASEC       0.0              0.0          0.0
CASED       0.0
PARAM    10
VALUES  - 1  4.0120       500.00    939.67     185.81     9000.
VALUES    6  .125         67.8         .008       1.0       2.0
RINLET     20    1    10000    1    2    3    4    3 -22
SHAFT      30    1    1    5
XPAND      40    1    1    2    1    2    6    8    9    8    9
ROUTLT     50    1    20000    1    7    2    7
TABID       8    8   33    0    0 1010001    3    0 1020001    3
TABT   EXPANDER: FLOW RATE (CFM) VS. PRESSURE RATIO AND RPM
TABV       0.0        0.125       1.0
TABV       0.0        0.125       1.0
TABV       0.0        0.125       1.0
TABV       4500.      9000.       18000.
TABV       0.7        0.434       0.0        1.4
TABV       0.868      0.0         2.8        1.736
TABV       0.0
TABID       8    7   33    0    0 1010001    3    0 1020001    3
TABT       EXPAND: EFFICIENCY AS A FUNCTION OF FLOW RATE AND RPM
TABV       0.0        0.434       0.7
TABV       0.0        0.868       1.4
TABV       0.0        1.736       2.8
TABV       4500.      9000.       18000.
TABV       0.0        0.85        0.7        0.0
TABV       0.85       0.7         0.0        0.85
TABV       0.7
PTAB        1    0    1    0
ENDCASE
ENDJOB
```

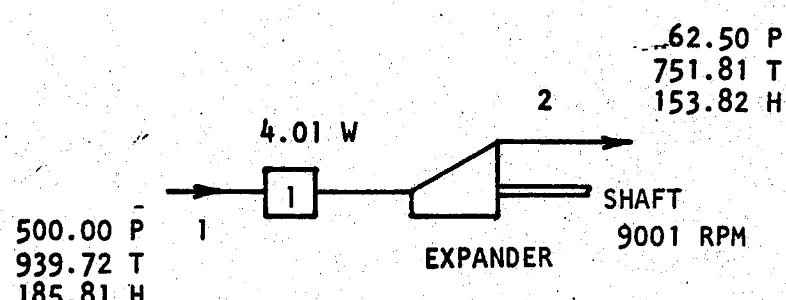


Exhibit 19.6-2: AECS Output for the Sample Case

```
                                                            PAGE          8
                                                            DATE 01/24/82
THE FOLLOWING LISTING IS FOR FILE    XPNRUN

COMPONENT SHAFT

     SHAFT    1    N    9001.
*AECS* EXAMPLE CASE FOR EXPANDER
    1  CASE XPAND

TIME E     133.93

FLOW RATE(S)-LB/MIN

(    1)    4.01

PRESSURE(S)-PSI

(    1)  500.00 (    2)   62.50

TEMPERATURE(S)-DEG R

(    1)  939.72 (    2)  751.81

HUMIDITY(S)/ENTHALPY(S)-LBW/LBA / BTU/LB

(    1)185.8100 (    2)153.8208

STATE VARIABLE TYPE(S)
(    1)     7

STATE VARIABLE(S)
(    1) 9.00137E+03

ERROR VARIABLE TYPE(S)
(    1)     7

ERROR VARIABLE(S)
(    1) 1.44678E-03

SOLUTION CONVERGED IN       1 TRY(S)

     0 ERROR(S) DETECTED

CASE END
```

Appendix A: Example of a Complicated Refrigeration System

A.1. Introduction

As part of this contract, we were to demonstrate the subroutines and solution techniques we developed by applying them to a complicated refrigeration system, such as shown in Exhibit A-1. The system depicted was taken from the contract documents, although we have added the leg and station numbers for later reference. The system involves all of the components developed except for QBOILR and XPAND. These are demonstrated in Appendix E.

The purposes of this appendix are (1) to demonstrate the use of the new subroutines and technqiues; and (2) to suggest appropriate ways of working with the new components and solution procedures. The first purpose pertains to fulfilling the contractural requirements. The second is important to the user because the new components make the successful operation of AECS more difficult. The non-linear characteristics of the refrigerants near the saturation line can make the Newton-Raphson solution procedure used by AECS fail. Therefore, the user will need greater skill in solving the problems. We hope to communicate some of the necessary skills in this appendix.

A.2. Description of the Example

As indicated in Exhibit A-1, the example consists primarily of a refrigerant loop. Air is cooled in two separate evaporators and air cools the one condenser. Two-stage, centrifugal compression, with interstage cooling, pumps the heat from the evaporators to the condenser. A second intercooler, following one of the evaporators, acts as an economizer to reduce the required refrigerant circulation rate.

A.3. Developing the Input Data

Developing the input data begins with the system schematic, on which the leg and station numbers are defined. Although we attempted to keep the station numbers sequential as we traversed the refrigeration loop, we overlooked several stations and were forced to insert non-sequential station numbers. AECS can handle any ordering. In any case, keeping the numbers sequential for the example would be impossible, because some of the loops split and turn back on themselves.

The components cards follow the usual deck of CASE cards and parameter cards. The number and values of the parameters cannot be easily determined a priori, so we proceeded directly to the components cards. The first component card is LOOPS, which begins LEG 2 at STATION 3. The values of flow, pressure, temperature and enthalpy at STATION 3 will eventually be matched, via LOOPE, with those of STATION 33. Station 3 is at the inlet to the high-pressure compressor.

Exhibit A-1 (a): Input Cards for the Sample Case

```
110=PERFORM
120=TITLE   REFRIGERANT TEST CASE
130=CASEA    R22-01  0000  13  28    0
140=CASEB      0   0   0   0   0
150=CASEC      0.0          0.0          0.0
160=CASED      0.0
170=PARAM   55
180=VALUES   1      1.0      158.600     595.5       122.00    10000.
190=VALUES   6   1.8900        0.85        1.93        1.0     8.0000
200=VALUES  11     14.7      540.0         0.0       0.001      0.1332
210=VALUES  16   0.0001     7956.00      0.001       0.001     90.0
220=VALUES  21    300.0       30.0         1.0         5.0      0.001
230=VALUES  26   0.001        90.0       300.0        30.0      1.0
240=VALUES  31   0.5       1099.50       1.800        14.7      540.0
250=VALUES  36   0.015         5.0       0.001         5.0    1099.50
260=VALUES  41   2.100        14.7       540.0       0.014        5.0
270=VALUES  46   0.001         5.0       0.4331       88.0      529.3
280=VALUES  51   53.24       1.7400      91.150     91.150     158.600
290=LOOPS      10   2   3  13  33   3 -220000   1   2   3   4
300=SHAFT      20   1   0   5
310=VCOMP      30   2   3   4   1   0   6   1  72   7   0
320=SPLIT      40   2   4   5  22   3  23   0   9
330=INLET      50   4 260000  10  11  12  13   2  -1
340=COND       60   5  22   5   4  26  27   0   1   2   3  14
350=SPLIT      70   5   5   6  51   7  52   0  15
360=CVALVE     80   6  51   6   0  16  17
370=NRCLR      90   6   6   7   7  52   8  18  19   4  20  21  22  23  23
380=SENSOR    100   6   7   2  55
390=INDATA    105  10  14  48  49  50  51
400=NRCLR     110  10  14  16   7   8   9  25  26   9  27  28  29  30  30
410=SPLIT     120   7   9   8  11  11  25   0  31
420=CVALVE    130   8  11  12   0  16  32
430=MERGE     140   8  12   3  23  10  13   0
440=INLET     150   9 280000  33  34  35  36   2  -1
450=EVAP      160  10  13  14   9  28  29   0   4   5  37   6  38   0
460=SENSOR    170  10  14   2  53
470=CVALVE    180  11  25  18   0  16  40
480=INLET     190  12 311000  41  42  43  44   2  -1
490=EVAP      200  11  18  19  12  31  30   0  14  15  45  16  46   0
500=SENSOR    210  11  19   2  54
510=MERGE     220  11  19  10  16   1  21   0
520=VCOMP     230   1  21   2   1   0  52   1   1   7   0
530=MERGE     240   1   2   6   7  13  33   0
540=LOOPE     250   2   3  13  330001
550=TABID      72   6  33   0   0  280001   2   0 101 101   2
560=TABT       VCOMP: EFFICIENCY = F(FLOW RATE,SHAFT SPEED)
570=TABV       0.0        1.0
580=TABV       0.0         11.0
590=TABV       1000.       11000.
600=TABV        0.85        0.85        0.85        0.85
610=TABID       1   1   2   0   0  410001   2
620=TABT       AIR SIDE PRESS DROP T=1 RN=1 (IND.VAR.=AIR FLOW)
```

```
C$
      SUBROUTINE QBLRPP
      COMMON /CC/ C(400)
      EQUIVALENCE (IRCD,C(45)),(IW,C(27)),(IP,C(28)),(IT,C(29))
     *,(IH,C(30)),(SCR(1),C(151)),(GC,C(370)),(JC,C(371))
     *,(ICPP,C(88)),(IFP,C(22)),(OUT,C(7)),(IGA,C(35))
     *,(PASS,C(17)),(IEVT,C(48)),(IEV,C(49)),(ITAD,C(54))
     *,(IFB,C(55)),(ISN,C(38))
      DIMENSION SCR(30)
      INTEGER OUT,PASS
      REAL L,MU,K,JC,ME,MI,MP
      EQUIVALENCE  (SCR(1),NL),(SCR(2),NSI),(SCR(3),NSO)
     *,(SCR(4),IOP),(SCR(5),FFT),(SCR(6),COT),(SCR(7),AF)
     *,(SCR(8),Q),(SCR(9),L),(SCR(10),AH),(SCR(11),DH)
      DIMENSION MU(2),CPY(2),V(2),PR(2),T(5),TW(5),HT(5),DP(2)
     *,K(2)
      COMMON /DC/ DZ(2),D(3201)
      DIMENSION ID(2)
      EQUIVALENCE (ID(1),D(1))
     *,(D(51),T(1)),(D(56),TW(1)),(D(61),HT(1))
     *,(D(71),HFG),(D(72),ST),(D(73),PT)
     *,(D(75),TIN),(D(76),W),(D(77),IRET),(D(78),CO)
     *,(D(79),FF),(D(81),VR),(D(82),DV)
     *,(D(83),SL),(D(84),HSAT),(D(86),TSAT)
     *,(D(87),X1),(D(88),X2),(D(89),TNB),(D(90),DD)
     *,(D(91),FD),(D(92),B),(D(93),EM),(D(94),RS)
C    1 COMP CODE
C    2 LEG NO
C    3 INLET STATION NO
C    4 OUTLET STATION NO
C    5 OPTION NO
C    6 FRICTION FACTOR TABLE
C    7 COLBURN FACTOR TABLE
C    8 HEAT EXCHANGER FLOW AREA
C    9 HEAT INPUT RATE IN (BTU/MIN)
C   10 HEAT EXCHANGER FLOW PATH LENGTH (FEET)
C   11 HT EXCHG/HT TRANSFER AREA INCLUDING FINS (SQUARE FEET)
C   12 HEAT EXCHANGER HYDRAULIC DIAMETER
C   13 ERROR VARIABLE OPTION
C*** ERROR-VARIABLE OPTION: 0 IF NO ERROR VARIABLE; 1 IF SUPERHEAT
C   14 ERROR VARIABLE INDEX
C   15 MAXIMUM BOILER WALL TEMPERATURE
C*** SET UP INTERNAL VARIABLES IN TERMS OF STORED ARRAY
      IRCD = IRCDB(15)
      NL=ID(IRCD+2)
      NSI=ID(IRCD+3)
      NSO=ID(IRCD+4)
      IOP=ID(IRCD+5)
      IF (ID(IRCD+13).EQ.0) GO TO 107
      TMAX=D(ID(IRCD+15))
      JEVI=ID(IRCD+14)
  107 CONTINUE
      LOCT=ID(IFB+NL)
      LOCT=ID(LOCT+3)
      AF=D(ID(IRCD+8))
      Q=D(ID(IRCD+9))
      L=D(ID(IRCD+10))
      AH=D(ID(IRCD+11))
      DH=D(ID(IRCD+12))
C*** COMPUTE THE SATURATION PROPERTIES
      TSAT=VTS(LOCT,D(IP+NSI))
C*** COMPUTE THE TRANSPORT PROPERTIES BASED ON INLET CONDITIONS
      CPY(1)=VCPF(LOCT,D(IP+NSI),TSAT)
      CPY(2)=VCPV(LOCT,D(IP+NSI),TSAT)
      MU(1)=VVISCF(LOCT,D(IP+NSI),TSAT)
      MU(2)=VVISCV(LOCT,D(IP+NSI),TSAT)
      K(1)=VCONDF(LOCT,D(IP+NSI),TSAT)
      K(2)=VCONDV(LOCT,D(IP+NSI),TSAT)
      V(1)=1.0/VDL(LOCT,TSAT)
      V(2)=VSV('QBLRPP 1',LOCT,D(IP+NSI),TSAT)
      HFG=VHFG(LOCT,D(IP+NSI),TSAT,V(2))
      ST=VST(LOCT,TSAT)
      PT=VDPDT(LOCT,D(IP+NSI))
      TIN=D(IT+NSI)
      W=D(IW+NL)
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IRITE=1
      IF (IRITE .NE. 1) GO TO 9010
      WRITE (OUT,9911)
 9911 FORMAT(' ',/)
      WRITE (OUT,9011)
 9011 FORMAT(' *********WRITE 9011 FROM "QBLRPP" *********************'
     *      ,'**************')
```

```
      WRITE (OUT,9012) AF     , Q      , L      , AH
     *                , DH     , TSAT   , CPY(1), CPY(2)
     *                , MU(1) , MU(2) , K(1)   , K(2)
     *                , V(1)   , V(2)   , HFG    , ST
     *                , PT     , TIN    , W
 9012 FORMAT(' AFLOW =', E12.5,  ' QRATE =', E12.5,  ' LFLOW =', E12.5
     *      ,' AHTRAN=', E12.5,/,' DHYD  =', E12.5,  ' TSAT  =', E12.5
     *      ,' CPY(1)=', E12.5,  ' CPY(2)=', E12.5,/,' MU(1) =', E12.5
     *      ,' MU(2) =', E12.5,  ' K(1)  =', E12.5,  ' K(2)  =', E12.5
     *    ,/ ,' V(1)  =', E12.5,  ' V(2)  =', E12.5,  ' HFG V2=', E12.5
     *      ,' ST    =', E12.5,/,' PTDPDT=', E12.5,  ' TIN   =', E12.5
     *      ,' W     =', E12.5)
 9010 CONTINUE
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      DO 1 I = 1,2
    1 PR(I)=3600.*CPY(I)*MU(I)/K(I)
      IRET=-1
C*** COMPUTE THE REYNOLDS NUMBER AS THE INDEPENDENT VARIABLE
      G=W/AF/60.0
C*** BASED ON 100% LIQUID FLOW
      D(IGA+21)=G*DH/MU(1)
C*** USE TULP FOR COLBURN FACTOR, THEN COMPUTE HEAT TRANSFER COEFF.
      CO=TLUP(ID(IRCD+7))
      HT(1)=CO*60.*G*CPY(1)/PR(1)**.67
C*** USE TULP FOR FRICTION FACTOR
      FF=TLUP(ID(IRCD+6))
C*** COMPUTE VOLUME RATIO AND SLIP FOR LATER TWO-PHASE COMPUTATIONS
      VR=V(2)/V(1)
      DV=1.0-1.0/VR
      SL=SQRT(SQRT(VR-1.))
C*** COMPUTE PRESSURE DROP AS IF 100% LIQUID FLOW
      DP(1)=4.*FF*L*G*G*V(1)/(2.*DH*GC)
C*** REPEAT THE ABOVE COMPUTATIONS AS IF 100% VAPOR FLOW
      D(IGA+21)=G*DH/MU(2)
      CO=TLUP(ID(IRCD+7))
      HT(5)=CO*60.*G*CPY(2)/PR(2)**.67
      FF=TLUP(ID(IRCD+6))
      DP(2)=4.*FF*L*G*G*V(2)/(2.*DH*GC)
C*** DETERMINE WHICH FLUID-PHASE IS FLOWING AT THE INLET
      HSAT=VH(LOCT,D(IP+NSI),TSAT,V(2))-HFG
      TIN=D(IT+NSI)
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IRITE=1
      IF (IRITE .NE. 1) GO TO 9020
      REF=G*DH/MU(1)
      D(IGA+21)=REF
      COLBF=TLUP(ID(IRCD+7))
      FFF=TLUP(ID(IRCD+6))
      REV=G*DH/MU(2)
      D(IGA+21)=REV
      COLBV=TLUP(ID(IRCD+7))
      FFV=TLUP(ID(IRCD+6))
      VHPTV2=VH(LOCT,D(IP+NSI),TSAT,V(2))
      WRITE (OUT,9021)
 9021 FORMAT(' WRITE 9021 FROM "QBLRPP"     ')
      WRITE (OUT,9022) PR(1) , PR(2) , G      , REF
     *                , COLBF , HT(1) , FFF    , VR
     *                , DV     , SL     , DP(1) , REV
     *                , COLBV , HT(5) , FFV    , DP(2)
     *                , HSAT  , TIN    , VHPTV2
 9022 FORMAT(' PR(1) =', E12.5,  ' PR(2) =', E12.5,  ' G     =', E12.5
     *      ,' REF   =', E12.5,/,' COLBF =', E12.5,  ' HT(1) =', E12.5
     *      ,' FFF   =', E12.5,  ' VR    =', E12.5,/,' DV    =', E12.5
     *      ,' SL    =', E12.5,  ' DP(1) =', E12.5,  ' REV   =', E12.5
     *    ,/ ,' COLBV =', E12.5,  ' HT(5) =', E12.5,  ' FFV   =', E12.5
     *      ,' DP(2) =', E12.5,/,' HSAT L=', E12.5,  ' TIN   =', E12.5
     *      ,' VHPTV2=', E12.5)
 9020 CONTINUE
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IF(D(IH+NSI)-HSAT)360,332,332
  332 IF(D(IH+NIS)-HSAT-HFG)333,1272,1272
C$        LONGER COMMENTS
C*** IN TWO-PHASE REGION   AT INLET
  333 XI=(D(IH+NSI)-HSAT)/HFG
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IRITE=1
      IF (IRITE .NE. 1) GO TO 9023
      WRITE (OUT,9024)
 9024 FORMAT(' WRITE 9024 FROM "QBLRPP"     ')
      WRITE (OUT,9025) XI
 9025 FORMAT(' XI    =', E12.5)
 9023 CONTINUE
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      TIN=TSAT
```

```
      GO TO 370
C*** IN LIQUID-ONLY REGION   AT INLET
  360 XI=0.0
  370 IF(D(IH+NSI)-HSAT)380,371,371
C*** IN TWO-PHASE REGION   AT INLET
  371 X1=0.0
      X2=0.0
      GO TO 750
C*** IN LIQUID-ONLY REGION   AT INLET
C*** COMPUTE FLUID TEMPERATURE (T) AND WALL TEMPERATURE (TW) AT OUTLET
  380 T(5)=TIN+Q/(W*CPY(1))
      TW(5)=T(5)+Q/(AH*HT(1))
C*** DETERMINE TEMPERATURE AT WHICH NUCLEATE BOILING BEGINS (TNB)
C    AND DETERMINE IF FLUID REACHES THE TEMPERATURE BEFORE OUTLET
      TNB=TSAT+SQRT(8.*60.*ST*Q/(K(1)*AH*PT))
      X1=(TNB-TIN)*W*CPY(1)*L/Q-W*CPY(1)*L/(HT(1)*AH)
C     WRITE(OUT,*) T(5),TW(5),TNB,X1
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IRITE=1
      IF (IRITE .NE. 1) GO TO 9030
      WRITE (OUT,9031)
 9031 FORMAT(' WRITE 9031 FROM "QBLRPP"     ')
      WRITE (OUT,9032) T(5)   , TW(5) , TNB    , X1
 9032 FORMAT(' T(5)  =', E12.5,  ' TW(5) =', E12.5,  ' TNB   =', E12.5
     *       ,' X1    =', E12.5)
 9030 CONTINUE
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IF(X1)430,450,450
C*** SUBCOOLED BOILING BEGINS IMMEDIATELY AT THE INLET
  430 X1=0.0
      GO TO 485
  450 IF(TW(5)-TNB)460,480,480
C*** THERE IS NO BOILING WITHIN THE BOILER
  460 X1=L
      GO TO 1310
C*** COMPUTE THE TEMPERATURES AT THE END OF THE NON-BOILING REGION
  480 T(1)=TIN+Q*X1/(L*W*CPY(1))
      TW(1)=T(1)+Q/(HT(1)*AH)
C*** COMPUTE THE LENGTH OF THE SUBCOOLED-BOILING REGION
  485 X2=(TSAT-TIN)*W*CPY(1)*L/Q-X1
      IF(X2.GE.(L-X1))X2=L-X1
C*** COMPUTE THE BUBBLE DEPARTURE DIAMETER (DD) IN FEET
  490 DD=4.65E-4*SQRT(GC/GC*ST*V(1)/DV)*(VR*CPY(1)*TSAT/HFG)
     ***1.25
C*** COMPUTE THE FREQUENCY OF DEPARTURE OF BUBBLES, 1/SEC.
      FD=.6*SQRT(SQRT(ST*GC*GC*V(1)*DV))/DD
C*** ASSUME THE SURFACE FACTORS: B(SURFACE COFFICIENT); EM (EXPONENT
C    RELATING THE NUMBER OF NUCLEATION SITES GO THE TEMPERATURE
C    DIFFERENCE); AND RS(RADIUS, FT., OF SMALLEST SITE)
      B=400.
      EM=2.0
      RS=0.0001
C*** COMPUTE THE NUMBER OF NUCLEATION SITES PER SQ. FT.
      XN=B*(JC*RS*HFG*(TNB-TSAT)/(2.*TSAT*ST*V(2)))**EM
C*** COMPUTE THE POOL BOILING HEAT-TRANSFER COEFFICIENT
      HP=3.5*(K(1)/DD/60.)*XN*DD*DD
      HP=HP*SQRT(PR(1))*SQRT(FD*DD*DD/(V(1)*MU(1)))
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IRITE=1
      IF (IRITE .NE. 1) GO TO 9040
      WRITE (OUT,9041)
 9041 FORMAT(' WRITE 9041 FROM "QBLRPP"     ')
      WRITE (OUT,9042) X1     , T(1)   , TW(1) , X2
     *                , DD     , FD     , B     , EM
     *                , RS     , XN     , HP
 9042 FORMAT(' X1    =', E12.5,  ' T(1)  =', E12.5,  ' TW(1) =', E12.5
     *      ,' X2    =', E12.5,/,' DD    =', E12.5,  ' FD    =', E12.5
     *      ,' B     =', E12.5,  ' EM    =', E12.5,/,' RS    =', E12.5
     *      ,' XN    =', E12.5,/,' HP    =', E12.5)
 9040 CONTINUE
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IF(IRET)500,500,980
C*** COMPUTE THE COMBINED CONVECTION/BOILING COEFFICIENT
  500 HT(2)=(HP*HP+HT(1)*HT(1))/(2.*HP)
C*** ITERATIVELY COMPUTE THE WALL TEMPERATURE IN THE SUBCOOLED REGION
      A1=HP/(TNB-TSAT)**2
      A0=2.0*(Q/(A1*AH))**2
      A1=4.0*((HT(1)/A1)**2)/3.0
      S0=SQRT(A0*A0-A1**3)
      XX=ABS((A0-S0)/(A0+S0))
      IF(XX-.0001)650,670,670
  650 U=(A0+S0)**(1./3.)
      GO TO 680
```

HT (1) =

= 5

$A1 = HP/(58)^2 = \cancel{18}\ 5.05$

$A\phi = 2 * (60/(\cancel{.75}\ 5.65 * 100))^2 = \cancel{.0000} = .0282$

$A1 = 4 * ((4.1)/5.05^2)/3. = \cancel{.10}\ .88$

$S\phi = \sqrt{.003^2 - .10^3} = \sqrt{9 \times 10^{-6} - .001} = \sqrt{\text{negative}}$

