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ANL/RBC: A Computer Code for the Analysis of Rankine Bottoming Cycles, Including System Cost Evaluation and Off-Design Performance

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1. INTRODUCTION

ANL/RBC is a FORTRAN computer program which calculates cycle performance and the sizes and costs of system components for Rankine Bottoming Cycles. This computer program is an expanded/modified version of an earlier undocumented computer program, originally developed by J. L. Krazinski of ANL and used for the comparison study reported in Ref. 1. As an option the code can be used to calculate performance for a given system for "off-design" conditions, which are defined below. The basic system model consists of a user-defined Rankine cycle, which extracts heat from a source gas stream, (e.g., the exhaust stream of a prime-mover), and rejects heat to a coolant stream. The gas flow rate and gas inlet temperature are assumed to be known fixed quantities. Using input data which define the working fluid and cycle conditions (e.g., turbine inlet pressure and temperature, condensing temperature, component efficiencies, etc.) the code calculates the power output of the Rankine cycle and the sizes of the heat exchangers for the cycle. An option is provided to calculate the costs of the various system components, using cost data supplied by the user. The code allows a number of cases to be run at one time, for different conditions of turbine inlet temperature and pressure. These different turbine inlet conditions may be specified by the user for each case, or calculated automatically for a user specified mesh over ranges of pressure and temperature.

The power output of the Rankine cycle is calculated from the total heat which can be extracted from the source gas stream, subject to two limiting constraints. The first of these constraints is a user specified minimum temperature for the source stream gas, which limits the total amount of heat which can be extracted from the gas. A common example of this minimum temperature is a vaporizer corrosion condition that limits the exhaust gas stream to a minimum temperature (say 300F). The second constraint condition relates to the "pinch-point" temperature difference between the gas stream and the cycle working fluid. If the gas stream temperature is "too close" to the working fluid temperature, at the point of the smallest temperature difference, then the heat-exchanger areas will become excessively large. The code limits the pinch-point temperature difference to be greater than or equal to a user specified minimum value.

The Rankine cycle model allows for a number of variations from the conventional ideal Rankine cycle. These variations are described in detail in this report. The cycle may be sub-critical with a distinct phase change in the vaporizer, or it may be super-critical. The state of the working fluid at the turbine exhaust may be superheated, saturated, or may be wet (limited to 10% wet). If the state at the turbine exhaust is superheated, an optional regenerator may be included in the cycle to transfer energy to the compressed liquid at the pump outlet. The liquid leaving the condenser may be sub-cooled, by a user specified temperature change. Pressure drops in the heat exchangers may be specified in terms of fixed percentages of the nominal working pressures.

The code logic is structured to calculate cycle performance and component sizes and costs for one or more cycles specified by the user; or optionally to calculate cycle performance and component sizes for a single cycle at its design point and then calculate the performance of this system when operated at off-design conditions. An off-design point is one where the temperature and/or the mass flow rate of the source gas stream is changed from the design point. For an off-design operating point, the heat transfer rates in the vaporizer (and regenerator, if used) will be different from that calculated for the design point. To account for these different heat transfer rates with fixed heat-transfer areas, the mass flow rate of the cycle working fluid must be changed so that the heat transfer capacity of the vaporizer (and regenerator, if used) is correct, using the heat transfer areas calculated for the design point. The code adjusts the turbine inlet pressure, and temperature if necessary, to find a new cycle mass flow rate for which the heat transfer areas are correct.

2. RANKINE THERMODYNAMIC CYCLE MODEL

Figure A-1 shows a schematic diagram of the Rankine bottoming cycle model used in the ANL/RBC. This model includes an optional regenerator at the turbine outlet, supplying heat to the compressed liquid at the pump outlet. The heat source for this cycle is a source (waste) gas stream, with an assumed known mass flow rate and inlet gas temperature. Figure A-2 shows a T-s diagram of one version of a Rankine cycle, with the gas stream superimposed

schematically (the entropy scale for the gas would be different from that for the working fluid). The cycle state points, labeled 1-9 starting with the saturated liquid in the condenser, are discussed below. The code allows for several variations of this basic cycle; for example, a supercritical cycle would not have the vaporization segment (4-5). Likewise, if a regenerator is not used, then state points 3 and 8 would degenerate to the preceding points 2 and 7. Sub-cooling of the liquid in the condenser is allowed, with the state-point for the sub-cooled liquid designated 1'.

2.1 CYCLE STATE POINT PRESSURES

For the cycle analysis, it is assumed that the working fluid properties are known for the saturated liquid in the condenser (point 1) and at the turbine inlet (point 6). User defined pressure drops for the working fluid in the vaporizer, condenser, and regenerator are included in the analysis. The pressure drops are specified