```
  670 U=(A0+S0)**(1./3.)+(A0-S0)**(1./3.)
  680 TC=(SQRT(U)+SQRT(U-4.*(U/2.-SQRT((U/2.)**2-.75*A1))))/2.
      T(2)=TSAT
      TW(2)=TSAT+TC
      TW(5)=TW(2)
      X3=0.0
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IRITE=1
      IF (IRITE .NE. 1) GO TO 9050
      WRITE (OUT,9051)
 9051 FORMAT(' WRITE 9051 FROM "QBLRPP"    ')
      WRITE (OUT,9052) IRET   , HT(2) , A0    , A1
     *                 ,S0    , XX    , U     , TC
     *                 ,T(2)  , TW(2) , TW(5)
 9052 FORMAT(' IRET  =', I4,8X,  ' HT(2) =', E12.5,  ' A0    =', E12.5
     *      ,' A1    =', E12.5,/,' S0    =', E12.5,  ' XX    =', E12.5
     *      ,' U     =', E12.5,  ' TC    =', E12.5,/,' T(2)  =', E12.5
     *      ,' TW(2) =', E12.5,  ' TW(5) =', E12.5)
 9050 CONTINUE
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C*** GO TO 1280 IF THE EXIT IS 100% LIQUID (NO NET BOILING)
      IF(X2.GE.(L-X1))GO TO 1280
C*** STARTING REGION 3: BULK BOILING
  750 XC=1.0
C*** COMPUTE THE DRYOUT POSITION
      X3=W*(CPY(1)*(TSAT-TIN)+HFG*(1.0-XI))*L/Q-X1-X2
C*** COMPUTE THE EXIT QUALITY
      XE=(Q/W-CPY(1)*(TSAT-TIN))/HFG+XI
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IRITE=1
      IF (IRITE .NE. 1) GO TO 9053
      WRITE (OUT,9054)
 9054 FORMAT(' WRITE 9054 BULK BOILING-DRYOUT POSITION  FROM "QBLRPP"')
      WRITE (OUT,9055) X3    , XE
 9055 FORMAT(' X3DRYO=', E12.5,  ' XE    =', E12.5)
 9053 CONTINUE
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IF(XE-1.)830,820,820
C*** FILM-BOILING OR VAPOR-ONLY HEATING OCCUR
  820 XE=1.0
      GO TO 1140
C*** COMPUTE THE CRITICAL EXIT QUALITY ABOVE WHICH FILM BOILING OCCURS
C$WAS COMPUTE THE CRITICAL EXIT QUALITY ABOVE WHICH VAPORIZATION OCCURS
  830 XC=JC*HFG*(XE-XI)/L
C$            NEED TO USE "REF" HERE AS ON P 97 COSTELLO
C$            CODE USED OLD "REV" VALUE... LINE BELOW SHOULD FIX
      D(IGA+21)=G*DH/MU(1)
      XC=1.04-1.14E-5*(D(IGA+21)*D(IGA+21)*XC)**.375
C*** COMPUTE LENGTH OF THE BULK-BOILING REGION (X3)
      X3=X3*(XC-XI)/(1.0-XI)
      IF (X3.LT.0.0) X3=0.0
      IF(X3.GT.(L-X1-X2))X3=L-X1-X2
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IRITE=1
      IF (IRITE .NE. 1) GO TO 9060
      WRITE (OUT,9061)
 9061 FORMAT(' WRITE 9061  FROM "QBLRPP"    ')
      WRITE (OUT,9062) X3    , XE    , XC
 9062 FORMAT(' X3    =', E12.5,  ' XE    =', E12.5,  ' XC    =', E12.5)
 9060 CONTINUE
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IF(XE.GE.XC)GO TO 1140
C*** COMPUTE THE TWO-PHASE PARAMETER
      TT=(1.0/XE-1.0)**0.9*SQRT(DP(1)/DP(2))
      X3=L-X1-X2
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IRITE=1
      IF (IRITE .NE. 1) GO TO 9070
      WRITE (OUT,9071)
 9071 FORMAT(' WRITE 9071    XE LESS THAN XC    FROM "QBLRPP"    ')
      WRITE (OUT,9072) TT    , X3
 9072 FORMAT(' TT    =', E12.5,  ' X3    =', E12.5)
 9070 CONTINUE
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C*** GO TO 1090 IF XE AND TT INDICATE THE RANGE FOR ELLERBROOK'S FORMULA
      IF(XE.GT.0.7.OR.TT.LT.0.01)GO TO 1090
C*** USE CHEN'S FORMULA
      F=1.0+1.88/TT**0.8
      Y=F*(G*DH/MU(1)*(1.0-XE))**0.8/10000.
      S=EXP(-Y)
C*** COMPUTE TNB AS A FIRST APPROXIMATION TO THE WALL TEMPERATURE
C    THEN GO TO 490 TO COMPUTE THE POOL-BOILING HEAT-TRANSFER COEFF.
      TNB=TSAT+SQRT(.8*60.*ST*Q/(K(1)*AH*PT))
```

```
      IRET=1
      GO TO 490
C*** COMPUTE THE BULK-BOILING COEFFICIENT WITH CHEN'S FACTORS
  980 HT(3)=F*HT(1)+S*HP
C*** COMPUTE THE WALL TEMPERATURE AT THE END OF THE TWO-PHASE REGION
C    UNDER THE ASSUMPTION THAT EM IS APPROXIMATELY 2.0
      A1=HP/(TNB-TSAT)**2
      A0=Q/(AH*S*A1*2.0)
      A1=F*HT(1)/(3.0*S*A1)
      S0=SQRT(A0*A0+A1**3)
      T(3)=TSAT
      TW(3)=TSAT+(A0+S0)**(1./3.)-(S0-A0)**(1./3.)
      TW(5)=TW(3)
      T(5)=TSAT
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IRITE=1
      IF (IRITE .NE. 1) GO TO 9080
      WRITE (OUT,9081)
 9081 FORMAT(' WRITE 9081      CHEN''S FORMULA       FROM "QBLRPP"     ')
      WRITE (OUT,9082) F      , Y      , S      , TNB
     *                ,IRET   , A0     , A1     , S0
     *                ,T(3)   , TW(3)  , TW(5)  , T(5)
     *                ,HT(3)
 9082 FORMAT(' F     =', E12.5,  ' Y     =', E12.5,  ' S     =', E12.5
     *      ,' TNB   =', E12.5,/,' IRET  =', I4,8X,  ' A0    =', E12.5
     *      ,' A1    =', E12.5,  ' S0    =', E12.5,/,' T(3)  =', E12.5
     *      ,' TW(3) =', E12.5,  ' TW(5) =', E12.5,  ' T(5)  =', E12.5,/
     *      ,' HT(3) =', E12.5)
 9080 CONTINUE
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C*** GO TO 1320 TO COMPUTE THE TWO-PHASE PRESSURE DROP
      GO TO 1320
C$     THE ELLERBROOK FORMULA GIVES AN H LOWER THAN FOR FILM BOILING
C$     AND LOWER THAN "HT(5)" (ALL VAPOR).  IS SOMETHING WRONG OR IS
C$     ELLERBROOK JUST A DAMN FLAKE??
C*** ELLERBROOK'S FORMULA FOR THE HEAT-TRANSFER COEFFICIENT
 1090 Y=2.35-ALOG(TT)*(.266+.0255*ALOG(TT))
      HT(3)=HT(5)*(Q/(AH*60.*G*HFG))**.4*EXP(Y)
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IRITE=1
      IF (IRITE .NE. 1) GO TO 9090
      WRITE (OUT,9091)
 9091 FORMAT(' WRITE 9091   ELLERBROOK''S HT(3) FORMULA FROM "QBLRPP"')
      WRITE (OUT,9092) Y      , HT(3)
 9092 FORMAT(' Y     =', E12.5,  ' HT(3) =', E12.5)
 9090 CONTINUE
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      GO TO 1180
C*** XE>XCRIT OR XE>1.  SO FILM BOILING OR VAPOR-ONLY HEATING OCCURS
C$WAS SO FILM BOILING OR VAPOR-ONLY HEATING OCCURS
 1140 HT(3)=HT(5)*(XE+SL/VR*(1.0-XE))**0.8
C*** FLUID AND WALL TEMPERATURES AT THE END OF THE TWO-PHASE REGION
C$WAS 1180 T(3)=TSAT+(Q*(X3+X2+X1)/W/L-CPY(1)*(TSAT-TIN)-HFG*(XE-XI))
C$         /CPY(2)
C$
C$   CERTAINLY WHILE TWO-PHASE, T=TSAT!!!
 1180 T(3)=TSAT
      TW(3)=T(3)+Q/(AH*HT(3))
      T(5)=T(3)
      TW(5)=TW(3)
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IRITE=1
      IF (IRITE .NE. 1) GO TO 9100
      WRITE (OUT,9101)
 9101 FORMAT(' WRITE 9101   FILM BOIL OR VAPOR ONLY HEATING   "QBLRPP"')
      WRITE (OUT,9102) T(3)   , HT(3)  , TW(3)  , T(5)
     *                ,TW(5)  , X1     , X2     , X3
     *                ,XI     , XE
 9102 FORMAT(' T(3)  =', E12.5,  ' HT(3) =', E12.5,  ' TW(3) =', E12.5
     *      ,' T(5)  =', E12.5,/,' TW(5) =', E12.5,  ' X1    =', E12.5
     *      ,' X2    =', E12.5,  ' X3    =', E12.5,/,' XI    =', E12.5
     *      ,' XE    =', E12.5)
 9100 CONTINUE
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C*** IF VAPOR-ONLY FLOW DOES NOT OCCUR, GO TO 1320 TO COMPUTE DELTA P
      IF(XE.LT.1.0)GO TO 1320
C*** COMPUTE OUTLET CONDITIONS FOR VAPOR-ONLY FLOW
      T(5)=(Q/W-CPY(1)*(TSAT-TIN)-HFG*(1.0-XI))/CPY(2)+TSAT
      XE=1.0
      TW(5)=T(5)+Q/(AH*HT(5))
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IRITE=1
      IF (IRITE .NE. 1) GO TO 9110
```

```
      WRITE (OUT,9111)
 9111 FORMAT(' WRITE 9111   VAPOR ONLY HEATING  "QBLRPP"')
      WRITE (OUT,9112) T(5)   , XE     , TW(5)
 9112 FORMAT(' T(5)  =', E12.5,  ' XE    =', E12.5,  ' TW(5) =', E12.5)
 9110 CONTINUE
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      GO TO 1320
C*** COMPUTE OUTLET CONDITIONS FOR VAPOR-ONLY FLOW FROM INLET TO OUTLET
 1272 T(5)=TIN+Q/W/CPY(2)
      TW(5)=T(5)+Q/AH/HT(5)
C$   ADD 144 FACTOR; DO NOT COMPUTE "D(IP+NSO)" HERE AND LINE 1475
      XDP=DP(2)/144.
C$    D(IP+NSO)=D(IP+NSI)-DP(2)/144.
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IRITE=1
      IF (IRITE .NE. 1) GO TO 9120
      WRITE (OUT,9121)
 9121 FORMAT(' WRITE 9121   VAPOR ONLY INLET TO OUTLET   "QBLRPP"')
      WRITE (OUT,9122) T(5)   , TW(5)
 9122 FORMAT(' T(5)  =', E12.5,  ' TW(5) =', E12.5)
 9120 CONTINUE
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      GO TO 1475
C*** COMPUTE THE OUTLET TEMPERATURE FOR NO NET VAPOR GENERATION
 1280 T(5)= TIN+Q/(AH*CPY(1))
 1310 PB=0.0
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IRITE=1
      IF (IRITE .NE. 1) GO TO 9130
      WRITE (OUT,9131)
 9131 FORMAT(' WRITE 9131 TOUT FOR NO NET VAPOR GENERATED  "QBLRPP"')
      WRITE (OUT,9132) T(5)   , PB
 9132 FORMAT(' T(5)  =', E12.5,  ' PB    =', E12.5)
 9130 CONTINUE
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      GO TO 1350
C*** COMPUTE THE TWO-PHASE PRESSURE DROP BY FAC. INC. CORRELATION
C    OF BAROCZY'S GRAPHICAL CORRELATION
 1320 PF=0.25*ALOG10(DP(1)/DP(2))
      PB=XE**.7/1.7-(1-XE)**2.3/2.3+(1.-(1.-XE)**3.3)/(3.3*2.3*XE)
C*** COMPUTE THE FRICTION PRESSURE DROP
      PB=-XE**1.65*PF/2.65+(1.0+PF)*PB
 1350 FP=DP(1)*(X1+X2)/L+(DP(1)+PB*(DP(2)-DP(1)))*X3/L
      FP=FP+DP(2)*(1.-(X1+X2+X3)/L)
      IF(XE) 1382,1382,1385
C*** ADD THE MOMENTUM PRESSURE DROP
 1382 MP=0.0
      GO TO 1470
 1385 VE=XE/(XE+SL*(1.0-XE)/VR)
      IF(VE-1.0)1388,1386,1386
 1386 ME=VR
      GO TO 1390
 1388 ME=((1.-XE)/(1.-VE))**2*(1.-VE*(1.-SL*SL/VR))
 1390 IF(XI)1395,1395,1400
 1395 MI=1.0
      GO TO 1440
 1400 VI=XI/(XI+SL*(1.0-XI)/VR)
      IF(VI-1.0)1430,1425,1425
 1425 MI=VR
      GO TO 1440
 1430 MI=((1.-XI)/(1.-VI))**2*(1.-VI*(1.-SL*SL/VR))
 1440 MP=G*G*V(1)*(ME-MI)/GC
 1470 XDP=(FP+MP)/144.
 1475 D(IP+NSO)=D(IP+NSI)-XDP
CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IRITE=1
      IF (IRITE .NE. 1) GO TO 9140
      XFPPSI= FP/144.
      XMPPSI= MP/144.
      WRITE (OUT,9141)
 9141 FORMAT(' WRITE 9141     DELTA P CALC         FROM "QBLRPP"     ')
      WRITE (OUT,9142) PF     , PB     , FP     , XE
     *                ,VE     , ME     , MI     , VI
     *                ,MP     , XMPPSI, XDP    , XFPPSI
 9142 FORMAT(' PF    =', E12.5,  ' PB    =', E12.5,  ' FP    =', E12.5
     *      ,' XE    =', E12.5,/,' VE    =', E12.5,  ' ME    =', E12.5
     *      ,' MI    =', E12.5,  ' VI    =', E12.5,/,' MP    =', E12.5
     *      ,' XMPPSI=', E12.5,  ' XDP   =', E12.5,  ' XFPPSI=', E12.5)
 9140 CONTINUE
CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IF (D(IP+NSO).GT.0.0)GO TO 1476
      WRITE(OUT,7655) D(IP+NSO),D(IP+NSI)
 7655 FORMAT(' *+* OUTLET PRESSURE IN QBOILER WAS',E14.7,
     *  ' RESET PRESSURE TO INLET VALUE',E14.7)
```

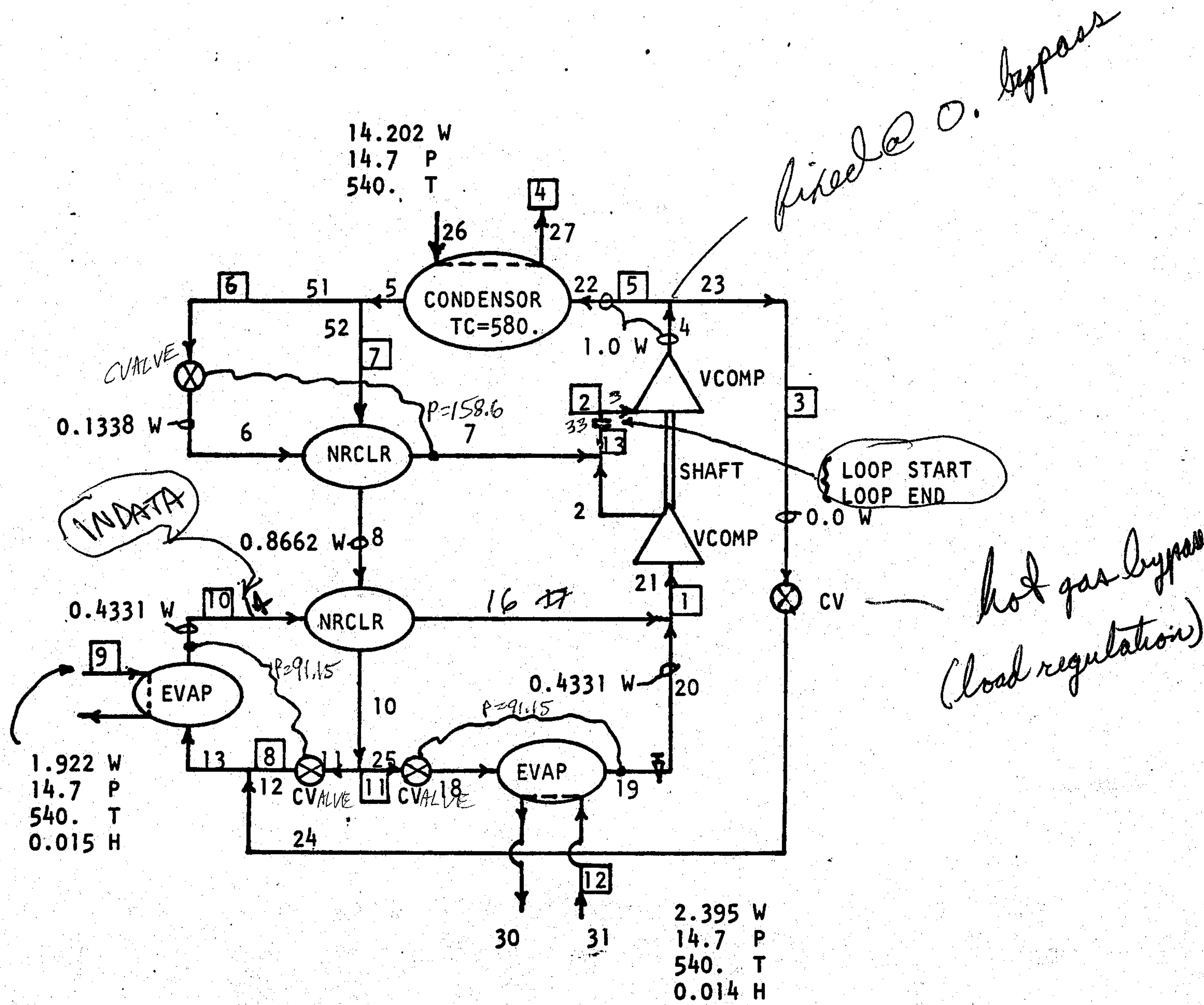
```
      XDP=0.0
      D(IP+NSO)=D(IP+NSI)
 1476 CONTINUE
C$WAS IF(T(5)-TSAT)1478,1479,1479
      IF(T(5)-TSAT)1478,14785,1479
 1478 D(IH+NSO)=VHLIQ(LOCT,D(IP+NSI),T(5))
      GO TO 1480
C$      NEW LINE BELOW CALCULATES EXIT ENTHALPY WHEN TWO-PHASE AT EXIT
14785 D(IH+NSO)=HSAT+XE*HFG
      GO TO 1480
 1479 VV=VSV('QBLRPP 2',LOCT,D(IP+NSO),T(5))
      D(IH+NSO)=VH(LOCT,D(IP+NSO),T(5),VV)
 1480 CONTINUE
      D(IT+NSO)=T(5)
CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IRITE=1
      IF (IRITE .NE. 1) GO TO 9150
      WRITE (OUT,9151)
 9151 FORMAT(' WRITE 9151   ASSIGN HOUT AND TOUT     FROM "QBLRPP"     ')
      WRITE (OUT,9152) T(5)  , VV     , TSAT  , HSAT
     *                 ,XE     , HFG
 9152 FORMAT(' T(5)  =', E12.5,  ' VV    =', E12.5,  ' TSAT  =', E12.5
     *       ,' HSAT  =', E12.5,/,' XE    =', E12.5,  ' HFG   =', E12.5)
 9150 CONTINUE
CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IF (ID(IRCD+13).EQ.0) GO TO 1579
      IF(PASS.NE.1) GO TO 1577
      ID(IEVT+JEVI)=3
 1577 IF (TMAX.GE.TSAT) GO TO 1576
      WRITE(OUT,1580) TMAX,TSAT,TW(5)
 1580 FORMAT(5X,'WARNING FROM QBOILER: ERROR VARIABLE CANNNOT BE '/
     *' CONTROLLED BECAUSE THE CONTROLLED WALL TEMPERATURE OF',E17.7/
     *' IS LESS THAN THE SATURATION TEMPERATURE OF',E17.7/
     *' THE WALL TEMPERATURE IS',E17.7)
 1576 IF(T(5).GT.TSAT)GO TO 1578
      WRITE(OUT,1590)XE
 1590 FORMAT(5X,'WARNING FROM QBOILER: TWO PHASE FLUID AT OUTLET',
     *' PROBABLY CANNOT CONTROL WALL TEMP. EXIT QUALITY IS',E12.4)
 1578 D(IEV+JEVI) = (TMAX-TW(5))/XE
 1579 CONTINUE
 1485 FORMAT(' OVERALL: DP,TW(5),T(5) ',3F10.3)
      IF (IFP.NE.1.OR. ICPP.NE.0) GO TO 99
      CALL PIOP(1,NL,NSI,NSO)
      CALL LINES(2)
      WRITE(OUT,1581) ID(ISN+NSO),TW(5)
 1581 FORMAT(5X,'BOILER AT STATION NO.',I4,' HAS A MAXIMUM WALL ',
     * 'TEMPERATURE OF',E15.5,' DEGREES R')
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      WRITE(OUT,9581) XI, XE
 9581 FORMAT('        INLET QUAL=', F8.3, '     EXIT QUAL=', F8.3)
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
   99 CONTINUE
      RETURN
C     QBLRPP
      END
```

WARNING - COMMON /CC/ is smaller than an earlier program unit declaration (See Section 6.4 in Lahey Language Reference Manual), File PCAECS.FOR, line 19633.
WARNING - COMMON /DC/ is smaller than an earlier program unit declaration (See Section 6.4 in Lahey Language Reference Manual), File PCAECS.FOR, line 19647.
WARNING - INTEGER VARIABLE (NIS) never assigned a value, File PCAECS.FOR, line 19784.

```
630=TABV          0.0         0.0         30.0       1.0
640=TABID       2   5   2   0   0  410001   2
650=TABT        AIR SIDE EFFECTIVENESS T=5 RN=2 (IND.VAR.=AIR FLOW)
660=TABV          0.0         1.0         30.0       0.5
670=TABID       3   1   2   0   0  420001   2
680=TABT        REFRIG SIDE PRESS DROP T=1 RN=3 (IND.VAR.=REFRIG FLOW)
690=TABV          0.0         0.0          2.0       6.0
700=TABID       4  61   2   0   0 1000101   2
710=TABT        PRESS-DROP,COLD SIDE: TYPE=61 REL.NO=4
720=TABV         0.0        0.0         1.0       10.0
730=TABID       4  62   2   0   0 1020001   2
740=TABT        PRESS-DROP,HOT SIDE: TYPE=62 REL.NO.=4
750=TABV        0.0         0.0         1.0        10.0
760=STAB        1   6  72   6
770=STAB        9  61   4  61
780=STAB        9  62   4  62
790=TABID       4   1   2   0   0  410001   2
800=TABT        AIR SIDE PRESS DROP T=1 RN=1 (IND VAR = AIR FLOW)
810=TABV         0.0        0.0          5.0        0.1
820=TABID       5   5   2   0   0  410001   2
830=TABT        AIR SIDE BYPASS FACTOR T=5 RN=2 (IND VAR = AIR FLOW)
840=TABV         0.0        0.0          5.0        0.3
850=TABID       6   2   2   0   0  420001   2
860=TABT        REFRIG SIDE PRESS DROP T=1 RN=3 (IND VAR = )
870=TABV         0.0        0.0          1.0       10.0
880=STAB       14   1   4   1
890=STAB       15   5   5   5
900=STAB       16   2   6   2
910=PTAB        1   0   1   0
920=ENDCASE
930=ENDJOB
940=*EOR
940=*EOR
B
```

make tabs 15 type 5 same as 5 type 5

Exhibit A-1 (b): Flow Diagram for the Sample Case



LOOPS must be strategically located to enhance the solution procedure. AECS proceeds in its computations from component to component in the order entered by the user. In addition, AECS is designed such that the inlet conditions to a component must be known before the component can be analyzed. Therefore, LOOPS must be placed such that subsequent inlet conditions are known. (Our new component INDATA permits violating this rule, but only at the cost of additional computer time. Therefore, we should use INDATA only where absolutely necessary.) In our case, we considered the inlets to the compressors as suitable locations for LOOPS, because we knew reasonably well the values of flow, pressure, temperature and enthalpy at these points. However, if we had chosen the low-pressure compressor, we would have found difficulties at the compressor outlet. We would have encountered a merge at which only one inlet port (the low-pressure compressor outlet) had known values. The other (coming from the intercooler) would not be defined until we had analyzed the high-pressure compressor, the condenser and the intercooler. INDATA could have been used, but a better choice in terms of computer time was to locate LOOPS at the inlet to the high-pressure compressor. The merge would be encountered last in the computations, so the thermodynamic states at both inlet stations to the merge would be known at the time of the computations.

The outlet conditions from LOOPS will be matched, eventually, by the outlet conditions from LOOPE. Therefore, we were led to the compressor inlets, where the pressures were almost known because the evaporator temperatures were almost deducible from the temperature to which we wanted to decrease the air. By choosing a point in the system at which the thermodynamic states were almost known, we were able to reduce the number of iterations required for AECS to solve the system.

STATION 4, at the outlet of the high-pressure compressor, is the inlet station to a SPLIT, which can divert some of the flow through the hot-gas-bypass (HGBP) valve to provide load regulation. However, we decided for the test case to experiment with the compressor characteristics such that there would be no flow through the HGBP valve. Notice if the HGBP flow were non-zero, we still would not have been able to proceed with the computations by way of the HGBP, because on arriving at STATION 24 we would not have known the thermodynamic states at STATION 12, so we could not analyze the MERGE. In either case, we should proceed along to STATION 22.

The input data, tabulated in Exhibit A-1, continues from Station 22 in the usual AECS manner. Some discussion of the selection of the state and error variables is required, but this is deferred until the next section. Notice that by analyzing LEG 6 before LEG 7, we are able to have both inlet stations to the high-temperature intercooler (STATION 6 and STATION 52) defined before the intercooler analysis is performed. Such an arrangement is not possible at the second (low-temperature) intercooler.

At the second intercooler (NRCLR) we find that the thermodynamic conditions at STATION 14 cannot be defined until the thermodynamic conditions at STATION 9 are calculated. But STATION 9 requires solving the second intercooler. Prior to this contract, AECS could not solve such a situation, so it could not solve a problem of the type shown in Exhibit A-1. We have introduced the component INDATA to give AECS the required capability. Before the second intercooler we place an INDATA (INitialize-the-DATA) component. This component accepts our estimated values for the thermodynamic states as the first guesses.

Following the second NRCLR, after STATION 9, we encounter a SPLIT, with one side of the SPLIT (LEG 8) returning to STATION 14 through the evaporator. As the computations proceed along Leg 8, Station 14 will be encountered and a contradiction will be realized between the guesses introduced by INDATA and the results of the computations along Leg 8. AECS is now designed to use the results of the computations as the next guesses. Note that, as in all of AECS, skillful guessing is required to reduce computation time and, frequently, to obtain a solution.

With the exception of the introduction of INDATA, the component sequence is similar to that of any other AECS analysis. The outlet of the second intercooler (STATION 16) is carried to the MERGE, where the computations are deferred until the analysis of LEG 11 arrives at the same merge. Then both inlet stations will have known thermodynamic states and the computations can proceed directly. The input definition ends with the LOOPE component.

Many of the parameters used in the example were chosen for input simplicity. For example, the tables were selected for convenience, so our work was decreased and so the reader would not be burdened by too many numbers. Therefore, the reader should not take the values as being typical. (Typical values are presented in Appendix D.) We have tried to keep the forms of the tables general. For example, we have used a 33-dimensional table to enter a constant efficiency, where a 3-dimensional table would have sufficed. We also used STAB (Same TABle) where possible for duplicate tables.

The reader might want to compare the component-card formats as presented in Section 2 of this report to the data in Exhibit A.1 (a); however, comparison to the data for the individual components (Sections 3 to 19) would be more instructive and easier to follow than Exhibit A.1.

A.3. Selection of the State and Error Variables

We are not entirely free in our selection of state and error variables because some components allow for state or error variables to be selected as options, whereas other components require one or the other. In our example, the three control valves automatically generate three state variables (the control-valve pressure-drop coefficients). However, we do have considerable freedom, a freedom essential to successfully solving the system equations.

Our first selection of state and error variables was unsuccessful. In addition to the three state variables required for the three control valves, we had:

- the pressure at the loop start
- the enthalpy at the loop start
- the pressure ratio of the low-pressure compressor
- the pressure ratio of the high-pressure compressor

The error variables were selected as follows:

- the superheat of the high-temperature intercooler, which we presumed would be controlled by the control valve just upstream of Station 6
- the superheat at the outlet of the evaporator in Leg 10, which would be controlled by the control valve upstream of Station 12
- the superheat at the outlet of the evaporator in Leg 11, which would be controlled by the control valve upstream of Station 18
- the pressure balance at the MERGE of Legs 10, 11 and 1, which we presumed would control the flows to the two evaporators
- the pressure balance at the MERGE of Legs 1, 6 and 13, which would control the flow through the intercooler
- the pressure match at the loop end (Stations 3 and 33)
- the enthalpy match at the loop end

conflicts w

The first guesses of the solution, entered via the PARAMETER cards, were developed with the aid of REFRIG, the refrigerant-properties program we developed under this contract. The pressures and temperatures were selected at each evaporator and at the condenser. The split at the high-pressure intercooler was chosen to give superheated refrigerant at the outlet with a heat-exchanger effectiveness of approximately 0.6. The low-temperature intercooler was also assumed to have an effectiveness of 0.6. The split between the evaporators was based on their respective cooling requirements. The interstage pressure between the two compressors was assumed to be the square root of the product of the pressure at Station 21 and the pressure at Station 4 (this approximates the optimal interstage pressure with interstage cooling).

Although we expected to find the initial guesses to be close to the final solution, the standard Newton-Raphson solution procedure would not converge. Perhaps the component sizes we selected were sufficiently different from the assumed performance that the solution was impossible. It is more likely that the linearization used by the Newton-Raphson procedure was too far in error near the saturation line of the refrigerant. In developing the example for the intercooler by itself, we found Newton-Raphson could not solve for the system performance if only 5 F of superheat were used, whereas it could solve the problem if 10 F of superheat were used.

Non-convergence of the Newton-Raphson method can stem from many causes other than its failure to extrapolate to physically reasonable thermodynamic states. For example, the problem formulation may preclude the necessary condition that the condensing temperature be higher than the condenser cooling-air temperature. Also the refrigerant temperature in the evaporators must be less than the temperature of the air being cooled. High flow rates might be required, whereas at high flow rates the component pressure drops might be so high that the system will tend to operate at negative absolute pressures.

Unfortunately, the Newton-Raphson method gives little or no information on the cause of its failing to converge. Although diagnostics could be developed, the development work was deemed beyond the scope of the present contract. However, we did observe the difficulties near the saturation line with NRCLR. In addition, we noticed that the control valves could not control the superheat temperatures because the control valves are, in effect, only pressure controllers. They give as the outlet pressure the value

```
Pout = Pin - AK * W**2
```

where AK is the control-valve setting, which is the independent (state) variable generated by the control valve component. Revising the control-valve treatment of the state variable would probably require a significant re-structuring of the ACES solution sequence, so it too was deemed beyond the scope of the present contract.

We solved the problem of non-convergence of the Newton-Raphson procedure in three ways: (1) we changed the sensors connected to the control valves such that they controlled pressure rather than superheat; (2) we reduced the number of state and error variables; and (3) we switched from the Newton-Raphson procedure to the Maximum-Rate-of-Descent (MRD) procedure. With the control valves controlling the pressure, the valve action (AK) and the value it controlled were more closely tied, so the solution would be more direct. The reduced number of state and error variables helped us observe how the solution was progressing. And the MRD method gave us control over the direction of the successive solutions, so we could observe the trends. Once we were close to the solution with MRD, we switched back to Newton-Raphson to obtain the final solution.

A.4. Solution to the Test Case

Obviously, the solution to the test case, or any other system, depends on many more parameters than those the solution algorithm controls (the state variables). Our first formulation of the test case, although seemingly in keeping with realm of physical possibilities, had no solution for the set of state and error variables chosen. Typically, both the Newton-Raphson and MRD procedures drove one or more of the state variables to unrealistic values that led to arithmetic mode errors in the computer.

The MRD solution technique helped greatly in that the step size of the state-variable change could be kept small enough so that the solution could be monitored for a number of passes in which the steps were at least in the direction of reducing the error. The same could be done with the Newton-Raphson procedure, but the direction of the step is not always in the direction of the reducing the error. On observing the evolution of the solution from pass to pass, we concluded that the superheat error variable was incompatible with the MERGE pressure-balance error variable. In addition, the superheat was too dependent on fixed parameters (parameters that were not state variables) such as the heat-transfer coefficients.

We tried to simplify the solution process by re-selecting the state and error variables such that one state variable controlled one error variable. Such complete separation of the causes and effects is practically impossible, but the dominant inter-dependence can be achieved. We first changed the superheat sensors such that they controlled the evaporator pressure instead, because the control valves have the greatest influence on the pressures and only a peripheral influence on the superheat. We selected the pressures to give pressure balances at the MERGEs, so we were able to delete the MERGE pressure balances as error variables. The pressures were also selected to match the pressures at the beginning and end of the loop, so pressure matching between LOOPE and LOOPS could be eliminated as an error variable. The remaining state and error variables were as follows:

State Variables:

- The setting of the control valve upstream of Station 6
- The setting of the control valve upstream of Station 12
- The setting of the control valve upstream of Station 18
- The air flow rate through the evaporator just upstream of Station 19

Error Variables

- The pressure at Station 7 (vs. the set point of the sensor)
- The pressure at Station 14
- The pressure at Station 19
- The enthalpy match between LOOPE and LOOPS

Selecting the pressure set points required hand computations to make sure that the MERGE and LOOP pressures would balance. Even with these hand computations, several computer runs were required to adjust and verify the hand results.

We verified by numerical experimentation with AECS that the program could easily adjust the control valve settings to satisfy the pressure error variables. However, we found that the enthalpy did not match between LOOPE and LOOPS. An enthalpy imbalance indicates that the energy flows are not being balanced. In particular, the heat added at the evaporators and by the compressors is not being rejected totally by the condenser.

To balance the energy flows, we re-defined the conditions at one of the evaporators (upstream of Station 19). Although we could have changed the bypass factor, instead, we made the air flow rate a state variable, so the solution procedure could make the necessary adjustments. We used MRD so we could monitor the effect of the varying flow rate. Once we had nearly balanced the enthalpies at LOOPE, we employed the Newton-Raphson method to obtain the final solution (in five tries!). The final output data are shown in Exhibit A-1 (a) and in Exhibit A-2.

Exhibit A-2: AECS Output for the Sample Case

```
THE FOLLOWING LISTING IS FOR FILE   APPENDIX A

COMPONENT SHAFT
     SHAFT    1   N   10000.
COMPONENT VCOMP
     NL        2   NSI      3   NSO      4   FT       3   FN     -22
     W      1.00   PI  158.60   PO  299.75   TI  595.32   TO  666.48   HI122.0000   HO131.2436
     NL********    NSI      1   NSO      4   FT       0   FN       0
     W      0.00   PI     .87   PO  299.75   TI  158.61   TO  666.48   HI596.6586   HO131.2436
*AECS*  REFRIGERANT TEST CASE                                                              PAGE        9
   1  CASE R22-01                                                                         DATE 01/24/82

     SHAFT    1   PR  1.8900   EFF  .8500   HP    -.26
COMPONENT COND
     NL        5   NSI     22   NSO      5   FT       3   FN     -22
     W      1.00   PI  299.75   PO  299.40   TI  666.48   TO  586.61   HI131.2436   HO 53.6323
     NL        4   NSI     26   NSO     27   FT       2   FN      -1
     W      8.00   PI   14.70   PO   14.43   TI  540.00   TO  580.39   HI  0.0000   HO  0.0000
     EFF  .8667    Q    77.61
COMPONENT CVALVE
     NL        6   NSI     51   NSO      6   FT       3   FN     -22
     W       .13   PI  299.40   PO  158.60   TI  586.61   TO  539.81   HI 53.6323   HO 53.6323
     K   7.935699E+03
COMPONENT CVALVE
     NL        8   NSI     11   NSO     12   FT       3   FN     -22
     W       .43   PI  299.34   PO   92.67   TI  537.44   TO  505.94   HI 32.7933   HO 32.7933
     K   1.100266E+03
COMPONENT EVAP
     NL       10   NSI     13   NSO     14   FT       3   FN     -22
```

$9.244 \times 1.00 = \frac{9.244}{.26} = 35.5$

Should be

$\frac{550 \frac{lbFft}{secHp}}{778 \frac{lbFft}{BTU}} = .707 \frac{BTU}{secHp} = 42.4 \frac{BTU}{MIN}/Hp$

```
   W      .43   PI    92.67   PO    91.15   TI   505.94   TO   505.94   HI 32.7933   HO 97.5007
   NL       9   NSI      28   NSO      29   FT        2   FN       -1
   W     1.80   PI    14.70   PO    14.66   TI   540.00   TO   509.62   HI   .0150   HO   .0073
    BYPASS FACTOR  .1080   Q    28.08
COMPONENT  CVALVE
   NL      11   NSI      25   NSO      18   FT        3   FN      -22
   W      .43   PI   299.34   PO    92.81   TI   537.44   TO   506.03   HI 32.7933   HO 32.7933
   K   1.099521E+03
COMPONENT  EVAP
   NL      11   NSI      18   NSO      19   FT        3   FN      -22
   W      .43   PI    92.81   PO    91.16   TI   506.03   TO   509.92   HI 32.7933   HO109.3639
*AECS*  REFRIGERANT TEST CASE                                                            PAGE      10
    1  CASE R22-01                                                                       DATE 01/24/82

   NL      12   NSI      31   NSO      30   FT        2   FN       -1
   W     2.36   PI    14.70   PO    14.65   TI   540.00   TO   510.84   HI   .0140   HO   .0075
    BYPASS FACTOR  .1417   Q    33.19
COMPONENT  VCOMP
   NL       1   NSI      21   NSO       2   FT        3   FN      -22
   W      .87   PI    91.16   PO   158.61   TI   539.62   TO   596.76   HI114.7567   HO122.2768
   NL********   NSI       1   NSO       2   FT        0   FN        0
   W     0.00   PI      .87   PO   158.61   TI   158.61   TO   596.76   HI596.7638   HO122.2768
   SHAFT    1   PR   1.7400   EFF   .8500   HP     -.18
*AECS*  REFRIGERANT TEST CASE                                                            PAGE      11
    1  CASE R22-01                                                                       DATE 01/24/82

TIME E      148.17

FLOW RATE(S)-LB/MIN

(   1)     .87 (   2)    1.00 (   3)    0.00 (   4)    8.00 (   5)    1.00 (   6)     .13
(   7)     .87 (   8)     .43 (   9)    1.80 (  10)     .43 (  11)     .43 (  12)    2.36
(  13)    1.00

PRESSURE(S)-PSI
```

7.52 × .87 = 6.54 / .18 = 36.3

```
(   2)  159.41 (   3) [illegible] (   4)  299.75 (   5)  299.40 (   6) [illegible] (   7) [illegible]
(   8)  299.34 (   9)  299.34 (  11)  299.36 (  12)   92.67 (  13)   92.67 (  14)   91.15
(  16)   91.15 (  18)   92.81 (  19)   91.16 (  21)   91.16 (  22)  299.75 (  23)  299.75
(  25)  299.34 (  26)   14.70 (  27)   14.43 (  28)   14.70 (  29)   14.66 (  30)   14.65
(  31)   14.70 (  33)  158.61 (  51)  299.40 (  52)  299.40
```

TEMPERATURE(S)-DEG R

```
(   2)  596.76 (   3)  595.32 (   4)  666.48 (   5)  586.61 (   6)  539.81 (   7)  586.51
(   8)  572.28 (   9)  537.44 (  11)  537.44 (  12)  505.94 (  13)  505.94 (  14)  505.94
(  16)  570.09 (  18)  506.03 (  19)  509.92 (  21)  539.62 (  22)  666.48 (  23)  666.48
(  25)  537.44 (  26)  540.00 (  27)  580.39 (  28)  540.00 (  29)  509.62 (  30)  510.84
(  31)  540.00 (  33)  595.40 (  51)  586.61 (  52)  586.61
```

HUMIDITY(S)/ENTHALPY(S)-LBW/LBA / BTU/LB

```
(   2)122.2768 (   3)122.0000 (   4)131.2436 (   5) 53.6323 (   6) 53.6323 (   7)120.3020
(   8) 43.4167 (   9) 32.7933 (  11) 32.7933 (  12) 32.7933 (  13) 32.7933 (  14) 97.5887
(  16)120.1495 (  18) 32.7933 (  19)109.3639 (  21)114.7567 (  22)131.2436 (  23)131.2436
(  25) 32.7933 (  26)  0.0000 (  27)  0.0000 (  28)   .0150 (  29)   .0073 (  30)   .0075
(  31)   .0140 (  33)122.0138 (  51) 53.6323 (  52) 53.6323
```

STATE VARIABLE TYPE(S)

```
(   1)     6 (   2)     6 (   3)     6 (   4)     1
```

STATE VARIABLE(S)

```
(   1) 7.93570E+03 (   2) 1.10027E+03 (   3) 1.09952E+03 (   4) 2.36157E+00
```

ERROR VARIABLE TYPE(S)

```
(   1)     2 (   2)     2 (   3)     2 (   4)     4
```

ERROR VARIABLE(S)

```
(   1)-3.21961E-10 (   2)-1.17447E-03 (   3) 7.34117E-03 (   4)-1.37507E-02
```

ZOOPE
.00017 for h match

SOLUTION CONVERGED IN   5 TRY(S)

0 ERROR(S) DETECTED

CASE END

Appendix B: Sample for the Skillful Use of the Maximum-Rate-of-Descent Method

B.1. Introduction

With this modification of AECS, we have given the user a new tool, the Maximum-Rate-of-Descent (MRD) method, by which he might obtain a solution otherwise unattainable. The method gives the user more control over the direction of the solution. It also gives him more information on the progress of the solution, so that he can estimate whether a solution is attainable or at least so that he can see the direction of the solution and thereby devise improved initial guesses. However, because the user has more control with the MRD method, he also requires more skill.

The purpose of this appendix is to give the user an example that shows some aspects of the MRD method and its skillful use.

B.2. Description of the Example

We choose as our example problem the simple refrigeration loop defined in Section 4 for the COP component. The loop consists of a vapor compressor, a condenser, an expansion valve, and an evaporator. This example was solved in Section 4 with the Newton-Raphson method, the only method available on AECS before our modification. This same example was further analyzed in Section 16 with the MRD method, as the sample case for SOLN, the new solution component.

B.3. Application of the MRD Method

We will consider in this appendix MRD2 only, because it is probably the most useful MRD tool in diagnosing difficulties with the Newton-Raphson method. MRD2 permits the user to develop a graphical image of the solution process but does not confine the direction of the solution to one state-variable at a time, as does MRD1. MRD changes all variables at once, so envisioning the process is frequently too difficult. Recall that, in Section 16, the MRD2 method was applied and the output was listed in detail. In this appendix, we will present the computational results in graphical form only; however, one- and two-dimensional variations will be considered: MRD1 (one dimension, i.e., one state variable changing at each iteration) and MRD2 (two state variables changing at each iteration). One AECS "try" consists of a change in all state variables, so that, if NSV equals the number of state variables, there are NSV iterations per try in MRD1 and NSV/2 iterations per try in MRD2. In MRD, there is one iteration per try.

The results of our first attempt at an MRD solution were unsatisfactory, but did indicate a remedy. The sample problem has two state variables (so the MRD and MRD2 results would be identical): the control-valve flow-resistance factor, AK, and the air flow rate through the evaporator, Wair. Because the solution could be somewhere between AK of 0 and 2000 and Wair between 1 to 3, we chose as scale factors 1000 for AK and 1 for Wair. The results of the MRD2 solution are illustrated in Exhibit B-1, along with the results of the Newton-Raphson solution. After 26 tries, the RMS error is 2.7 (Exhibit B-1), whereas Newton-Raphson gives an RMS error of 0.00003 after 6 tries. The MRD2 solution is also quite far from the Newton-Raphson solution.

The cause of the slow convergence of MRD2 is evident: the successive MRD2 steps oscillate between AK of 1120 and AK of 1170, with slight changes being made in Wair. The scale factor for AK was poorly chosen, because the solution range is not 0 to 2000, but approximately 1120 to 1170.

By reducing the scale factor for AK from 1000 to 40, we were able to obtain the results depicted in Exhibit B-2. MRD2 converged after 26 tries, agreeing with the Newton-Raphson solution, although the RMS error was still higher than that of Newton-Raphson (recall that an RMS error less than 1.0 indicates that, on the average, each error variable is acceptably small, but not that each error variable individually is acceptably small). The importance of the scale factor is evident.

Our method of selecting the scale factor is typical of the process that would be used in unfamiliar cases. We made our best estimate, then examined the range in each state variable as the solution progressed. We changed our scale factors to reflect this range, and re-ran the AECS program with the new scale factors. Notice that the MRD1 method could also have been used to determine the range of variation in either state variable, so suitable scale factors could have been established (equal to the range) with MRD1. In this case, with a scale factor of 40, the MRD1 method converges in 10 tries (Exhibit B-3).

This example is almost trivial. Your immediate reaction is probably that MRD2 is not helpful, because the Newton-Raphson method is obviously superior. Indeed it is --- if it converges. The MRD methods are to be used only if Newton-Raphson does not converge.

Therefore, you should first attempt to solve the problem with the Newton-Raphson method. If it fails, and you cannot readily determine why, then analyze the causes with the MRD methods. Once you have a good estimate of the solution, as obtained with MRD, then obtain the final solution with Newton-Raphson. However, do not be surprised if the Newton-Raphson method never converges. We have encountered such cases with a system consisting only of two RINLETs, a CVALVE, an NRCLR, and a SENSOR, when 5 degrees of superheat were desired. Apparently the Newton-Raphson linearization process is too crude when the refrigerant is near the saturation line.

Exhibit B-1: Graphical Representation of the MRD2 Solution with the AK Scale Factor of 1000

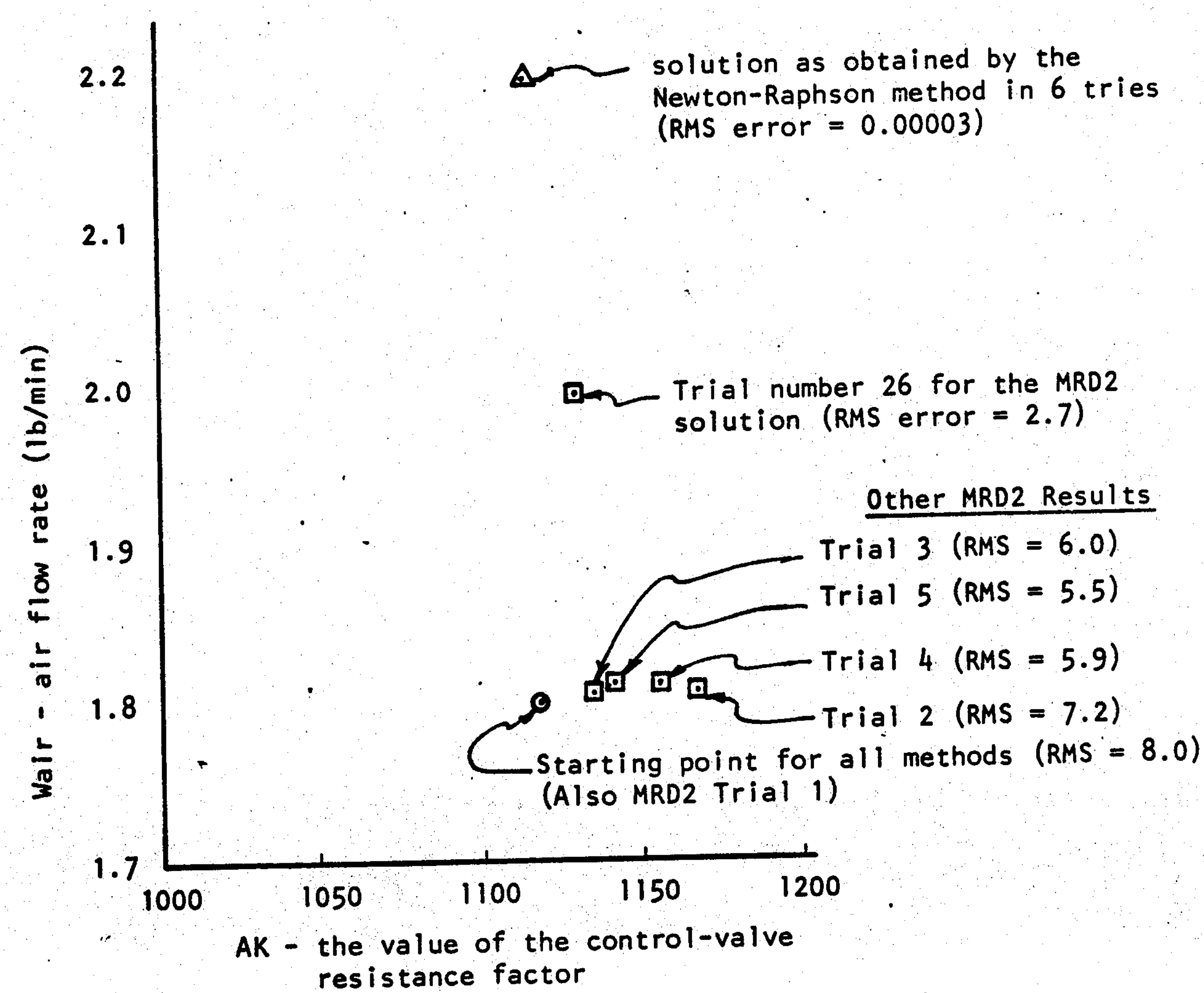


Exhibit B-2: Graphical Representation of the MRD2 Solution with the AK Scale Factor of 40

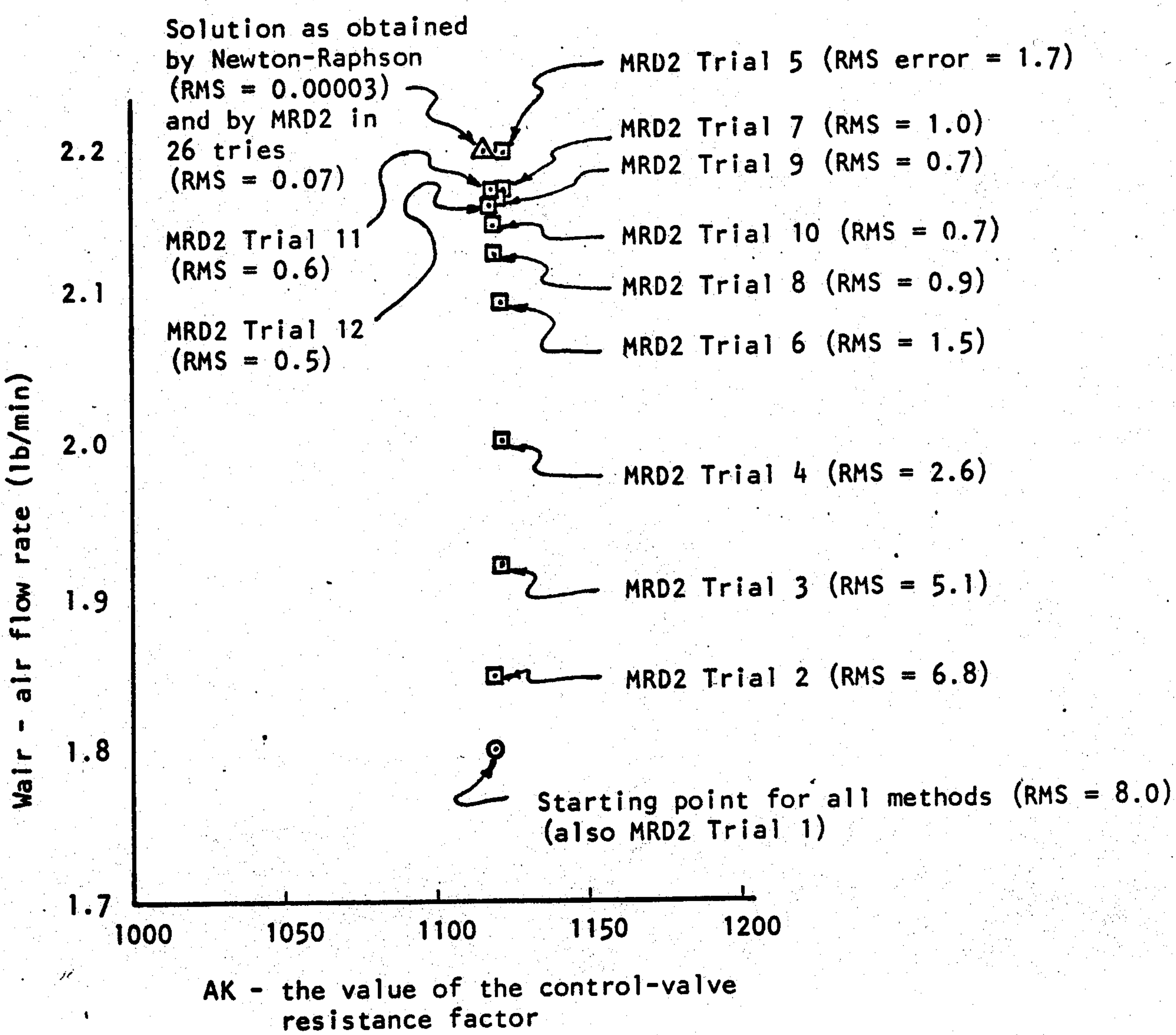
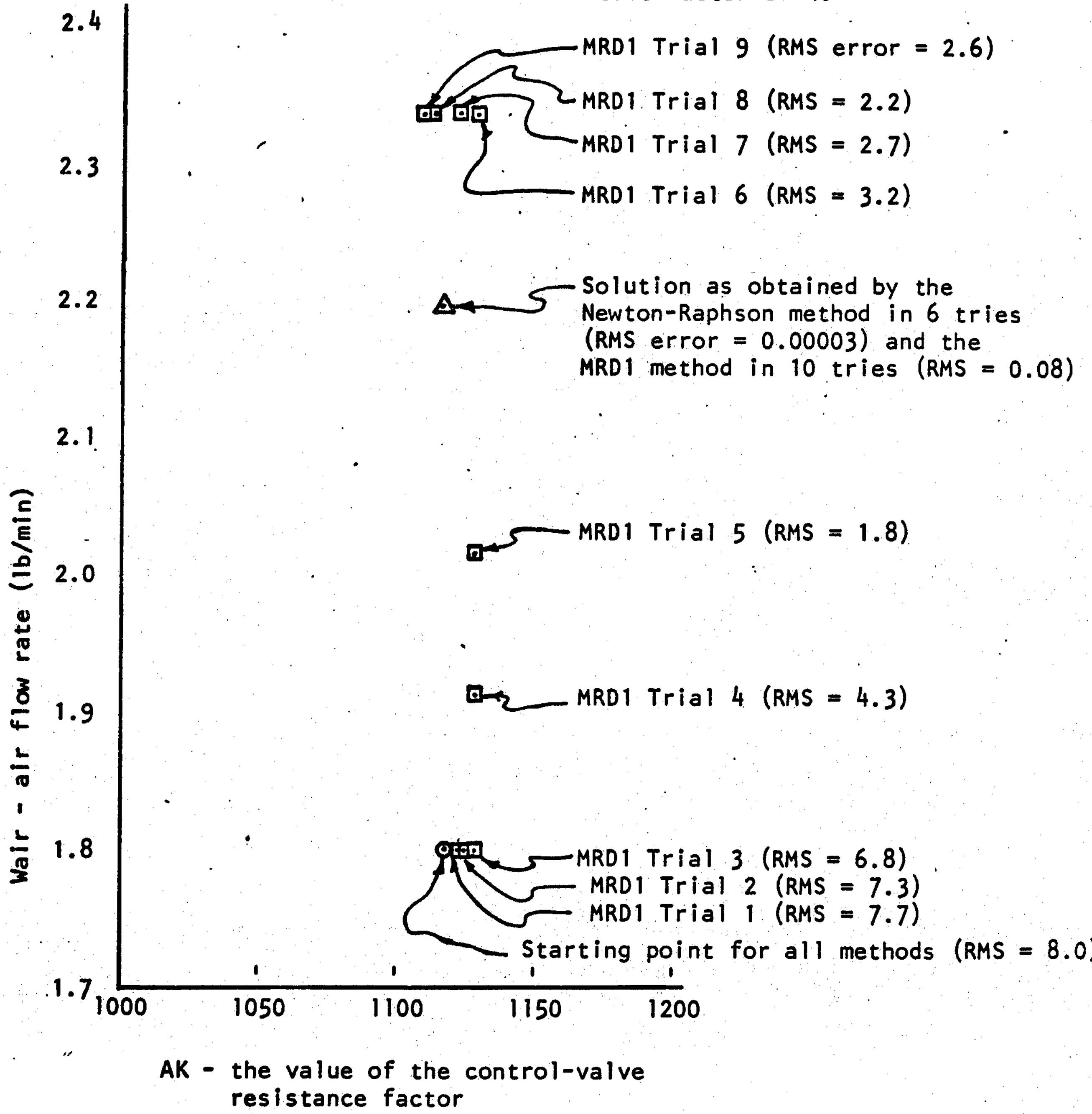


Exhibit B-3: Graphical Representation of the MRD1 Solution with the AK Scale Factor of 40



Appendix C: Some Notes on Entering the Tables

C.1. Introduction

The previously existing AECS manuals have extensive sections on the entry of data in tables. However, we have found two aspects of the data entry that are not clearly defined in the previous documentation:

1. The 33 dimensional tables with many input points; and
2. The -1 dimensional table with few input points.

In this appendix, we describe how these tables shoule be entered.

C.2. The 33-Dimensional Table

Suppose you have a table giving Y(X,Z), with six values of X and two values of Z. The table must be entered in the following form:

```
X1   X2   X3   X4
X5   X6
X1'  X2'  X3'  X4'
X5'  X6'
Z1   Z1'
Y11  Y21  Y31  Y41
Y51  Y61  Y11' Y12'
Y13' Y14' Y15' Y16'
```

where, for example, Y21 is Y at X2 and Z1 and Y21' is Y at X2' and Z1'. Notice that the X values for two different values of Z cannot be on the same line, whereas the Y values for two different values of Z must be on the same line.

C.3. The -1 Dimensional Table

Suppose you have an array of values, such as the weighting factors for the error variables. Because the program is designed for more than one error variable, a -1 dimensional table must be used. A potential problem arises, however, if there is only one state or error variable, so the -1 dimensional table has only one entry.

If there is only one entry in a -1 dimensional table, the user must enter the value 2 for the number of points (NPTS) on the TABID card. In all other cases, the number of points (NPTS) should be equal to the number of entries in the table. The AECS computational technique for -1 dimensional tables is based on an interpolation procedure. Therefore, the table-look-up routine must have at least two values between which to interpolate.

Appendix D: Typical Characteristics for Compressors, Expanders and Pumps

D.1. Introduction

For the convenience of the AECS user, we present in this section typical characteristics of refrigerant compressors, expanders and pumps. The performances are presented in dimensionless form, but examples are given to show how to convert the dimensionless forms to the dimensional forms required for AECS input.

The component characteristics presented in this appendix are hypothetical. Because we did not undertake a study of existing equipment, we were not able either to devise a baseline component characteristic or to verify the scaling laws. However, the hypothetical characteristics are consistent with the phenomena that occur in equipment of this type.

D.2. Refrigerant Pumps

Two sets of characteristics are presented for pumps: one for positive-displacement pumps and another for dynamic pumps. The positive-displacement pumps could include gear, vane, or piston types. The dynamic pumps can be centrifugal, axial or combinations.

The volume of fluid delivered by a positive displacement pump is nearly independent of the pressure difference from inlet to outlet. However, as the pressure difference increases, the amount of fluid leaking from the outlet back to the inlet through the seals increases. A typical positive-displacement pump might have the characteristics shown in Exhibit D-1.

Exhibit D-1: Typical Values of Flow Rate, Pressure Increase and Efficiency for a Positive-Displacement Pump Operating at the Rated Shaft Speed

Ratio of Flow Rate to Flow Rate at Rated Conditions	Ratio of Pressure Increase to Pressure Increase at Rated Conditions	Ratio of Efficiency to Efficiency at Rated Conditions
0.0	2.50	0.00
0.1	2.00	0.20
0.2	1.90	0.38
0.3	1.80	0.54
0.4	1.70	0.68
0.5	1.40	0.70
0.6	1.33	0.80
0.7	1.26	0.88
0.8	1.17	0.94
0.9	1.09	0.98
1.0	1.00	1.00
1.1	0.73	0.80
1.2	0.00	0.00

The ratios presented in Exhibit D-1 are based on the pump running at the rated shaft speed. The pressure rise is independent of shaft speed, but the flow rate is proportional to shaft speed. The efficiency can be assumed to be independent of shaft speed.

Example D-1: Suppose we have a system with a flow rate of 100 lbs per minute and we need a pump to produce a 250 psi pressure increase at a shaft speed of 25000 rpm. We assume that we can find a pump with exactly these ratings and that its nominal efficiency is 85%. To develop the tables for AECS, we first convert the values in Exhibit D-1 for the nominal shaft speed. To simplify the example, we will represent the pump with only 4 values of the flow rate: 0.0, 0.5, 1.0, and 1.2. We multiply each of these values by 100 lb/min to obtain the dimensional flow rates. The corresponding pressure rises are obtained by multiplying the values in Exhibit D-1 by 250 psi to obtain 625, 350, 250 and 0. The corresponding efficiencies are obtained by multiplying the values in Exhibit D-1 by 85% to obtain 0.0, 0.595, 0.85 and 0.0. We should also enter data for shaft speeds greater than and less than the nominal 25000 rpm, so that the input data will cover all possible operating conditions. At 12500 rpm (half of 25000 rpm), the flow rates will be half, so the flows will be 0, 25, 50 and 60 lb/min. The efficiencies and pressure rises remain the same. We also enter the data for 50000 rpm (twice 25000 rpm), so the flow rates will be 0, 100, 200 and 240. The performance of the pump can therefore be represented by the data in Exhibit D-2. When entered in AECS format, 33 dimensional tables will be required.

Exhibit D-2: Values of Flow Rate, Pressure Increase and Efficiency for Example D-1

Flow Rate (lb/min)	Shaft Speed (rpm): 12500 Press. Rise	12500 Eff.	25000 Press. Rise	25000 Eff.	50000 Press. Rise	50000 Eff.
0	625	0.000	625	0.000	625	0.000
25	350	0.595				
50	250	0.850	350	0.595		
60	0	0.000				
100			250	0.850	350	0.595
120			0	0.000		
200					250	0.850
240	0	0.000	0	0.000	0	0.000

Notes: AECS interpolates 33-dimensional tables in a potentially unrealistic manner. To avoid the lack of realism, we have entered data at the maximum flow rate for all three speeds. If we did not, AECS would interpolate to obtain the pressure rise at 100 lb/min and 15000 rpm, for example, by extrapolating the 12500 rpm data (linearly) to obtain -1000 psi. AECS would then interpolate between the -1000 and +250 (linearly) to obtain -250 psi, a unrealistic value, at 20000 rpm. With the data point at 240 lb/min, AECS will get 150 psi.

Dimensionless data for dynamic pumps can be represented similarly (Exhibit D-3). However, the conversion to dimensional form differs, because the pressure rise is no longer independent of shaft speed. Instead, the pressure rise increases with the square of the shaft speed. The flow rate is again proportional to the rpm.

Exhibit D-3: Typical Values of Flow Rate, Pressure Increase and Efficiency for a Dynamic Pump

Ratio of Flow Rate to Flow Rate at Rated Conditions	Ratio of Pressure Increase to Pressure Increase at Rated Conditions	Ratio of Efficiency to Efficiency at Rated Conditions
0.0	1.20	0.00
0.1	1.19	0.12
0.2	1.18	0.24
0.3	1.17	0.35
0.4	1.16	0.46
0.5	1.15	0.58
0.6	1.14	0.68
0.7	1.12	0.78
0.8	1.10	0.88
0.9	1.08	0.95
1.0	1.00	1.00
1.1	0.55	0.50
1.2	0.00	0.00

Example D-2: Suppose we need to characterize a pump having a flow rate of 200 lb/min and a pressure increase of 100 psi at a rated speed of 10000 rpm. We assume that the pump efficiency at these conditions will be 85%. Again, for convenience, we represent the pump at the dimensionless flow rates of 0, 0.5, 1.0 and 1.2 (the dimensional values of 0, 100, 200 and 240 lb/min). The corresponding pressure rises at 10000 rpm will be 120, 115, 100 and 0, as found by multiplying the dimensionless pressure rises by 100 psi. The corresponding efficiencies are found by multiplying the dimensionless values by 85% to obtain 0.0, 0.493, 0.85 and 0.0. At 5000 rpm, the flows will be 0, 50, 100 and 120. The corresponding pressure rises, which are proportional to the square of the shaft speed, will be one-quarter of the values at 10000 rpm, or 30, 28.75, 25 and 0. The efficiencies remain unchanged. Exhibit D-4 summarizes the results.

Exhibit D-4: Values of Flow Rate, Pressure Increase and Efficiency for Example D-2

Flow Rate (lb/min)	Shaft Speed (rpm) 5000 Press. Rise	5000 Eff.	10000 Press. Rise	10000 Eff.	20000 Press. Rise	20000 Eff.
0	30	0.000	120	0.000	480	0.000
50	29	0.493				
100	25	0.850	115	0.493		
120	0	0.000				
200			100	0.850	460	0.493
240			0	0.000		
400					400	0.850
480	0	0.000	0	0.000	0	0.000

D.3. Vapor Compressors

The dimensionless characteristics of a vapor compressor are the same as those for the refrigerant pump (Exhibits D-1 and D-3). The conversion to AECS input differs slightly because the input data for the compressor is the pressure ratio rather than the pressure rise. To obtain the pressure ratio, the following formula is used:

$$\text{Pressure ratio} = 1 + (\text{Pressure rise})/(\text{Inlet pressure})$$

Therefore, a two-step conversion to AECS format is required. The dimensionless pressure rise is first converted to a dimensional rise. Then the pressure rises are converted to pressure ratios using the above formula.

Example D-3: Suppose the data of Example D-2 were to be applied to a vapor compressor having an inlet pressure of 20 psi. Then each pressure rise in Exhibit D-4 is divided by 20 psi and 1.0 is added to the result. The input data would appear as shown in Exhibit D-5.

Exhibit D-5: Values of Flow Rate, Pressure Ratio and Efficiency for Example D-3

Flow Rate (lb/min)	Shaft Speed (rpm) 5000 Press. Ratio	5000 Eff.	10000 Press. Ratio	10000 Eff.	20000 Press. Ratio	20000 Eff.
0	2.50	0.000	7.00	0.000	25.0	0.000
50	2.45	0.493				
100	2.25	0.850	6.75	0.493		
120	1.00	0.000				
200			6.00	0.850	24.0	0.493
240			1.00	0.000		
400					21.0	0.850
480	1.00	0.000	1.00	0.000	1.0	0.000

D.4. Expanders

The dimensionless data for the expanders (Exhibit D-6) must be converted to AECS input in a manner similar to that for the vapor compressor. The dimensionless data for the expander is the same for positive-displacement expanders and for dynamic machines. In preparing the AECS input, the pressure decreases are converted to pressure ratios by the formula:

$$\text{Pressure ratio} = 1 - (\text{pressure decrease})/(\text{inlet pressure})$$

where the inlet pressure is the high pressure. We assume that the valves (nozzles and ports) limit the flow, so the flow rate is proportional to the square root of the pressure decrease at any speed. Ideally, the shaft speed is proportional to the flow rate.

Exhibit D-6: Typical Dimensionless Values of Flow Rate, Pressure Decrease and Efficiency for Expanders

Ratio of Flow Rate to Flow Rate at Rated Conditions	Ratio of Pressure Decrease to Pressure Decrease at Rated Conditions	Ratio of Efficiency to Efficiency at Rated Conditions
0.0	0.00	0.00
0.2	0.04	0.20
0.4	0.16	0.40
0.6	0.36	0.60
0.8	0.64	0.80
0.9	0.81	0.90
1.0	1.00	1.00
1.1	1.40	0.75
1.3	2.00	0.50
1.5	3.00	0.30

Example D-4: Suppose we have a system with a flow rate of 100 lbs per minute and we need an expander operating with an inlet pressure of 250 psia and an outlet pressure of 50 psia (a pressure decrease of 200 psi) at a shaft speed of 25000 rpm. We assume that we can find an expander with exactly these ratings and that its nominal efficiency is 85%. To develop the tables for AECS, we first convert the values in Exhibit D-6 for the nominal shaft speed. To simplify the example, we attempt to represent the expander with only 4 values of the flow rate: 0.0, 0.6, 1.0, and 1.3. We multiply each of these values by 100 lb/min to obtain the dimensional flow rates. The corresponding pressure rises are obtained by multiplying the values in Exhibit D-6 by the pressure decrease of 200 psi to obtain 0, 72, 200 and 400. However, the 400 psi decrease exceeds the inlet pressure (250 psia), so we cannot have a flow-rate ratio of 1.3. Instead, at a 250 psi pressure decrease, the pressure-decrease ratio is 250/200 = 1.25, which corresponds to a 1.06 flow-rate ratio (as obtained by linear interpolation). Therefore, the flow rates to be used at the nominal speed are 0, 60, 100 and 106 lb/min. The corresponding pressure decreases are 0, 72, 200 and 250. The above formula can be used to convert these to pressure ratios of 1, 0.712, 0.2 and 0.0. The corresponding efficiencies are 0, 0.51, 0.85 and 0.84, as found by multiplying the dimensionless values by 0.85, the nominal efficiency.

To continue Example D-4, we must compute the expander characteristics at two other shaft speeds. We choose 12500 and 40000 rpm. The flow is proportional to the shaft speed and the pressure decrease is proportional to the square of the shaft speed, so at 12500 rpm, the flow rates are 0, 30, 50 and 65 lb/min (the last being for a flow-rate ratio of 1.3). The corresponding pressure decreases are 0, 18, 50 and 100 (pressure ratios of 1, 0.93, 0.8 and 0.6) and the efficiencies are 0, 0.51, 0.85 and 0.43. At 40000 rpm, the flow rates would be 0, 96, 160 and 208 and pressure decreases would be 0, 184, 512 and 640 (pressure ratios of 1, 0.26, -1.05 and -1.56). Only the first two are possible with a 250 psia inlet pressure. Therefore, the AECS input would appear as shown in Exhibit D-7. A 33-dimensional table is required. Notice that we again enter the pressure ratios for the highest flow rates and for all shaft speeds, to avoid the difficulties that can be encountered with the AECS interpolation routines.

Exhibit D-7: Values of Flow Rate, Pressure Increase and Efficiency for Example D-4 (Expander)

Flow Rate (lb/min)	Shaft Speed (rpm): 12500 Press. Ratio	12500 Eff.	25000 Press. Ratio	25000 Eff.	40000 Press. Ratio	40000 Eff.
0	1.00	0.00	1.00	0.00	1.00	0.000
30	0.93	0.51				
50	0.80	0.85				
60			0.71	0.51		
65	0.60	0.43				
100			0.20	0.85		
106			0.00	0.84		
120	0.00	0.00	0.00	0.00	0.26	0.51

Appendix E: Application to a Power Cycle

E.1. Introduction

As part of the requirements of the contract, the refrigerant subroutines were to be applied to a combined power and refrigeration cycle such as shown in Exhibit E-1. In particular, a cooling load of 6600 Btu/min was chosen. The purpose of this appendix is to present the steps taken to analyze the system and to present the final result.

E.2. Thermodynamic Analysis

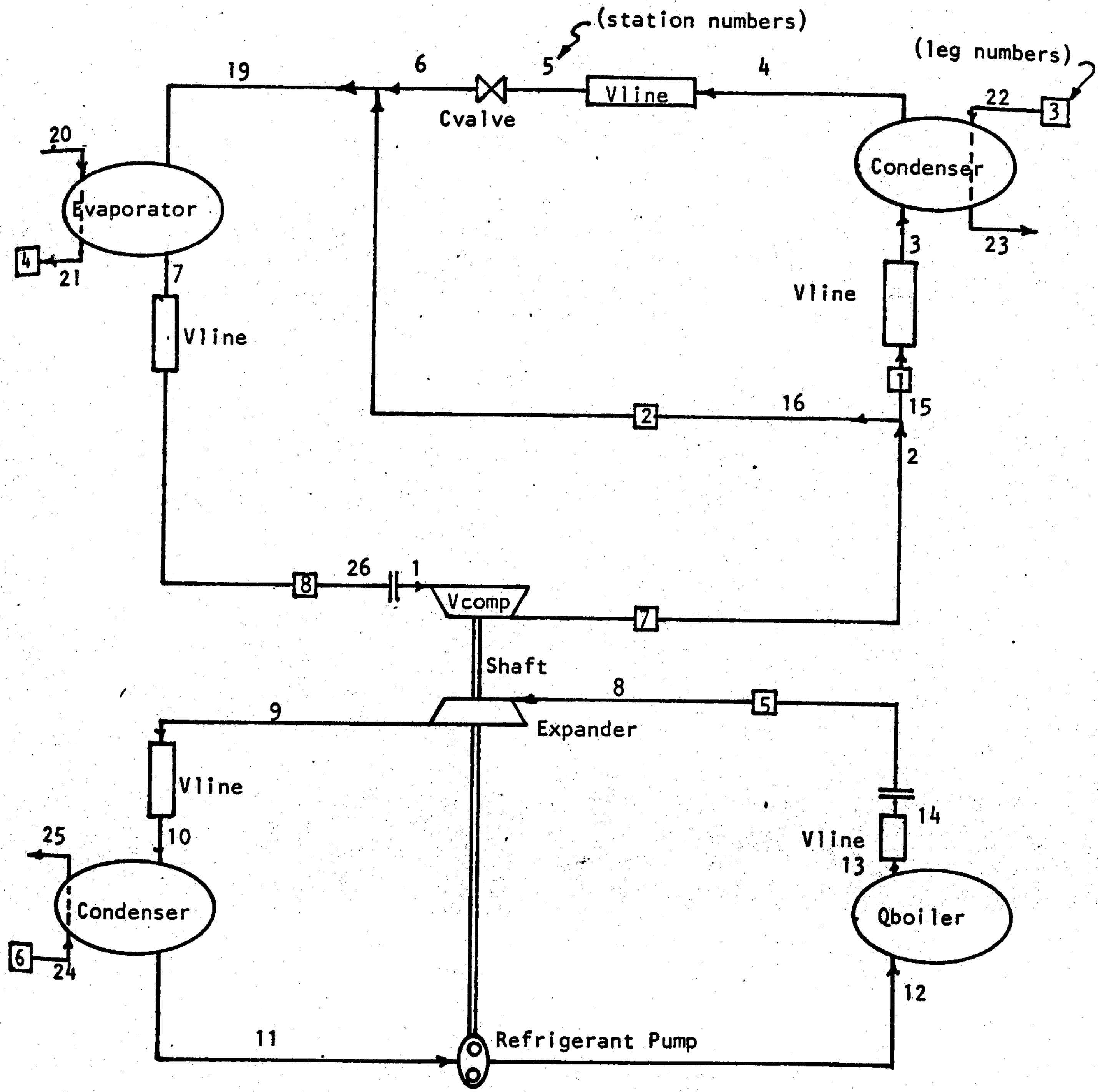
The first step in analyzing the system is to estimate the thermodynamic states at each station in the cycle. With the aid of the refrigerant-properties program developed under this contract, the states can be determined in approximately 30 minutes. The results are shown in Exhibit E-2.

Exhibit E-2: Estimated Thermodynamic States

Station	Flow Rate lb/min	Pressure psia	Temperature R	Enthalpy Btu/lb	Specific Volume cu.ft./lb	Entropy Btu/lb-R
			Refrigeration Cycle (R-22)			
1*	100	77.0	500.00	108.59	0.7191	0.22234
2(ideal)		245.0		121.19		0.22234
2	100	245.0	619.98	123.41	0.2607	0.22594
3	100	244.5		123.41		
4	100	244.0	570.00	42.55	0.0144	0.08508
5	100	244.0		42.55		
6	100	78.0	496.02	42.55	0.1868	0.08894
7	100	78.0	500.00	108.53	0.7086	0.22195
			Power Cycle (R-11)			
8*	100	280.0	800.00	132.62	0.1798	0.20437
9(ideal)		30.0		112.45		0.20437
9	100	30.0	639.99	115.48	1.5962	0.20918
10	100	29.5		115.48		
11	100	29.0	570.00	30.87	0.0112	0.06270
12(ideal)		281.0		31.39		
12	100	281.0		31.48		
13	100	281.0	800.00	132.58	0.1750	

Notes: The refrigeration effect is Q=100*(H7-H6)=6598 Btu/min. The compressor input is W=100*(H2-H1)=1482 Btu/min. The turbine output is WT=100*(H8-H9)*0.85=1457 Btu/min. The pump input is WP=100*(H12-H11)= 61 Btu/min. The heat input to the boiler is QB=100*(H13-H12)=10119 Btu/min. Turbine, pump and compressor efficiencies were assumed to be 85%. The AECS solution will correct for the slight imbalance in powers. Stations marked with an * were the stations at which the thermodynamic analysis was started.

Exhibit E-1: Flow Diagram for the Combined Refrigeration-Power Cycle



E.3. Equipment Sizes

With the thermodynamic states into and out of each component now known, the sizes of each of the components can be determined. We proceed with the components in the order of the thermodynamic states, starting with Station 1.

Vapor Compressor

We will choose the compression ratio for the vapor compressor as 245/77, or 3.182. A map will not be required. We will assume a mechanical efficiency of 95%. The efficiency must be entered as a function of shaft speed (RPM) and flow rate (CFM). The flow rate will be approximately 100*0.7191=71.91 CFM.

The data of Exhibit D-3 will be used to characterize the compressor, except with the flow rate expressed in cfm. Because the pressure ratio is fixed, only the efficiency needs to be considered. We will use the flow-rate ratios of 0, 0.8, 1.0 and 1.2 (0, 57.53, 71.91 and 86.29 cfm) at 25000 rpm. The corresponding efficiencies are 0, 0.748, 0.85 and 0, based on a nominal efficiency of 85%. The flow rates at 12500 rpm are 0, 28.77, 35.96 and 43.15 cfm; the efficiencies are unchanged. The flow rates at 50000 rpm are 0, 115.06, 143.82 and 172.58 cfm; the efficiencies are again unchanged.

Refrigerant Line

The refrigerant vapor lines will be selected to give a vapor velocity of 50 ft/sec. The flow rate at the outlet of the compressor is 26.07 CFM, so the line must have a diameter of 0.105 feet.

Condenser

The air into the condenser is assumed to be moisture-free and at 550 R so that the implied effectiveness, based on a condensing temperature of 570.6 R, is approximately 100*(H3-H4)/(Wair*0.24*(570.6-550)). For an effectiveness of 0.65, Wair = 1636 lb/min (123 CFM). The pressure drop on the air side will be assumed at 0.02 psi for this flow rate and to be proportional to the square of the flow rate. The refrigerant flow rate is 26.07 CFM at the inlet. If the inlet velocity is limited to 100 ft/sec, the flow area on the refrigerant side must be 0.0044 square feet. The friction factor will be assumed as a constant 0.004.

Refrigerant Line

The flow rate in the liquid line leaving the condenser is 1.44 CFM. If we limit the liquid velocity to 3 ft/sec, the diameter of the line must be 0.101 feet.

Throttling Valve

The pressure drop in the throttling valve is given by the formula

Pin - Pout = AK * (lb/min)**2

For a flow rate of 100 lb/min and a pressure drop of 245-77=168 psi, AK would be 0.0168.

Evaporator

Dry air is assumed to enter the evaporator at 550 R. The heat transfer rate is 6598 Btu/min. The air flow rate is assumed to be 800 lb/min. Based on the evaporation temperature of 495.3 R, the effectiveness is computed to be 6598/(800*0.24*(550-495.3))=0.628. This is the design-point value. The effectiveness is assumed to vary linearly, with the effectiveness being 1.0 when the flow rate is zero. Because the air is dry, the effectiveness is equal to 1.-BF, where BF is the bypass factor. Therefore, the design-point value of the bypass factor is 0.372. The air-side pressure drop is assumed to be 0.02 psi at the design flow rate and is assumed to be proportional to the square of the flow rate. The flow area on the refrigerant side is selected to give an evaporator-outlet velocity of 50 ft/sec, so the required area is 0.024 square feet. The friction factor is assumed to be a constant 0.004.

Refrigerant Line

The diameter of the pipe at the refrigerant outlet is selected to give a vapor velocity of 25 ft/sec, so its area must be 0.048 square feet and its diameter, 0.247 feet.

Expander

Although we will assume the pressure ratio is fixed for the expander, we will still need both the flow table (as a function of pressure ratio and shaft speed) and the efficiency table (as a function of flow rate and shaft speed). The design shaft speed must be the same as for the directly driven compressor, 25000 RPM. We can use the dimensionless characteristics for the expander presented in Exhibit D-6. The inlet flow rate is 17.98 cfm and the pressure decrease, 280 - 30 = 250 psi. We will characterize the efficiency at dimensionless flow rates of 0, 1.0 and 1.5 (0, 17.98 and 26.97 cfm) at 25000 rpm. The corresponding efficiencies are 0, 0.85 and 0.255, based on a nominal efficiency of 85%. At a shaft speed of 12500 rpm, the flow rates are 0, 8.99 and 13.49 cfm and the efficiencies are unchanged. At 50000 rpm, the flow rates are 0, 35.96 and 53.94 cfm and the efficiencies are unchanged. At these flow rates, the pressure decreases are 0, 250 and 750 psi, (0, 1 and 3 as read from Exhibit D-6, multiplied by the nominal pressure decrease of 250 psi). From the formula for expanders, we obtain the corresponding pressure ratios. For example, a pressure decrease of 250 psi gives a pressure ratio of 1-250/280 = 0.107. The three pressure ratios are, therefore, 1.0, 0.107, and -1.68. The negative pressure ratio is not physically possible, so only the first two are used in the input tables.

The outlet flow rate of 159.62 cfm could give rise to an appreciable outlet-velocity loss. We select an exit speed of 100 fps to get an outlet area of 159.62/(60*100) = 0.027 square feet. If the outlet area is equal to the diameter of the expander, then the diameter must be 0.185 feet. The corresponding enthalpy loss is

(100*100)/(2*32.2*778) = 0.2 Btu/lb

which is a tolerable value.

The input data card calls for the diameter to be entered, as well as the mechanical efficiency, which is assumed to be 95%.

Refrigerant Line

The exhaust refrigerant line has a flow rate of 159.62 CFM. We limit the velocity to 25 ft/sec, so the diameter of the line must be 0.368 feet.

Condenser

The condensing temperature at 29 psia is approximately 572.2 R. The air inlet temperature to the condenser is assumed to be 550 R. The effectiveness is assumed to be 0.65, based on the condensing temperature. Therefore, the air outlet temperature is 564.4 R. To remove the 8461 Btu/min requires an air flow rate of 2448 lb/min. The pressure drop on the air side is assumed to be proportional to the square of the flow rate and to be 0.02 psia at 2448 lb/min. The effectiveness is assumed to vary linearly with flow rate, being 1.0 at a flow rate of zero. The refrigerant-side friction factor is assumed to be constant at 0.004. The flow area on the refrigerant side is selected to give an inlet velocity of 50 ft/sec, so the area is 0.053 square feet.

Refrigerant Pump

The refrigerant pump is assumed to be positive-displacment pump, with the dimensionless characteristics being given in Exhibit D-1. The design flow rate is 100 lb/min. The pressure rise at design is approximately 281-29=252 psi. The design speed is 25000 rpm. These conditions are close to enough to the Example D-1 (Appendix D), that we can use the values presented in Exhibit D-2 directly. The rated output of the driver is required for the mechanical-efficiency table, which we take as a constant 95%. Nominally, 1.44 HP is required, so we extend the table from 0. to 5. HP.

Boiler

The heat input to the boiler is 10110 Btu/min. The outlet flow rate is 17.5 CFM. We will assume the friction factor is a constant 0.004, and the Colburn factor, 0.004. The flow area is selected to give an outlet velocity of 5 ft/sec, so AF=0.06 sq.ft. Under these conditions, the heat-transfer coefficient at the vapor exit is:

h = 0.004 * G * CP = 0.004 * 100 * 0.19 = 0.076 Btu/min-sf-R

The outlet flow rate of 159.62 cfm could give rise to an appreciable outlet-velocity loss. We select an exit speed of 25 fps to get an outlet area of 159.62/(60*25) = 0.11 square feet. The corresponding enthalpy loss is

$$(25*25)/(2*32.2*778) = 0.01 \text{ Btu/lb}$$

which is negligible.

We enter the displacement as 0.0365 cubic feet, the ratio of the outlet area to the displacement to the 2/3 power (approximately the outlet area) as 1.0, and the mechanical efficiency as 95%.

Refrigerant Line

The exhaust refrigerant line has a flow rate of 159.62 CFM. We limit the velocity to 25 ft/sec, so the diameter of the line must be 0.368 feet.

Condenser

The condensing temperature at 29 psia is approximately 572.2 R. The air inlet temperature to the condenser is assumed to be 550 R. The effectiveness is assumed to be 0.65, based on the condensing temperature. Therefore, the air outlet temperature is 564.4 R. To remove the 8461 Btu/min requires an air flow rate of 2448 lb/min. The pressure drop on the air side is assumed to be proportional to the square of the flow rate and to be 0.02 psia at 2448 lb/min. The effectiveness is assumed to vary linearly with flow rate, being 1.0 at a flow rate of zero. The refrigerant-side friction factor is assumed to be constant at 0.004. The flow area on the refrigerant side is selected to give an inlet velocity of 50 ft/sec, so the area is 0.053 square feet.

Refrigerant Pump

The refrigerant pump is assumed to be a positive-displacment pump, with the dimensionless characteristics being given in Exhibit D-1. The design flow rate is 100 lb/min. The pressure rise at design is approximately 281-29=252 psi. The design speed is 25000 rpm. These conditions are close to enough to the Example D-1 (Appendix D), that we can use the values presented in Exhibit D-2 directly. The rated output of the driver is required for the mechanical-efficiency table, which we take as a constant 95%. Nominally, 1.44 HP is required, so we extend the table from 0. to 5. HP.

Boiler

The heat input to the boiler is 10110 Btu/min. The outlet flow rate is 17.5 CFM. We will assume the friction factor is a constant 0.004, and the Colburn factor, 0.004. The flow area is selected to give an outlet velocity of 5 ft/sec, so AF=0.06 sq.ft. Under these conditions, the heat-transfer coefficient at the vapor exit is:

$$h = 0.004 * G * CP = 0.004 * 100 * 0.19 = 0.076 \text{ Btu/min-sf-R}$$

Therefore, the required heat-transfer area for a 50 r temperature difference would be 2660 sq.ft., if all of the heat transfer were in the vapor phase. In the boiling region, h=1.5 would be typical, so the required heat-transfer area would be 135 sq.ft. We will assume 150 sq.ft. If the heat exchanger surface has 300 sq.ft. of heat exchanger surface per cubic foot of volume, then the length of the heat exchanger would be

$$L = 150/(300*0.06) = 8.3 \text{ feet.}$$

The hydraulic diameter corresponding to 300 sq.ft./cu.ft. would be approximately

$$DH = 4/300 = 0.013 \text{ feet.}$$

Refrigerant Line

The line from the boiler to the expander carries 17.5 CFM. If we limit the velocity to 50 ft/sec, the diameter of the line must be 0.086 feet.

E.3. State and Error Variables

Our initial reasoning for the selection of state and error variables was as follows. The air flow rate through the evaporator will be fixed, under the assumption that the cooling load is a requirement of the system. The two control valves in the refrigeration loop will give one state variable each. The refrigerant flow rate and the split ratio will be selected as a state variable so that the enthalpy at the end of the loop will balance that at the beginning and so that the pressures will balance at the merge. The error variables will be the differences between the pressures and enthalpies at the loop start and end and the air temperature leaving the evaporator, as controlled by the hot-gas bypass valve. In the power loop, the outlet temperature from the boiler will be sensed and controlled by the flow rate in the power loop. Therefore, the simulation will have 5 state variables and 5 error variables.

In attempting to implement our initial reasoning, we found difficulties with the hot-gas-bypass valve and the corresponding line, because the flow through these was so small that we consistently had arithmetic errors (underflows). Therefore, we switched from the valve and line combination to having the split be fixed and not requiring a pressure balance at the merge (a control valve would eventually be used to achieve the pressure balance in a physical system). We thereby reduced the number of state and error variables to 3.

To achieve the desired cooling, we found that controlling the thermodynamic states was inadequate. AECS did not converge with either the Newton-Raphson technique or the MRD techniques. The MRD techniques did arrive at a minimum error, but it was unacceptably large.

First we separated the refrigerant loop from the power loop and studied the refrigerant loop by itself. Examination of the MRD results indicated that our heat exchangers were not large enough to handle the loads. Therefore, we reduced the number of error variables to the pressure balance at the loop end, which we controlled by the expansion valve flow factor (State Variable 1). The solution was obtained immediately (by Newton-Raphson) and we could see the shortfall of the heat exchangers. First, we increased the effectiveness of the condenser, until the expected outlet enthalpy was obtained (Exhibit E-2). Then we decreased the bypass factor of the evaporator until the enthalpies at the loop end balanced. To obtain the final solution, we reinstated the requirement that the enthalpies balance and we made the refrigerant flow a state variable.

We next examined the power loop by itself. Again we relaxed the loop balancing requirements so we could study the performance of the heat exchangers. The shaft speed was set as a state variable so the pump could balance the pressures; however, we did not require an enthalpy balance. The solution converged immediately and we saw that more heat had to be supplied to the boiler (the system efficiency was lower than computed from the data of Exhibit E-2). We adjusted the boiler input to achieve the enthalpy balance. The shaft speed remained the only state variable (the solution gave 25247 rpm).

The two separate loops were combined to obtain the final solution. We retained the shaft speed and control valves as state variables, but we switched from the refrigerant-loop flow rate to the refrigerant-loop split ratio for the third state variable. (Newton-Raphson did not converge when the flow rate was retained as the third state variable.) The pressures were required to balance at the ends of the loops; the enthalpy was required to balance at the end of the refrigeration loop. However, the separate analysis of the power loop showed that the enthalpy would balance at the end of loop in the power cycle; therefore, we did not need the enthalpy balance as another error variable.

E.4. Input Data Cards

The input data for the refrigerant loop as run by itself are presented in Exhibit E-3; the data cards for the power loop, in Exhibit E-4; and the data cards for the combined system, in Exhibit E-5.

E.5. Computational Results

The solution, as obtained with the Newton-Raphson method, is presented in Exhibit E-6. The thermodynamic analysis of Section E.2 is seen to give similar results, although the thermodynamic analysis does not include the equipment characteristics to the exactness of the AECS analysis. This case demonstrates that the simulation can solve combined power and refrigeration cycles.

Exhibit E-3: Input Cards for the Refrigeration Loop

```
PERFORM
TITLE    EXAMPLE CASE FOR POWER CYCLE AND REFRIGERATION CYCLE
CASEA   POWER    0000    6   15    1
CASEB      0    0    0    0    0
CASEC      0.0        14.696     530.
CASED      0.0
PARAM   65
VALUES   1 100.         77.          500.         108.59      25000.
VALUES   6   3.182      0.95         0.9936       0.0         0.105
VALUES  11   2.0        0.0          4.0          530.0       1871.0
VALUES  16 14.7         550.         0.0          0.0044      0.101
VALUES  21 10.0         0.0          3.0          550.0       0.0001
VALUES  26 0.01694      0.024       10.0          0.247       2.0
VALUES  31 800.0        14.696       550.0        0.0         100.0
VALUES  36 280.0        800.0        132.62       0.107       0.95
VALUES  41 0.0017       1.0          2.0          0.368       1.0
VALUES  46 2448.0       14.696       550.0        0.0         0.053
VALUES  51 102.4        478.8        25000.       1.44        0.06
VALUES  56 10110.0      8.3          150.0        0.013       800.0
VALUES  61 0.086        5.0          570.0        0.20        1.3
LOOPS      10    7    1    8   26    3 -221000    1    2    3    4
SHAFT      20    1    0    5
VCOMP      30    7    1    2    1    0    6    1    1    7    0
SPLIT      40    7    2    1   15    2   16    0    8
VLINE      50    1   15    3        -1    9   10   11   12   13   14
INLET      60    3 220000   15   16   17   18    2   -1
COND       70    1    3    4    3   22   23    0    2    2    3   19
VLINE      80    1    4    5        -1    9   20   21   22   23   24
CVALVE     90    1    5    6    0   25   26
MERGE     120    1    6    2   16    8   19    0
INLET     125    4 200000   31   32   33   34    2   -1
EVAP      130    8   19    7    4   20   21    0    4    4         5   27    0
VLINE     150    8    7   26        -1    9   29   30    9    9   24
LOOPE     160    7    1    8  260101
SOLN      170    0    1    1   64   65
TABID       1   51   -1    0    0    0    0    3
TABT    SCALE FACTORS FOR ERROR VARIABLES (TCOND OUT,LOOPE P AND H)
TABV       0.1          0.1          0.1
TABID       1   50   -1    0    0    0    0    3
TABT    SCALE FACTORS FOR STATE VARIABLES (SPLIT,COND AIR,CVALVE)
TABV       1.0          0.003
TABID       1    6   33    0    0  280001    5    0 1010001    3
TABT    EFFICIENCY OF VAPOR COMPRESSOR (CFM,RPM)
TABV       0.0          28.77        35.96        43.15
TABV       173.
TABV       0.0          57.53        71.91        86.29
TABV       173.
TABV       0.0          115.06       143.82       172.58
TABV       173.
TABV       12500.       25000.       50000.
TABV       0.0          0.748        0.85         0.0
```

```
TABV      0.0        0.0        0.748      0.85
TABV      0.0        0.0        0.0        0.748
TABV      0.85       0.0        0.0
TABID      2    1    2    0    0   410001    4
TABT  AIR-SIDE PRESSURE DROP FOR REFRIG CONDENSER (LB/MIN)
TABV      0.0        0.0        1000.      0.0075
TABV      2000.      0.0299     3000.      0.0673
TABID      2    5    2    0    0   410001    4
TABT  AIR-SIDE EFFECTIVENESS FOR REFRIG CONDENSER (LB/MIN)
TABV      0.0        1.0        3000.      0.786
TABV      6000.      0.572      9000.      0.358
TABID      3    1    2    0    0   420001    4
TABT  REFRIG-SIDE PRESSURE DROP FOR REFRIG CONDENSER (CFM OF VAPOR)
TABV      0.0        0.0        50.0       0.125
TABV      100.0      0.50       200.0      2.0
TABID      4    1    2    0    0   410001    4
TABT  AIR-SIDE PRESSURE DROP FOR REFRIG EVAP (LB/MIN)
TABV      0.0        0.0        400.0      0.005
TABV      800.0      0.02       1600.0     0.08
TABID      4    5    2    0    0   410001    4
TABT  AIR-SIDE BYPASS FACTOR FOR REFRIG EVAP (LB/MIN)
TABV      0.0        0.0        400.0      0.186
TABV      800.0      0.3608     1600.0     0.744
TABID      5    2    2    0    0   420001    4
TABT  REFRIG-SIDE PRESSURE DROP FOR REFRIG EVAP (CFM OF VAPOR)
TABV      0.0        0.0        50.0       0.125
TABV      100.0      0.5        200.0      2.0
ENDCASE
ENDJOB
END
```

Exhibit E-4: Input Cards for the Power Loop

```
PERFORM  EXAMPLE CASE FOR POWER CYCLE AND REFRIGERATION CYCLE
TITLE   POWER    0000    2    9    1
CASEA        0     0     0     0     0
CASEB        0.0        14.696      530.
CASEC        0.0
CASED   65
PARAM    1 100.       77.          500.        108.59      25000.
VALUES   6  3.182     0.95         1.0         0.0         0.105
VALUES  11  2.0       0.0          4.0         530.0       1636.
VALUES  16 14.7       550.         0.0         0.0044      0.101
VALUES  21 10.0       0.0          3.0         550.0       0.0001
VALUES  26 0.0168     0.024        5.0         0.247       2.0
VALUES  31 800.0      14.696       550.0       0.0         100.0
VALUES  36 280.0      800.0        132.62      0.107       0.95
VALUES  41 0.0365     1.0          2.0         0.368       1.0
VALUES  46 2200.0     14.696       550.0       0.0         0.053
VALUES  51 102.4      478.8        25000.      1.44        0.06
VALUES  56 10839.0    8.3          150.0       0.013       800.0
VALUES  61 0.086      5.0
LOOPS     170    5    8    5   14    3 -110000   35   36   37   38
SHAFT     175    1    1    5
XPAND     180    5    8    9    1    0   39    6   40   41   42    0    9
VLINE     190    5    9   10        -1    9   44   45    9    9   14
INLET     200    6  240000   46   47   48   49    2   -1
COND      210    5   10   11    6   24   25    0    7    7    8   50
RPMP      220    5   11   12    1    9    9    9    8    8    8    8
QBOILR    230    5   12   13    0   10   10   55   56   57   58   59    0
VLINE     250    5   13   14        -1    9   61   62    9    9   14
LOOPE     260    5    8    5  140100
TABID       6    8   33    0    0 1010001    2    0 1020001    3
TABT    EXPANDER FLOW RATE VS. PRESSURE RATIO AND RPM
TABV        0.107       1.0
TABV        0.107       1.0
TABV        0.107       1.0
TABV        12500.      25000.      50000.
TABV        8.99        0.0         17.98       0.0
TABV        35.96       0.0
TABID       6    7   33    0    0 1010001    4    0 1020001    3
TABT    EXPANDER EFFICIENCY VS. CFM AND RPM
TABV        0.0         8.99        13.49       55.0
TABV        0.0         17.98       26.97       55.0
TABV        0.0         35.96       53.95       55.0
TABV        12500.      25000.      50000.
TABV        0.0         0.85        0.255       0.0
TABV        0.0         0.85        0.255       0.0
```

```
TABV      0.0          0.85         0.255        0.0
TABID       7    1    2    0    0   410001     4
TABT   AIR-SIDE PRESSURE DROP FOR POWER CONDENSER (LB/MIN)
TABV      0.0          0.0          1224.        0.005
TABV      2448.        0.02         3672.        0.08
TABID       7    5    2    0    0   410001     4
TABT   AIR-SIDE EFFECTIVENESS FOR POWER CONDENSER (LB/MIN)
TABV      0.0          1.0          1224.        0.825
TABV      2448.        0.65         3672.        0.475
TABID       8    1    2    0    0   420001     4
TABT   TWO-PHASE-SIDE PRESSURE DROP FOR POWER CONDENSER (CFM OF VAPOR)
TABV      0.0          0.0          50.0         0.25
TABV      100.0        1.0          200.0        4.0
TABID       9    8   33    0    0 1020001     5    0 1010001    3
TABT   PRESSURE-RISE TABLE FOR POWER-CYCLE PUMP VS. LB/MIN, RPM
TABV      0.0          25.0         50.0         60.0
TABV      250.0
TABV      0.0          50.0         100.0        120.0
TABV      250.0
TABV      0.0          100.         200.         240.
TABV      250.0
TABV      12500.       25000.       50000.
TABV      625.         350.         250.         0.0
TABV      0.0          625.         350.         250.
TABV      0.0          0.0          625.         350.
TABV      250.         0.0          0.0
TABID       9    9   33    0    0 1020001     5    0 1010001    3
TABT   EFFICIENCY TABLE FOR POWER-CYCLE PUMP VS LB/MIN, RPM
TABV      0.0          25.          50.          60.
TABV      250.
TABV      0.0          50.          100.         120.
TABV      250.
TABV      0.0          100.         200.         240.
TABV      250.
TABV      12500.       25000.       50000.
TABV      0.0          0.595        0.85         0.0
TABV      0.0          0.0          0.595        0.85
TABV      0.0          0.0          0.0          0.595
TABV      0.85         0.0          0.0
TABID       9   10    2    0    0 1010001     2
TABT   MECHANICAL EFFICIENCY TABLE FOR POWER-CYCLE PUMP (HP/HPR)
TABV      0.0          0.85         5.0          0.85
TABID      10   32    2    0    0   210001     2
TABT   FRICTION-FACTOR OF BOILER (REYNOLDS NUMBER)
TABV      0.0          0.004        1000000.     0.004
TABID      10   33    2    0    0   210001     2
TABT   COLBURN-FACTOR OF BOILER (REYNOLDS NUMBER)
TABV      0.0          0.004        1000000.     0.004
ENDCASE
ENDJOB
```

Exhibit E-5: Input Cards for the Combined Refrigeration and Power Loops

```
PERFORM
TITLE     EXAMPLE CASE FOR POWER CYCLE AND REFRIGERATION CYCLE
CASEA    POWER    0000    8   26    1
CASEB       0    0    0    0    0
CASEC      0.0        14.696      530.
CASED      0.0
PARAM    65
VALUES    1 100.        77.         500.        108.59      25000.
VALUES    6  3.182      0.95        0.9936        0.0         0.105
VALUES   11  2.0        0.0         4.0         530.0       1871.
VALUES   16 14.7        550.        0.0         0.0044      0.101
VALUES   21 10.0        0.0         3.0         550.0       0.0001
VALUES   26 0.01694     0.024       10.0        0.247       2.0
VALUES   31 800.0       14.696      550.0       0.0         100.0
VALUES   36 280.0       800.0       132.62      0.107       0.95
VALUES   41 0.0365      1.0         2.0         0.368       1.0
VALUES   46 2200.0      14.696      550.0       0.0         0.053
VALUES   51 102.4       478.8       25000.      1.44        0.06
VALUES   56 10836.2     8.3         150.0       0.013       800.0
VALUES   61 0.086       5.0         570.0       0.20        1.3
LOOPS      10   7   1      8  26   3 -220000   1   2   3   4
SHAFT      20   1   1      5
VCOMP      30   7   1      2   1   0   6   1   1   7   0
SPLIT      40   7   2      1  15   2  16   1   8
VLINE      50   1  15      3      -1   9  10  11  12  13  14
INLET      60   3 220000  15  16  17  18   2  -1
COND       70   1   3      4   3  22  23   0   2   2   3  19
VLINE      80   1   4      5      -1   9  20  21  22  23  24
CVALVE     90   1   5      6   0  25  26
MERGE     120   1   6      2  16   8  19   0
INLET     125   4 200000  31  32  33  34   2  -1
EVAP      130   8  19      7   4  20  21   0   4   4       5  27   0
VLINE     150   8   7     26      -1   9  29  30   9   9  24
LOOPE     160   7   1      8 260101
LOOPS     170   5   8      5  14   3 -110000  35  36  37  38
EXPAND    180   5   8      9   1   0  39   6  40  41  42   0   9
VLINE     190   5   9     10      -1   9  44  45   9   9  14
INLET     200   6 240000  46  47  48  49   2  -1
COND      210   5  10     11   6  24  25   0   7   7   8  50
PMP       220   5  11     12   1   9   9   9   8   8   8   8
BOILR     230   5  12     13   0  10  10  55  56  57  58  59   0
VLINE     250   5  13     14      -1   9  61  62   9   9  14
LOOPE     260   5   8      5 140100
TABID       1   6  33      0   0 280001   5   0 1010001   3
TABT   EFFICIENCY OF VAPOR COMPRESSOR (CFM,RPM)
TABV      0.0         28.77       35.96       43.15
```

```
TABV      173.
TABV      0.0          57.53        71.91        86.29
TABV      173.
TABV      0.0          115.06       143.82       172.58
TABV      173.
TABV      12500.       25000.       50000.
TABV      0.0          0.748        0.85         0.0
TABV      0.0          0.0          0.748        0.85
TABV      0.0          0.0          0.0          0.748
TABV      0.85         0.0          0.0
TABID       2    1    2    0    0   410001    4
TABT   AIR-SIDE PRESSURE DROP FOR REFRIG CONDENSER (LB/MIN)
TABV      0.0          0.0          1000.        0.0075
TABV      2000.        0.0299       3000.        0.0673
TABID       2    5    2    0    0   410001    4
TABT   AIR-SIDE EFFECTIVENESS FOR REFRIG CONDENSER (LB/MIN)
TABV      0.0          1.0          3000.        0.786
TABV      6000.        0.572        9000.        0.358
TABID       3    1    2    0    0   420001    4
TABT   REFRIG-SIDE PRESSURE DROP FOR REFRIG CONDENSER (CFM OF VAPOR)
TABV      0.0          0.0          50.0         0.125
TABV      100.0        0.50         200.0        2.0
TABID       4    1    2    0    0   410001    4
TABT   AIR-SIDE PRESSURE DROP FOR REFRIG EVAP (LB/MIN)
TABV      0.0          0.0          400.0        0.005
TABV      800.0        0.02         1600.0       0.08
TABID       4    5    2    0    0   410001    4
TABT   AIR-SIDE BYPASS FACTOR FOR REFRIG EVAP (LB/MIN)
TABV      0.0          0.0          400.0        0.186
TABV      800.0        0.3608       1600.0       0.744
TABID       5    2    2    0    0   420001    4
TABT   REFRIG-SIDE PRESSURE DROP FOR REFRIG EVAP (CFM OF VAPOR)
TABV      0.0          0.0          50.0         0.125
TABV      100.0        0.5          200.0        2.0
TABID       6    8   33    0    0 1010001    2    0 1020001    3
TABT   EXPANDER FLOW RATE VS. PRESSURE RATIO AND RPM
TABV      0.107        1.0
TABV      0.107        1.0
TABV      0.107        1.0
TABV      12500.       25000.       50000.
TABV      8.99         0.0          17.98        0.0
TABV      35.96        0.0
TABID       6    7   33    0    0 1010001    4    0 1020001    3
TABT   EXPANDER EFFICIENCY VS. CFM AND RPM
TABV      0.0          8.99         13.49        55.0
TABV      0.0          17.98        26.97        55.0
TABV      0.0          35.96        53.95        55.0
TABV      12500.       25000.       50000.
TABV      0.0          0.85         0.255        0.0
TABV      0.0          0.85         0.255        0.0
```

```
TABV      0.0         0.85   -    0.255      0.0
TABID       7    1    2    0    0  410001    4
TABT   AIR-SIDE PRESSURE DROP FOR POWER CONDENSER (LB/MIN)
TABV      0.0         0.0         1224.      0.005
TABV      2448.       0.02        3672.      0.08
TABID       7    5    2    0    0  410001    4
TABT   AIR-SIDE EFFECTIVENESS FOR POWER CONDENSER (LB/MIN)
TABV      0.0         1.0         1224.      0.825
TABV      2448.       0.65        3672.      0.475
TABID       8    1    2    0    0  420001    4
TABT   TWO-PHASE-SIDE PRESSURE DROP FOR POWER CONDENSER (CFM OF VAPOR)
TABV      0.0         0.0         50.0       0.25
TABV      100.0       1.0         200.0      4.0
TABID       9    8   33    0    0 1020001    5    0 1010001    3
TABT   PRESSURE-RISE TABLE FOR POWER-CYCLE PUMP VS. LB/MIN AND RPM
TABV      0.0         25.0        50.0       60.0
TABV      250.0
TABV      0.0         50.0        100.0      120.0
TABV      250.0
TABV      0.0         100.0       200.0      240.0
TABV      250.0
TABV      12500.      25000.      50000.
TABV      625.        350.        250.       0.0
TABV      0.0         625.        350.       250.
TABV      0.0         0.0         625.       350.
TABV      250.        0.0         0.0
TABID       9    9   33    0    0 1020001    5    0 1010001    3
TABT   EFFICIENCY TABLE FOR POWER-CYCLE PUMP VS. LB/MIN AND RPM
TABV      0.0         25.0        50.0       60.0
TABV      250.
TABV      0.0         50.0        100.0      120.0
TABV      250.
TABV      0.0         100.0       200.0      240.0
TABV      250.
TABV      12500.      25000.      50000.
TABV      0.0         0.595       0.85       0.0
TABV      0.0         0.0         0.595      0.85
TABV      0.0         0.0         0.0        0.595
TABV      0.85        0.0         0.0
TABID       9   10    2    0    0 1010001    2
TABT   MECHANICAL EFFICIENCY TABLE FOR POWER-CYCLE PUMP VS. HP
TABV      0.0         0.85        5.0        0.85
TABID      10   32    2    0    0  210001    2
TABT   FRICTION-FACTOR OF BOILER (REYNOLDS NUMBER)
TABV      0.0         0.004       1000000.   0.004
TABID      10   33    2    0    0  210001    2
TABT   COLBURN-FACTOR OF BOILER (REYNOLDS NUMBER)
TABV      0.0         0.004       1000000.   0.004
ENDCASE
ENDJOB
```

Exhibit E-6: Complete AECS Output for the Combined Refrigeration/Power System

```
LG0123
                                                                                              PAGE        1
*AECS* GENERAL ECS PROGRAM                                                                    DATE 01/23/82
   1  CASE PERFOR

TIME M        3.18 SEC.                                                                       PAGE        2
*AECS*     EXAMPLE CASE FOR POWER CYCLE AND REFRIGERATION CYCLE                               DATE 01/23/82
   1  CASE PERFOR

TIME Z        3.28

        EXAMPLE CASE FOR POWER CYCLE AND REFRIGERATION CYCLE                                  PAGE        3
*AECS*     EXAMPLE CASE FOR POWER CYCLE AND REFRIGERATION CYCLE                               DATE 01/23/82
   1  CASE POWER


        CASE POWER                    8 LEG(S)                  26 STATION(S)

ATM P     14.70

ATM T   530.00

ALTITUDE          0.                                                                          PAGE        4
*AECS*     EXAMPLE CASE FOR POWER CYCLE AND REFRIGERATION CYCLE                               DATE 01/23/82
   1  CASE POWER

PARAMETER TABLE         65 VALUE(S)
                                                                                        6) 3.18200E+00
(   1) 1.00000E+02 (   2) 7.70000E+01 (   3) 5.00000E+02 (   4) 1.08590E+02 (   5) 2.50000E+04 (
(   7) 9.50000E-01 (   8) 9.93600E-01 (   9) 0.          (  10) 1.05000E-01 (  11) 2.00000E+00 (  12) 0.
(  13) 4.00000E+00 (  14) 5.30000E+02 (  15) 1.87100E+03 (  16) 1.47000E+01 (  17) 5.50000E+02 (  18) 0.
(  19) 4.40000E-03 (  20) 1.01000E-01 (  21) 1.00000E+01 (  22) 0.          (  23) 3.00000E+00 (  24) 5.50000E+02
(  25) 1.00000E-04 (  26) 1.69400E-02 (  27) 2.40000E-02 (  28) 1.00000E+01 (  29) 2.47000E-01 (  30) 2.00000E+00
(  31) 8.00000E+02 (  32) 1.46960E+01 (  33) 5.50000E+02 (  34) 0.          (  35) 1.00000E+02 (  36) 2.80000E+02
(  37) 8.00000E+02 (  38) 1.32620E+02 (  39) 1.07000E-01 (  40) 9.50000E-01 (  41) 3.65000E-02 (  42) 1.00000E+00
(  43) 2.00000E+00 (  44) 3.68000E-01 (  45) 1.00000E+00 (  46) 2.20000E+03 (  47) 1.46960E+01 (  48) 5.50000E+02
(  49) 0.          (  50) 5.30000E-02 (  51) 1.02400E+02 (  52) 4.78800E+02 (  53) 2.50000E+04 (  54) 1.44000E+00
(  55) 6.00000E-02 (  56) 1.08362E+04 (  57) 8.30000E+00 (  58) 1.50000E+02 (  59) 1.30000E-02 (  60) 8.00000E+02
(  61) 8.60000E-02 (  62) 5.00000E+00 (  63) 5.70000E+02 (  64) 2.00000E-01 (  65) 1.30000E+00
*AECS*     EXAMPLE CASE FOR POWER CYCLE AND REFRIGERATION CYCLE                               PAGE        5
   1  CASE POWER                                                                              DATE 01/23/82

COMPONENT(S)
                                                                             60   64   68   72   76   80
  1    6   8   12   16   20   24   28   32   36   40   44   48   52   56
                                                                              0    0    0    0    0    0
 LOOPS         10    7    1    8   26    3  -22    0    1    2    3    4    0    0    0    0    0    0
 SHAFT         20    1    1    5    0    0    0    0    0    0    0    0    0    0    0
                                                                                     SV N   1  T   7
```

```
VCOMP     30   7   1   2   1   0   6   1   1   7   0   0   0   0   0   0   0   0
SPLIT     40   7   2   1  15   2  16   1   8   0   0   0   0   0   0   0   0   0
                                                                                SV N   2  T   5
VLINE     50   1  15   3   0  -1   9  10  11  12  13  14   0   0   0   0   0   0
INLET     60   3  22   0  15  16  17  18   2  -1   0   0   0   0   0   0   0   0
COND      70   1   3   4   3  22  23   0   2   2   3  19   0   0   0   0   0   0
VLINE     80   1   4   5   0  -1   9  20  21  22  23  24   0   0   0   0   0   0
CVALVE    90   1   5   6   0  25  26   0   0   0   0   0   0   0   0   0   0   0
                                                                                SV N   3  T   6
MERGE    120   1   6   2  16   8  19   0   0   0   0   0   0   0   0   0   0   0
INLET    125   4  20   0  31  32  33  34   2  -1   0   0   0   0   0   0   0   0
EVAP     130   8  19   7   4  20  21   0   4   4   0   5  27   0   0   0   0   0
VLINE    150   8   7  26   0  -1   9  29  30   9   9  24   0   0   0   0   0   0
LOOPE    160   7   1   8  26 101   0   0   0   0   0   0   0   0   0   0   0   0
                                                                                EV N   1  T   2
                                                                                EV N   2  T   4
LOOPS    170   5   8   5  14   3 -11   0  35  36  37  38   0   0   0   0   0   0
XPAND    180   5   8   9   1   0  39   6  40  41  42   0   9   0   0   0   0   0
VLINE    190   5   9  10   0  -1   9  44  45   9   9  14   0   0   0   0   0   0
INLET    200   6  24   0  46  47  48  49   2  -1   0   0   0   0   0   0   0   0
COND     210   5  10  11   6  24  25   0   7   7   8  50   0   0   0   0   0   0
RPMP     220   5  11  12   1   9   9   9   8   8   8   8   0   0   0   0   0   0
QBOILR   230   5  12  13   0  10  10  55  56  57  58  59   0   0   0   0   0   0
VLINE    250   5  13  14   0  -1   9  61  62   9   9   1 4000  0   0   0   0   0
LOOPE    260   5   8   5  14 100   0   0   0   0   0   0   0   0   0   0   0   0
                                                                                EV N   3  T   2

  STATE/ERROR VARIABLE(S)      3
*AECS*    EXAMPLE CASE FOR POWER CYCLE AND REFRIGERATION CYCLE                         PAGE        6
    1   CASE POWER                                                                     DATE 01/23/82

TABLES             22 REQUIRED

PERMANENT TABLE    22     10

PERMANENT TABLE     1      3

PERMANENT TABLE     1     10

PERMANENT TABLE    11     10

TABLE      1       6
    TITLE/EFFICIENCY OF VAPOR COMPRESSOR (CFM,RPM)

    NDIM      33     IST      0
    ARGUMENT 1       TYPE     0      RELN   28     EXTRAP    0     INTERP    1     NPTS    5
    ARGUMENT 2       TYPE     0      RELN  101     EXTRAP    0     INTERP    1     NPTS    3

            0.             2.87700E+01     3.59600E+01     4.31500E+01
            1.73000E+02
```

```
          0.             5.75300E+01    7.19100E+01    8.62900E+01
          1.73000E+02

          0.             1.15060E+02    1.43820E+02    1.72580E+02
          1.73000E+02

          1.25000E+04    2.50000E+04    5.00000E+04

          0.             7.48000E-01    8.50000E-01    0.
          0.             0.             7.48000E-01    8.50000E-01
          0.             0.             0.             7.48000E-01
          8.50000E-01    0.             0.

TABLE      2     1
     TITLE/AIR-SIDE PRESSURE DROP FOR REFRIG CONDENSER (LB/MIN)

     NDIM      2      IST     0
     ARGUMENT 1       TYPE    0      RELN    41      EXTRAP    0     INTERP     1      NPTS     4

          0.             0.             1.00000E+03    7.50000E-03
          2.00000E+03    2.99000E-02    3.00000E+03    6.73000E-02

TABLE      2     5
     TITLE/AIR-SIDE EFFECTIVENESS FOR REFRIG CONDENSER (LB/MIN)

     NDIM      2      IST     0
     ARGUMENT 1       TYPE    0      RELN    41      EXTRAP    0     INTERP     1      NPTS     4

          0.             1.00000E+00    3.00000E+03    7.86000E-01
          6.00000E+03    5.72000E-01    9.00000E+03    3.58000E-01

TABLE      3     1
     TITLE/REFRIG-SIDE PRESSURE DROP FOR REFRIG CONDENSER (CFM OF VAPOR)

     NDIM      2      IST     0
*AECS*    EXAMPLE CASE FOR POWER CYCLE AND REFRIGERATION CYCLE                          PAGE        7
     1   CASE POWER                                                                     DATE 01/23/82

     ARGUMENT 1       TYPE    0      RELN    42      EXTRAP    0     INTERP     1      NPTS     4

          0.             0.             5.00000E+01    1.25000E-01
          1.00000E+02    5.00000E-01    2.00000E+02    2.00000E+00

TABLE      4     1
     TITLE/AIR-SIDE PRESSURE DROP FOR REFRIG EVAP (LB/MIN)

     NDIM      2      IST     0
     ARGUMENT 1       TYPE    0      RELN    41      EXTRAP    0     INTERP     1      NPTS     4
```

```
          0.              0.              4.00000E+02    5.00000E-03
          8.00000E+02     2.00000E-02     1.60000E+03    8.00000E-02

TABLE       4     5
   TITLE/AIR-SIDE BYPASS FACTOR FOR REFRIG EVAP (LB/MIN)

   NDIM       2       IST       0
   ARGUMENT 1        TYPE      0      RELN    41      EXTRAP     0      INTERP      1      NPTS     4

          0.              0.              4.00000E+02    1.86000E-01
          8.00000E+02     3.60800E-01     1.60000E+03    7.44000E-01

TABLE       5     2
   TITLE/REFRIG-SIDE PRESSURE DROP FOR REFRIG EVAP (CFM OF VAPOR)

   NDIM       2       IST       0
   ARGUMENT 1        TYPE      0      RELN    42      EXTRAP     0      INTERP      1      NPTS     4

          0.              0.              5.00000E+01    1.25000E-01
          1.00000E+02     5.00000E-01     2.00000E+02    2.00000E+00

TABLE       6     8
   TITLE/EXPANDER FLOW RATE VS. PRESSURE RATIO AND RPM

   NDIM      33       IST       0
   ARGUMENT 1        TYPE      0      RELN   101      EXTRAP     0      INTERP      1      NPTS     2
   ARGUMENT 2        TYPE      0      RELN   102      EXTRAP     0      INTERP      1      NPTS     3

          1.07000E-01     1.00000E+00

          1.07000E-01     1.00000E+00

          1.07000E-01     1.00000E+00

          1.25000E+04     2.50000E+04     5.00000E+04

          8.99000E+00     0.              1.79800E+01    0.
          3.59600E+01     0.

TABLE       6     7
   TITLE/EXPANDER EFFICIENCY VS. CFM AND RPM

   NDIM      33       IST       0
   ARGUMENT 1        TYPE      0      RELN   101      EXTRAP     0      INTERP      1      NPTS     4
   ARGUMENT 2        TYPE      0      RELN   102      EXTRAP     0      INTERP      1      NPTS     3
```



```
          0.              8.99000E+00     1.34900E+01    5.50000E+01
```

```
          0.            1.79800E+01   2.69700E+01   5.50000E+01

          0.            3.59600E+01   5.39500E+01   5.50000E+01

          1.25000E+04   2.50000E+04   5.00000E+04

          0.            8.50000E-01   2.55000E-01   0.
          0.            8.50000E-01   2.55000E-01   0.
          0.            8.50000E-01   2.55000E-01   0.

TABLE       7     1
    TITLE/AIR-SIDE PRESSURE DROP FOR POWER CONDENSER (LB/MIN)

    NDIM      2     IST     0
    ARGUMENT  1     TYPE    0     RELN   41     EXTRAP    0     INTERP    1     NPTS    4

          0.            0.            1.22400E+03   5.00000E-03
          2.44800E+03   2.00000E-02   3.67200E+03   8.00000E-02

TABLE       7     5
    TITLE/AIR-SIDE EFFECTIVENESS FOR POWER CONDENSER (LB/MIN)

    NDIM      2     IST     0
    ARGUMENT  1     TYPE    0     RELN   41     EXTRAP    0     INTERP    1     NPTS    4

          0.            1.00000E+00   1.22400E+03   8.25000E-01
          2.44800E+03   6.50000E-01   3.67200E+03   4.75000E-01

TABLE       8     1
    TITLE/TWO-PHASE-SIDE PRESSURE DROP FOR POWER CONDENSER (CFM OF VAPOR)

    NDIM      2     IST     0
    ARGUMENT  1     TYPE    0     RELN   42     EXTRAP    0     INTERP    1     NPTS    4

          0.            0.            5.00000E+01   2.50000E-01
          1.00000E+02   1.00000E+00   2.00000E+02   4.00000E+00

TABLE       9     8
    TITLE/PRESSURE-RISE TABLE FOR POWER-CYCLE PUMP VS. LB/MIN AND RPM

    NDIM     33     IST     0
    ARGUMENT  1     TYPE    0     RELN  102     EXTRAP    0     INTERP    1     NPTS    5
    ARGUMENT  2     TYPE    0     RELN  101     EXTRAP    0     INTERP    1     NPTS    3

          0.            2.50000E+01   5.00000E+01   6.00000E+01
          2.50000E+02

          0.            5.00000E+01   1.00000E+02   1.20000E+02
          2.50000E+02
```

```
          0.              1.00000E+02    2.00000E+02    2.40000E+02
          2.50000E+02
```



```
          1.25000E+04    2.50000E+04    5.00000E+04

          6.25000E+02    3.50000E+02    2.50000E+02    0.
          0.             6.25000E+02    3.50000E+02    2.50000E+02
          0.             0.             6.25000E+02    3.50000E+02
          2.50000E+02    0.             0.

TABLE      9     9
    TITLE/EFFICIENCY TABLE FOR POWER-CYCLE PUMP VS. LB/MIN AND RPM

    NDIM     33     IST     0
    ARGUMENT 1      TYPE    0     RELN  102     EXTRAP    0     INTERP    1     NPTS    5
    ARGUMENT 2      TYPE    0     RELN  101     EXTRAP    0     INTERP    1     NPTS    3

          0.             2.50000E+01    5.00000E+01    6.00000E+01
          2.50000E+02

          0.             5.00000E+01    1.00000E+02    1.20000E+02
          2.50000E+02

          0.             1.00000E+02    2.00000E+02    2.40000E+02
          2.50000E+02

          1.25000E+04    2.50000E+04    5.00000E+04

          0.             5.95000E-01    8.50000E-01    0.
          0.             0.             5.95000E-01    8.50000E-01
          0.             0.             0.             5.95000E-01
          8.50000E-01    0.             0.

TABLE      9    10
    TITLE/MECHANICAL EFFICIENCY TABLE FOR POWER-CYCLE PUMP VS. HP

    NDIM      2     IST     0
    ARGUMENT 1      TYPE    0     RELN  101     EXTRAP    0     INTERP    1     NPTS    2

          0.             8.50000E-01    5.00000E+00    8.50000E-01

TABLE     10    32
    TITLE/FRICTION-FACTOR OF BOILER (REYNOLDS NUMBER)

    NDIM      2     IST     0
    ARGUMENT 1      TYPE    0     RELN   21     EXTRAP    0     INTERP    1     NPTS    2
```

```
         0.              4.00000E-03    1.00000E+06    4.00000E-03

TABLE      10    33
   TITLE/COLBURN-FACTOR OF BOILER (REYNOLDS NUMBER)

   NDIM      2      IST      0
   ARGUMENT 1       TYPE     0      RELN    21      EXTRAP    0      INTERP    1      NPTS    2

         0.              4.00000E-03    1.00000E+06    4.00000E-03
*AECS*    EXAMPLE CASE FOR POWER CYCLE AND REFRIGERATION CYCLE                          PAGE       10
    1  CASE POWER                                                                      DATE 01/23/82

TIME P        3.61

SVT
(   1)    7 (   2)    5 (   3)    6

EVT
(   1)    2 (   2)    4 (   3)    2

PASS      1

S.V.
(   1) 2.50000E+04 (   2) 9.93600E-01 (   3) 1.69400E-02

E.V.
(   1)-7.52063E+00 (   2) 6.31001E+00 (   3) 9.88496E-01

W
(   7) 1.00000E+02 (   8) 1.00000E+02 (   1) 9.93600E+01 (   2) 6.40000E-01 (   3) 1.87100E+03 (   4) 8.00000E+02
(   5) 1.00000E+02 (   6) 2.20000E+03

P
(   1) 7.70000E+01 (  26) 8.45206E+01 (   2) 2.45014E+02 (  15) 2.45014E+02 (  16) 2.45014E+02 (   3) 2.45007E+02
(  22) 1.47000E+01 (   4) 2.52419E+02 (  23) 1.46730E+01 (   5) 2.52417E+02 (   6) 8.51786E+01 (  19) 8.51786E+01
(  20) 1.46960E+01 (   7) 8.45211E+01 (  21) 1.46760E+01 (   8) 2.80000E+02 (  14) 2.79012E+02 (   9) 2.99600E+01
(  10) 2.99598E+01 (  24) 1.46960E+01 (  11) 2.90988E+01 (  25) 1.46790E+01 (  12) 2.79099E+02 (  13) 2.79018E+02
(   0) 0.          (   0) 0.

T
(   1) 4.99996E+02 (  26) 5.01034E+02 (   2) 6.20038E+02 (  15) 6.20038E+02 (  16) 6.20038E+02 (   3) 6.20038E+02
(  22) 5.50000E+02 (   4) 5.66926E+02 (  23) 5.68130E+02 (   5) 5.66926E+02 (   6) 5.01034E+02 (  19) 5.01034E+02
(  20) 5.50000E+02 (   7) 5.01034E+02 (  21) 5.18701E+02 (   8) 8.00005E+02 (  14) 7.99732E+02 (   9) 6.42328E+02
(  10) 6.42328E+02 (  24) 5.50000E+02 (  11) 5.65627E+02 (  25) 5.66397E+02 (  12) 5.66063E+02 (  13) 7.99732E+02
(   0) 0.          (   0) 0.

H
(   1) 1.08590E+02 (  26) 1.02280E+02 (   2) 1.23421E+02 (  15) 1.23421E+02 (  16) 1.23421E+02 (   3) 1.23421E+02
(  22) 0.          (   4) 4.15934E+01 (  23) 0.          (   5) 4.15934E+01 (   6) 4.15934E+01 (  19) 4.21171E+01
```

```
(  20) 0.          (   7) 1.02200E+02 (  21) 0.          (   8) 1.32620E+02 (  14) 1.32605E+02 (   9) 1.15835E+02
(  10) 1.15935E+02 (  24) 0.          (  11) 2.99571E+01 (  25) 0.          (  12) 3.05640E+01 (  13) 1.32605E+02
(   0) 0.          (   0) 0.
*AECS*    EXAMPLE CASE FOR POWER CYCLE AND REFRIGERATION CYCLE                                         PAGE        11
    1  CASE POWER                                                                                      DATE 01/23/82

TIME E        5.35

FLOW RATE(S)-LB/MIN

(   1)    99.80 (   2)      .20 (   3) 1871.00 (   4)   800.00 (   5)   100.00 (   6) 2200.00
(   7)   100.00 (   8)   100.00

PRESSURE(S)-PSI

(   1)    77.00 (   2)   245.01 (   3)   245.01 (   4)   252.49 (   5)   252.49 (   6)    77.83
(   7)    77.00 (   8)   280.00 (   9)    29.96 (  10)    29.96 (  11)    29.10 (  12)   280.09
(  13)   280.01 (  14)   280.00 (  15)   245.01 (  16)   245.01 (  19)    77.83 (  20)    14.70
(  21)    14.68 (  22)    14.70 (  23)    14.67 (  24)    14.70 (  25)    14.68 (  26)    77.00
(   0)     0.00 (   0)     0.00

TEMPERATURE(S)-DEG R

(   1)   500.00 (   2)   620.35 (   3)   620.35 (   4)   568.10 (   5)   568.10 (   6)   495.90
(   7)   500.28 (   8)   800.00 (   9)   642.88 (  10)   642.88 (  11)   565.88 (  12)   566.32
(  13)   800.02 (  14)   800.02 (  15)   620.35 (  16)   620.35 (  19)   495.90 (  20)   550.00
(  21)   515.42 (  22)   550.00 (  23)   568.13 (  24)   550.00 (  25)   566.40 (  26)   500.28
(   0)     0.00 (   0)     0.00

HUMIDITY(S)/ENTHALPY(S)-LBW/LBA / BTU/LB

(   1)108.5900 (   2)123.4875 (   3)123.4875 (   4) 41.9569 (   5) 41.9569 (   6) 41.9569
(   7)108.5880 (   8)132.6200 (   9)115.9176 (  10)115.9176 (  11) 30.0073 (  12) 30.6186
(  13)132.6228 (  14)132.6228 (  15)123.4875 (  16)123.4875 (  19) 42.1163 (  20)  0.0000
(  21)  0.0000 (  22)  0.0000 (  23)  0.0000 (  24)  0.0000 (  25)  0.0000 (  26)108.5880
(   0)  0.0000 (   0)  0.0000

STATE VARIABLE TYPE(S)
(   1)     7 (   2)     5 (   3)     6

STATE VARIABLE(S)
(   1) 2.52469E+04 (   2) 9.98045E-01 (   3) 1.75346E-02

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

ERROR VARIABLE(S)
(   1)-2.12693E-03 (   2) 2.03641E-03 (   3) 0.

SOLUTION CONVERGED IN       6 TRY(S)
```

COMMENTS HAVE BEEN INCORPORATED

```
      SUBROUTINE QBLRPP
      COMMON /CC/ C(400)
      EQUIVALENCE (IRCD,C(45)),(IW,C(27)),(IP,C(28)),(IT,C(29))
     *,(IH,C(30)),(SCR(1),C(151)),(GC,C(370)),(JC,C(371))
     *,(ICPP,C(88)),(IFP,C(22)),(OUT,C(7)),(IGA,C(35))
     *,(PASS,C(17)),(IEVT,C(48)),(IEV,C(49)),(ITAD,C(54))
     *,(IFB,C(55)),(ISN,C(38))
      DIMENSION SCR(30)
      INTEGER OUT,PASS
      REAL L,MU,K,JC,ME,MI,MP
      EQUIVALENCE  (SCR(1),NL),(SCR(2),NSI),(SCR(3),NSO)
     *,(SCR(4),IOP),(SCR(5),FFT),(SCR(6),COT),(SCR(7),AF)
     *,(SCR(8),Q),(SCR(9),L),(SCR(10),AH),(SCR(11),DH)
      DIMENSION MU(2),CPY(2),V(2),PR(2),T(5),TW(5),HT(5),DP(2)
     *,K(2)
      COMMON /DC/ DZ(2),D(3201)
      DIMENSION ID(2)
      EQUIVALENCE (ID(1),D(1))
     *,(D(51),T(1)),(D(56),TW(1)),(D(61),HT(1))
     *,(D(71),HFG),(D(72),ST),(D(73),PT)
     *,(D(75),TIN),(D(76),W),(D(77),IRET),(D(78),CO)
     *,(D(79),FF),(D(81),VR),(D(82),DV)
     *,(D(83),SL),(D(84),HSAT),(D(86),TSAT)
     *,(D(87),X1),(D(88),X2),(D(89),TNB),(D(90),DD)
     *,(D(91),FD),(D(92),B),(D(93),EM),(D(94),RS)
C    1 COMP CODE
C    2 LEG NO
C    3 INLET STATION NO
C    4 OUTLET STATION NO
C    5 OPTION NO
C    6 FRICTION FACTOR TABLE
C    7 COLBURN FACTOR TABLE
C    8 HEAT EXCHANGER FLOW AREA
C    9 HEAT INPUT RATE IN (BTU/MIN)
C   10 HEAT EXCHANGER FLOW PATH LENGTH (FEET)
C   11 HT EXCHG/HT TRANSFER AREA INCLUDING FINS (SQUARE FEET)
C   12 HEAT EXCHANGER HYDRAULIC DIAMETER
C   13 ERROR VARIABLE OPTION
C*** ERROR-VARIABLE OPTION: 0 IF NO ERROR VARIABLE; 1 IF SUPERHEAT
C   14 ERROR VARIABLE INDEX
C   15 MAXIMUM BOILER WALL TEMPERATURE
C*** SET UP INTERNAL VARIABLES IN TERMS OF STORED ARRAY
      IRCD = IRCDB(15)
      NL=ID(IRCD+2)
      NSI=ID(IRCD+3)
      NSO=ID(IRCD+4)
      IOP=ID(IRCD+5)
      IF (ID(IRCD+13).EQ.0) GO TO 107
      TMAX=D(ID(IRCD+15))
      JEVI=ID(IRCD+14)
  107 CONTINUE
      LOCT=ID(IFB+NL)
      LOCT=ID(LOCT+3)
      AF=D(ID(IRCD+8))
      Q=D(ID(IRCD+9))
      L=D(ID(IRCD+10))
      AH=D(ID(IRCD+11))
      DH=D(ID(IRCD+12))
C*** COMPUTE THE SATURATION PROPERTIES
      TSAT=VTS(LOCT,D(IP+NSI))
```

```
C*** COMPUTE THE TRANSPORT PROPERTIES BASED ON INLET CONDITIONS
C$ MOVE "TIN" DEFINITION UP AND USE "TIN" (WAS "TSAT") FOR FLUID PROPS
C$      LEAVE TSAT FOR VAPOR PROPERTIES
      TIN=D(IT+NSI)
      CPY(1)=VCPF(LOCT,D(IP+NSI),TIN)
      CPY(2)=VCPV(LOCT,D(IP+NSI),TSAT)
      MU(1)=VVISCF(LOCT,D(IP+NSI),TIN)
      MU(2)=VVISCV(LOCT,D(IP+NSI),TSAT)
      K(1)=VCONDF(LOCT,D(IP+NSI),TIN)
      K(2)=VCONDV(LOCT,D(IP+NSI),TSAT)
      V(1)=1.0/VDL(LOCT,TIN)
      V(2)=VSV('QBLRPP 1',LOCT,D(IP+NSI),TSAT)
      HFG=VHFG(LOCT,D(IP+NSI),TSAT,V(2))
      ST=VST(LOCT,TSAT)
      PT=VDPDT(LOCT,D(IP+NSI))
      W=D(IW+NL)
C$      ADD TO INITIALIZE (WAS SOMETIMES BEING PASSED
C$                                                FROM PREVIOUS COMPONENT)
      XE=0.0
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IRITE=1
      IF (IRITE .NE. 1) GO TO 9010
      WRITE (OUT,9911)
 9911 FORMAT(' ',/)
      WRITE (OUT,9011)
 9011 FORMAT(' *********WRITE 9011 FROM "QBLRPP" *********************'
     *       ,'**************')
      WRITE (OUT,9012) AF    , Q    , L     , AH
     *                , DH    , TSAT , CPY(1), CPY(2)
     *                , MU(1) , MU(2) , K(1)  , K(2)
     *                , V(1)  , V(2)  , HFG   , ST
     *                , PT    , TIN   , W     , D(IP+NSI)
     *                , D(IH+NSI)
 9012 FORMAT(' AFLOW =', E12.5,  ' QRATE =', E12.5,  ' LFLOW =', E12.5
     *       ,' AHTRAN=', E12.5,/,' DHYD  =', E12.5,  ' TSAT  =', E12.5
     *       ,' CPY(1)=', E12.5,  ' CPY(2)=', E12.5,/,' MU(1) =', E12.5
     *       ,' MU(2) =', E12.5,  ' K(1)  =', E12.5,  ' K(2)  =', E12.5
     *   ,/ ,' V(1)  =', E12.5,  ' V(2)  =', E12.5,  ' HFG V2=', E12.5
     *       ,' ST    =', E12.5,/,' PTDPDT=', E12.5,  ' TIN   =', E12.5
     *       ,' W     =', E12.5,  ' P IN  =', E12.5,/,' H IN  =', E12.5)
 9010 CONTINUE
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      DO 1 I = 1,2
    1 PR(I)=3600.*CPY(I)*MU(I)/K(I)
      IRET=-1
C*** COMPUTE THE REYNOLDS NUMBER AS THE INDEPENDENT VARIABLE
      G=W/AF/60.0
C*** BASED ON 100% LIQUID FLOW
      D(IGA+21)=G*DH/MU(1)
C*** USE TULP FOR COLBURN FACTOR, THEN COMPUTE HEAT TRANSFER COEFF.
      CO=TLUP(ID(IRCD+7))
      HT(1)=CO*60.*G*CPY(1)/PR(1)**.67
C*** USE TULP FOR FRICTION FACTOR
      FF=TLUP(ID(IRCD+6))
C*** COMPUTE VOLUME RATIO AND SLIP FOR LATER TWO-PHASE COMPUTATIONS
      VR=V(2)/V(1)
      DV=1.0-1.0/VR
      SL=SQRT(SQRT(VR-1.))
C*** COMPUTE PRESSURE DROP AS IF 100% LIQUID FLOW
      DP(1)=4.*FF*L*G*G*V(1)/(2.*DH*GC)
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```
C*** REPEAT THE ABOVE COMPUTATIONS AS IF 100% VAPOR FLOW
      D(IGA+21)=G*DH/MU(2)
      CO=TLUP(ID(IRCD+7))
      HT(5)=CO*60.*G*CPY(2)/PR(2)**.67
      FF=TLUP(ID(IRCD+6))
      DP(2)=4.*FF*L*G*G*V(2)/(2.*DH*GC)
C*** DETERMINE WHICH FLUID-PHASE IS FLOWING AT THE INLET
      HSAT=VH(LOCT,D(IP+NSI),TSAT,V(2))-HFG
      TIN=D(IT+NSI)
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IRITE=1
      IF (IRITE .NE. 1) GO TO 9020
      REF=G*DH/MU(1)
      D(IGA+21)=REF
      COLBF=TLUP(ID(IRCD+7))
      FFF=TLUP(ID(IRCD+6))
      REV=G*DH/MU(2)
      D(IGA+21)=REV
      COLBV=TLUP(ID(IRCD+7))
      FFV=TLUP(ID(IRCD+6))
      VHPTV2=VH(LOCT,D(IP+NSI),TSAT,V(2))
      QPSIF=DP(1)*DH/(4.*FFF*L)/144.
      QPSIV=DP(2)*DH/(4.*FFV*L)/144.
      WRITE (OUT,9021)
 9021 FORMAT(' WRITE 9021 FROM "QBLRPP"     ')
      WRITE (OUT,9022) PR(1) , PR(2) , G      , REF
     *                , COLBF , HT(1) , FFF    , VR
     *                , DV    , SL    , DP(1) , REV
     *                , COLBV , HT(5) , FFV    , DP(2)
     *                , HSAT  , TIN   , VHPTV2,QPSIF
     *                , QPSIV
 9022 FORMAT(' PR(1) =', E12.5,  ' PR(2) =', E12.5,  ' G     =', E12.5
     *     ,' REF   =', E12.5,/,' COLBF =', E12.5,  ' HT(1) =', E12.5
     *     ,' FFF   =', E12.5,  ' VR    =', E12.5,/,' DV    =', E12.5
     *     ,' SL    =', E12.5,  ' DP(1) =', E12.5,  ' REV   =', E12.5
     *   ,/ ,' COLBV =', E12.5,  ' HT(5) =', E12.5,  ' FFV   =', E12.5
     *     ,' DP(2) =', E12.5,/,' HSAT L=', E12.5,  ' TIN   =', E12.5
     *     ,' VHPTV2=', E12.5,  ' QPSIF =', E12.5,/,' QPSIV =', E12.5)
 9020 CONTINUE
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C*** IN LIQUID-ONLY REGION AT INLET OR NOT?
      IF(D(IH+NSI)-HSAT)360,332,332
C*** IN TWO-PHASE REGION AT INLET OR ALL VAPOR?
  332 IF(D(IH+NSI)-HSAT-HFG)333,1272,1272
C*** IN TWO-PHASE REGION AT INLET
  333 XI=(D(IH+NSI)-HSAT)/HFG
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IRITE=1
      IF (IRITE .NE. 1) GO TO 9023
C         APPROX FOR Q HERE IS GOOD ONLY FOR TWO-PHASE
      XILIM1=AMIN1(1.,XI)
      QVAP=1/64.4 * V(2) * (XILIM1*G)**2/144.
      WRITE (OUT,9024)
 9024 FORMAT(' WRITE 9024 FROM "QBLRPP" ... TWO PHASE AT INLET   ')
      WRITE (OUT,9025) XI     , QVAP
 9025 FORMAT(' XI    =', E12.5,  ' QVAP  =', E12.5)
 9023 CONTINUE
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      TIN=TSAT
      X1=0.0
```

```
      X2=0.0
      GO TO 750
C*** IN LIQUID-ONLY REGION AT INLET
  360 XI=0.0
C$$        (OLD CODE FAILED TO CONSIDER THE POSSIBILITY OF ALL-LIQUID
C$$         FORCED CONVECTION HEATING UP TO TSAT AND THEN SATURATED
C$$         BOILING STARTING THERE.  IF THERE WAS NO NUCLEATE (SUBCOOLED)
C$$         BOILING, IT ASSUMED THERE WAS NO TWO-PHASE FLOW AT ALL.)

C*** COMPUTE FLUID TEMPERATURE (T) AND WALL TEMPERATURE (TW) AT OUTLET
C***  ASSUMING LIQUID-ONLY FORCED CONVECTION HEATING ALL THE WAY
      T(1)=TIN+Q/(W*CPY(1))          T5CNVC
      TW(1)=T(1)+Q/(AH*HT(1))             TW5CNVC
C$ THIS COMMENT USED TO SAY SEE IF FLUID REACHED THE "TNB" BEFORE EXIT.
C$                                 ?????
C$    SINCE TNB IS GREATER THAN TSAT (OBVIOUS FROM EQUATION), HOW CAN
C$    TFLUID BE GREATER THAN TNB (AND ALSO TSAT) AND STILL BE SUBCOOLED?
C$    OBVIOUSLY THEY MEANT "TWALL", NOT "TFLUID", BUT THAT WASN'T WHAT
C$    WAS CODED TO COMPUTE "X1".
C$
C*** DETERMINE TEMPERATURE AT WHICH NUCLEATE BOILING BEGINS (TNB)
C    AND DETERMINE IF WALL REACHES THE TEMPERATURE BEFORE OUTLET
      DELT=TW(5)-T(5)             DT5CNVC= TW5CNVC - T5CNVC
TW(1) TWALIN=TIN+DELT           TW1CNVC=TIN+ DT5CNVC
      IF (Q) 420,425,425
  420 TNB=9999.
      GO TO 428                                                   TSAT=330
  425 TNB=TSAT+SQRT(8.*60.*ST*Q/(K(1)*AH*PT))
  428 CONTINUE                                                    TNB=340
C$WAS X1=(TNB-TIN)*W*CPY(1)*L/Q-W*CPY(1)*L/(HT(1)*AH)
C*** FIND X AT WHICH NUCLEATE BOILING WOULD BEGIN     X1NUC=.2L    X1NUC=[1-
      X1NUC=(1. - (TW(1)-TNB)/(TW(5)-TWALIN))   * L            (500-340)/(500-300)]
C*** FIND X AT WHICH BULK BOILING WOULD BEGIN (TSAT IS REACHED)
C***   IF FORCED-CONVECTION HEATED ALL THE WAY.
      X1SAT=(TSAT-TIN)/(T(1)-TIN)   * L   = (330-280)/(480-280) = 50/200 =.25L
C     WRITE(OUT,*) T(1),TW(1),TNB,X1                          =(1-.8)* L
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IRITE=1                                X1SAT=.25L        = .2L ✓
      IF (IRITE .NE. 1) GO TO 9030
      WRITE (OUT,9031)
 9031 FORMAT(' WRITE 9031 FROM "QBLRPP"     ')
      WRITE (OUT,9032) T(1)   , TW(1) , TNB    , X1
     *                   ,X1NUC  , X1SAT , TWALIN
 9032 FORMAT(' T(1)  =', E12.5,  ' TW(1) =', E12.5,  ' TNB   =', E12.5
     *      ,' X1    =', E12.5,/,' X1NUC =', E12.5,  ' X1SAT =', E12.5
     *      ,' TWALIN=', E12.5)
 9030 CONTINUE                  TW1CNVC 300
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IF(TNB-TWALIN)430,450,450
C*** NUCLEATE BOILING BEGINS IMMEDIATELY AT THE INLET
  430 X1=0.0
      GO TO 485                                     NOT
C*** NO NUKE BOILING BEFORE TSAT REACHED (455);OR X1NUC (451) LESS THAN L
  450 IF(X1SAT-X1NUC)455,455,451
C*** X1NUC IS LESS THAN X1SAT, BUT IS X1NUC LESS THAN L?
  451 IF(TW(1)-TNB)455,480,480
C*** NO NUCLEATE BOILING, BUT IS LIQUID EXIT TEMP BELOW TSAT OR ABOVE?
  455 IF(T(1)-TSAT)460,460,477          T5CNVC
C*** TEXIT BELOW TSAT, THERE IS NO BOILING WITHIN THE BOILER
  460 X1=L
```

L-X1NUC

```
      X2=0.
      X3=0.
      XE=0.
      T(5)=~~T(1)~~ T5CNVC
      TW(5)=TW~~(1)~~ TW5CNVC
      GO TO 1310
C*** FORCED CONV. HEATS TEXIT TO ABOVE TSAT; WILL BE TWO-PHASE FLOW
  477 X1=X1SAT
      X2=0.
      T(1)=TSAT                      TSAT + DT5CNVC
      TW(1)=~~T(1)+Q/(HT(1)*AH)~~
      T(2)=TSAT
      TW(2)=TW(1)
      GO TO 750
C*** THERE IS FORCED-CONVECTION HEATING FOLLOWED BY NUCLEATE BOILING
  480 X1=X1NUC
      T(1)=TIN+Q*X1/(L*W*CPY(1))
      TW(1)=T(1)+Q/(HT(1)*AH)
C*** COMPUTE THE LENGTH OF THE NUCLEATE-BOILING REGION
C***        ALSO ENTRY FOR NUCLEATE BOILING IMMED AT INLET
C$   WAS 485 X2=XSAT-X1
  485 X2=X1SAT-X1
      IF(X2.GE.(L-X1))X2=L-X1
C*** COMPUTE THE BUBBLE DEPARTURE DIAMETER (DD) IN FEET
  490 DD=4.65E-4*SQRT(GC/GC*ST*V(1)/DV)*(VR*CPY(1)*TSAT/HFG)
     ***1.25
C*** COMPUTE THE FREQUENCY OF DEPARTURE OF BUBBLES, 1/SEC.
      FD=.6*SQRT(SQRT(ST*GC*GC*V(1)*DV))/DD
C*** ASSUME THE SURFACE FACTORS: B(SURFACE COFFICIENT); EM (EXPONENT
C    RELATING THE NUMBER OF NUCLEATION SITES GO THE TEMPERATURE
C    DIFFERENCE); AND RS(RADIUS, FT., OF SMALLEST SITE)
      B=400.
      EM=2.0
      RS=0.0001
C*** COMPUTE THE NUMBER OF NUCLEATION SITES PER SQ. FT.
C*** JC=778.28 PER LINE 265 OF FORT(FTB1S)
      XN=B*(JC*RS*HFG*(TNB-TSAT)/(2.*TSAT*ST*V(2)))**EM
C*** COMPUTE THE POOL BOILING HEAT-TRANSFER COEFFICIENT
      HP=3.5*(K(1)/DD/60.)*XN*DD*DD
      HP=HP*SQRT(PR(1))*SQRT(FD*DD*DD/(V(1)*MU(1)))
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IRITE=1
      IF (IRITE .NE. 1) GO TO 9040
      WRITE (OUT,9041)
 9041 FORMAT(' WRITE 9041 FROM "QBLRPP"     ')
      WRITE (OUT,9042) X1    , T(1)  , TW(1) , X2
     *                , DD    , FD    , B     , EM
     *                , RS    , XN    , HP
 9042 FORMAT(' X1    =', E12.5,  ' T(1)  =', E12.5,  ' TW(1) =', E12.5
     *       ,' X2    =', E12.5,/,' DD    =', E12.5,  ' FD    =', E12.5
     *       ,' B     =', E12.5,  ' EM    =', E12.5,/,' RS    =', E12.5
     *       ,' XN    =', E12.5,/,' HP    =', E12.5)
 9040 CONTINUE
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IF(IRET)500,500,980
C*** COMPUTE THE COMBINED CONVECTION/BOILING COEFFICIENT
  500 HT(2)=(HP*HP+HT(1)*HT(1))/(2.*HP)
C*** ITERATIVELY COMPUTE THE WALL TEMPERATURE IN THE NUCLEATE REGION
      A1=HP/(TNB-TSAT)**2
      A0=2.0*(Q/(A1*AH))**2
```

```
      A1=4.0*((HT(1)/A1)**2)/3.0
      S0=SQRT(A0*A0-A1**3)
C$WAS XX=ABS((A0-S0)/(A0+S0))
C$WAS IF(XX-.0001)650,670,670
C$     SIMPLIFY AND MAKE SURE NO NEGATIVE # IS RAISED TO A POWER
      IF(A0-S0)650,670,670
  650 U=(A0+S0)**(1./3.)
      GO TO 680
  670 U=(A0+S0)**(1./3.)+(A0-S0)**(1./3.)
  680 TC=(SQRT(U)+SQRT(U-4.*(U/2.-SQRT((U/2.)**2-.75*A1))))/2.
      T(2)=TSAT
      TW(2)=TSAT+TC
      TW(5)=TW(2)
      X3=0.0
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IRITE=1
      IF (IRITE .NE. 1) GO TO 9050
      WRITE (OUT,9051)
 9051 FORMAT(' WRITE 9051 FROM "QBLRPP"     ')
      WRITE (OUT,9052) IRET   , HT(2) , A0     , A1
     *                ,S0     , XX    , U      , TC
     *                ,T(2)   , TW(2) , TW(5)  , XE
 9052 FORMAT(' IRET  =', I4,8X,  ' HT(2) =', E12.5,  ' A0    =', E12.5
     *      ,' A1    =', E12.5,/,' S0    =', E12.5,  ' XX    =', E12.5
     *      ,' U     =', E12.5,  ' TC    =', E12.5,/,' T(2)  =', E12.5
     *      ,' TW(2) =', E12.5,  ' TW(5) =', E12.5,  ' XE CHK=', E12.5)
 9050 CONTINUE
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C*** GO TO 1280 IF THE EXIT IS 100% LIQUID (NO NET BOILING)
C$ WAS   IF(X2.GE.(L-X1))GO TO 1280
      IF(X2.GE.(L-X1-.0001))GO TO 1280
C*** STARTING REGION 3: BULK BOILING
  750 XC=1.0
C*** COMPUTE THE DRYOUT POSITION
      X3=W*(CPY(1)*(TSAT-TIN)+HFG*(1.0-XI))*L/Q-X1-X2
C*** COMPUTE THE EXIT QUALITY
      XE=(Q/W-CPY(1)*(TSAT-TIN))/HFG+XI
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IRITE=1
      IF (IRITE .NE. 1) GO TO 9053
      WRITE (OUT,9054)
 9054 FORMAT(' WRITE 9054 BULK BOILING-DRYOUT POSITION  FROM "QBLRPP"')
      WRITE (OUT,9055) X3     , XE
 9055 FORMAT(' X3DRYO=', E12.5,  ' XE    =', E12.5)
 9053 CONTINUE
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IF(XE-1.)830,820,820
C*** FILM-BOILING OR VAPOR-ONLY HEATING OCCUR
  820 XE=1.0
      GO TO 1140
C*** COMPUTE THE CRITICAL EXIT QUALITY ABOVE WHICH FILM BOILING OCCURS
C$WAS COMPUTE THE CRITICAL EXIT QUALITY ABOVE WHICH VAPORIZATION OCCURS
  830 XC=JC*HFG*(XE-XI)/L
C$             NEED TO USE "REF" HERE AS ON P 97 COSTELLO
C$             CODE USED OLD "REV" VALUE... LINE BELOW SHOULD FIX
      D(IGA+21)=G*DH/MU(1)
      XC=1.04-1.14E-5*(D(IGA+21)*D(IGA+21)*XC)**.375
C*** COMPUTE LENGTH OF THE BULK-BOILING REGION (X3)
      X3=X3*(XC-XI)/(1.0-XI)
      IF (X3.LT.0.0) X3=0.0
```

```
      IF(X3.GT.(L-X1-X2))X3=L-X1-X2
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IRITE=1
      IF (IRITE .NE. 1) GO TO 9060
      WRITE (OUT,9061)
 9061 FORMAT(' WRITE 9061  FROM "QBLRPP"    ')
      WRITE (OUT,9062) X3    , XE    , XC
 9062 FORMAT(' X3    =', E12.5,  ' XE    =', E12.5,  ' XC    =', E12.5)
 9060 CONTINUE
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IF(XE.GE.XC)GO TO 1140
C*** COMPUTE THE TWO-PHASE PARAMETER
      TT=(1.0/XE-1.0)**0.9*SQRT(DP(1)/DP(2))
      X3=L-X1-X2
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IRITE=1
      IF (IRITE .NE. 1) GO TO 9070
      WRITE (OUT,9071)
 9071 FORMAT(' WRITE 9071    XE LESS THAN XC    FROM "QBLRPP"    ')
      WRITE (OUT,9072) TT    , X3
 9072 FORMAT(' TT    =', E12.5,  ' X3    =', E12.5)
 9070 CONTINUE
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C*** GO TO 1090 IF XE AND TT INDICATE THE RANGE FOR ELLERBROOK'S FORMULA
      IF(XE.GT.0.7.OR.TT.LT.0.01)GO TO 1090
C*** USE CHEN'S FORMULA
      F=1.0+1.88/TT**0.8
      Y=F*(G*DH/MU(1)*(1.0-XE))**0.8/10000.
      S=EXP(-Y)
C*** COMPUTE TNB AS A FIRST APPROXIMATION TO THE WALL TEMPERATURE
C    THEN GO TO 490 TO COMPUTE THE POOL-BOILING HEAT-TRANSFER COEFF.
      TNB=TSAT+SQRT(.8*60.*ST*Q/(K(1)*AH*PT))
      IRET=1
      GO TO 490
C*** COMPUTE THE BULK-BOILING COEFFICIENT WITH CHEN'S FACTORS
  980 HT(3)=F*HT(1)+S*HP
C*** COMPUTE THE WALL TEMPERATURE AT THE END OF THE TWO-PHASE REGION
C    UNDER THE ASSUMPTION THAT EM IS APPROXIMATELY 2.0
      A1=HP/(TNB-TSAT)**2
      A0=Q/(AH*S*A1*2.0)
      A1=F*HT(1)/(3.0*S*A1)
      S0=SQRT(A0*A0+A1**3)
      T(3)=TSAT
      TW(3)=TSAT+(A0+S0)**(1./3.)-(S0-A0)**(1./3.)
      TW(5)=TW(3)
      T(5)=TSAT
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IRITE=1
      IF (IRITE .NE. 1) GO TO 9080
      WRITE (OUT,9081)
 9081 FORMAT(' WRITE 9081     CHEN''S FORMULA       FROM "QBLRPP"    ')
      WRITE (OUT,9082) F     , Y     , S     , TNB
     *                ,IRET  , A0    , A1    , S0
     *                ,T(3)  , TW(3) , TW(5) , T(5)
     *                ,HT(3)
 9082 FORMAT(' F     =', E12.5,  ' Y     =', E12.5,  ' S     =', E12.5
     *      ,' TNB   =', E12.5,/,' IRET  =', I4,8X,  ' A0    =', E12.5
     *      ,' A1    =', E12.5,  ' S0    =', E12.5,/,' T(3)  =', E12.5
     *      ,' TW(3) =', E12.5,  ' TW(5) =', E12.5,  ' T(5)  =', E12.5,/
     *      ,' HT(3) =', E12.5)
```

```
 9080 CONTINUE
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C*** GO TO 1320 TO COMPUTE THE TWO-PHASE PRESSURE DROP
      GO TO 1320
C$     THE ELLERBROOK FORMULA GIVES AN H LOWER THAN FOR FILM BOILING
C$     AND LOWER THAN "HT(5)" (ALL VAPOR).  IS SOMETHING WRONG OR IS
C$     ELLERBROOK JUST A DAMN FLAKE??
C*** ELLERBROOK'S FORMULA FOR THE HEAT-TRANSFER COEFFICIENT
 1090 Y=2.35-ALOG(TT)*(.266+.0255*ALOG(TT))
      HT(3)=HT(5)*(Q/(AH*60.*G*HFG))**.4*EXP(Y)
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IRITE=1
      IF (IRITE .NE. 1) GO TO 9090
      WRITE (OUT,9091)
 9091 FORMAT(' WRITE 9091   ELLERBROOK''S HT(3) FORMULA FROM "QBLRPP"')
      WRITE (OUT,9092) Y     , HT(3)
 9092 FORMAT(' Y     =', E12.5,  ' HT(3) =', E12.5)
 9090 CONTINUE
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      GO TO 1180
C*** XE>XCRIT OR XE>1.  SO FILM BOILING OR VAPOR-ONLY HEATING OCCURS
C$WAS SO FILM BOILING OR VAPOR-ONLY HEATING OCCURS
 1140 HT(3)=HT(5)*(XE+SL/VR*(1.0-XE))**0.8
C*** FLUID AND WALL TEMPERATURES AT THE END OF THE TWO-PHASE REGION
C$WAS 1180 T(3)=TSAT+(Q*(X3+X2+X1)/W/L-CPY(1)*(TSAT-TIN)-HFG*(XE-XI))
C$         /CPY(2)
C$
C$   CERTAINLY WHILE TWO-PHASE, T=TSAT!!!
 1180 T(3)=TSAT
      TW(3)=T(3)+Q/(AH*HT(3))
      T(5)=T(3)
      TW(5)=TW(3)
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IRITE=1
      IF (IRITE .NE. 1) GO TO 9100
      WRITE (OUT,9101)
 9101 FORMAT(' WRITE 9101   FILM BOIL OR VAPOR ONLY HEATING  "QBLRPP"')
      WRITE (OUT,9102) T(3)  , HT(3) , TW(3) , T(5)
     *                ,TW(5) , X1    , X2    , X3
     *                ,XI    , XE
 9102 FORMAT(' T(3)  =', E12.5,  ' HT(3) =', E12.5,  ' TW(3) =', E12.5
     *      ,' T(5)  =', E12.5,/,' TW(5) =', E12.5,  ' X1    =', E12.5
     *      ,' X2    =', E12.5,  ' X3    =', E12.5,/,' XI    =', E12.5
     *      ,' XE    =', E12.5)
 9100 CONTINUE
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C*** IF VAPOR-ONLY FLOW DOES NOT OCCUR, GO TO 1320 TO COMPUTE DELTA P
      IF(XE.LT.1.0)GO TO 1320
C*** COMPUTE OUTLET CONDITIONS FOR VAPOR-ONLY FLOW
      T(5)=(Q/W-CPY(1)*(TSAT-TIN)-HFG*(1.0-XI))/CPY(2)+TSAT
      XE=1.0
      TW(5)=T(5)+Q/(AH*HT(5))
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IRITE=1
      IF (IRITE .NE. 1) GO TO 9110
      WRITE (OUT,9111)
 9111 FORMAT(' WRITE 9111   VAPOR ONLY HEATING  "QBLRPP"')
      WRITE (OUT,9112) T(5)  , XE    , TW(5)
 9112 FORMAT(' T(5)  =', E12.5,  ' XE    =', E12.5,  ' TW(5) =', E12.5)
 9110 CONTINUE
```

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C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      GO TO 1320
C*** COMPUTE OUTLET CONDITIONS FOR VAPOR-ONLY FLOW FROM INLET TO OUTLET
 1272 T(5)=TIN+Q/W/CPY(2)
      TW(5)=T(5)+Q/AH/HT(5)
      XI=1.000
C$    ADD 144 FACTOR; DO NOT COMPUTE "D(IP+NSO)" HERE AND LINE 1475
      XDP=DP(2)/144.
C$    D(IP+NSO)=D(IP+NSI)-DP(2)/144.
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IRITE=1
      IF (IRITE .NE. 1) GO TO 9120
      WRITE (OUT,9121)
 9121 FORMAT(' WRITE 9121   VAPOR ONLY INLET TO OUTLET   "QBLRPP"')
      WRITE (OUT,9122) T(5)  , TW(5)
 9122 FORMAT(' T(5)  =', E12.5,  ' TW(5) =', E12.5)
 9120 CONTINUE
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      GO TO 1475
C*** COMPUTE THE OUTLET TEMPERATURE FOR NO NET VAPOR GENERATION
C$ WAS  1280 T(5)= TIN+Q/(AH*CPY(1))
 1280 T(5)= TIN+Q/(W*CPY(1))
 1310 PB=0.0
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IRITE=1
      IF (IRITE .NE. 1) GO TO 9130
      WRITE (OUT,9131)
 9131 FORMAT(' WRITE 9131 TOUT FOR NO NET VAPOR GENERATED  "QBLRPP"')
      WRITE (OUT,9132) T(5)  , PB
 9132 FORMAT(' T(5)  =', E12.5,  ' PB    =', E12.5)
 9130 CONTINUE
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      GO TO 1350
C*** COMPUTE THE TWO-PHASE PRESSURE DROP BY FAC. INC. CORRELATION
C    OF BAROCZY'S GRAPHICAL CORRELATION
 1320 PF=0.25*ALOG10(DP(1)/DP(2))
      PB=XE**.7/1.7-(1-XE)**2.3/2.3+(1.-(1.-XE)**3.3)/(3.3*2.3*XE)
C*** COMPUTE THE FRICTION PRESSURE DROP
      PB=-XE**1.65*PF/2.65+(1.0+PF)*PB
 1350 FP=DP(1)*(X1+X2)/L+(DP(1)+PB*(DP(2)-DP(1)))*X3/L
      FP=FP+DP(2)*(1.-(X1+X2+X3)/L)
      IF(XE) 1382,1382,1385
C*** ADD THE MOMENTUM PRESSURE DROP
 1382 MP=0.0
      GO TO 1470
 1385 VE=XE/(XE+SL*(1.0-XE)/VR)
      IF(VE-1.0)1388,1386,1386
 1386 ME=VR
      GO TO 1390
 1388 ME=((1.-XE)/(1.-VE))**2*(1.-VE*(1.-SL*SL/VR))
 1390 IF(XI)1395,1395,1400
 1395 MI=1.0
      GO TO 1440
 1400 VI=XI/(XI+SL*(1.0-XI)/VR)
      IF(VI-1.0)1430,1425,1425
 1425 MI=VR
      GO TO 1440
 1430 MI=((1.-XI)/(1.-VI))**2*(1.-VI*(1.-SL*SL/VR))
 1440 MP=G*G*V(1)*(ME-MI)/GC
 1470 XDP=(FP+MP)/144.
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 1475 D(IP+NSO)=D(IP+NSI)-XDP
CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IRITE=1
      IF (IRITE .NE. 1) GO TO 9140
      XFPPSI= FP/144.
      XMPPSI= MP/144.
      WRITE (OUT,9141)
 9141 FORMAT(' WRITE 9141     DELTA P CALC          FROM "QBLRPP"     ')
      WRITE (OUT,9142) PF     , PB     , FP     , XE
     *                ,VE     , ME     , MI     , VI
     *                ,MP     , XMPPSI, XDP    , XFPPSI
     *                ,X1     , X2     , X3
 9142 FORMAT(' PF     =', E12.5,  ' PB     =', E12.5,  ' FP     =', E12.5
     *      ,' XE     =', E12.5,/,' VE     =', E12.5,  ' ME     =', E12.5
     *      ,' MI     =', E12.5,  ' VI     =', E12.5,/,' MP     =', E12.5
     *      ,' XMPPSI=', E12.5,  ' XDP    =', E12.5,  ' XFPPSI=', E12.5,/
     *      ,' X1     =', E12.5,  ' X2     =', E12.5,  ' X3     =', E12.5)
 9140 CONTINUE
CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IF (D(IP+NSO).GT.0.0)GO TO 1476
      WRITE(OUT,7655) D(IP+NSO),D(IP+NSI)
 7655 FORMAT(' *+* OUTLET PRESSURE IN QBOILER WAS',E14.7,
     *  ' RESET PRESSURE TO INLET VALUE',E14.7)
      XDP=0.0
      D(IP+NSO)=D(IP+NSI)
 1476 CONTINUE
C$  IS
      D(IH+NSO)=D(IH+NSI)+Q/W
C$  WAS:
C$    C$WAS IF(T(5)-TSAT)1478,1479,1479
C$          IF(T(5)-TSAT)1478,14785,1479
C$     1478 D(IH+NSO)=VHLIQ(LOCT,D(IP+NSI),T(5))
C$          GO TO 1480
C$    C$      NEW LINE BELOW CALCULATES EXIT ENTHALPY WHEN TWO-PHASE AT
C$    14785 D(IH+NSO)=HSAT+XE*HFG
C$          GO TO 1480
C$     1479 VV=VSV('QBLRPP 2',LOCT,D(IP+NSO),T(5))
C$          D(IH+NSO)=VH(LOCT,D(IP+NSO),T(5),VV)
C$     1480 CONTINUE
C$
      D(IT+NSO)=T(5)
CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IRITE=1
      IF (IRITE .NE. 1) GO TO 9150
      WRITE (OUT,9151)
 9151 FORMAT(' WRITE 9151   ASSIGN HOUT AND TOUT    FROM "QBLRPP"     ')
      WRITE (OUT,9152) T(5)   , VV     , TSAT   , HSAT
     *                ,XE     , HFG
 9152 FORMAT(' T(5)   =', E12.5,  ' VV     =', E12.5,  ' TSAT   =', E12.5
     *      ,' HSAT   =', E12.5,/,' XE     =', E12.5,  ' HFG    =', E12.5)
 9150 CONTINUE
CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      IF (ID(IRCD+13).EQ.0) GO TO 1579
      IF(PASS.NE.1) GO TO 1577
      ID(IEVT+JEVI)=3
 1577 IF (TMAX.GE.TSAT) GO TO 1576
      WRITE(OUT,1580) TMAX,TSAT,TW(5)
 1580 FORMAT(5X,'WARNING FROM QBOILER: ERROR VARIABLE CANNNOT BE '/
     *' CONTROLLED BECAUSE THE CONTROLLED WALL TEMPERATURE OF',E17.7/
     *' IS LESS THAN THE SATURATION TEMPERATURE OF',E17.7/
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     *' THE WALL TEMPERATURE IS',E17.7)
 1576 IF(T(5).GT.TSAT)GO TO 1578
      WRITE(OUT,1590)XE
 1590 FORMAT(5X,'WARNING FROM QBOILER: TWO PHASE FLUID AT OUTLET',
     *' PROBABLY CANNOT CONTROL WALL TEMP. EXIT QUALITY IS',E12.4)
 1578 D(IEV+JEVI) = (TMAX-TW(5))/XE
 1579 CONTINUE
 1485 FORMAT(' OVERALL: DP,TW(5),T(5) ',3F10.3)
      IF (IFP.NE.1.OR. ICPP.NE.0) GO TO 99
      CALL PIOP(1,NL,NSI,NSO)
      CALL LINES(2)
      WRITE(OUT,1581) ID(ISN+NSO),TW(5)
 1581 FORMAT(5X,'BOILER AT STATION NO.',I4,' HAS A MAXIMUM WALL ',
     * 'TEMPERATURE OF',E15.5,' DEGREES R')
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      WRITE(OUT,9581) XI, XE
 9581 FORMAT('        INLET QUAL=', F8.3, '    EXIT QUAL=', F8.3)
C$XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
   99 CONTINUE
      RETURN
C     QBLRPP
      END
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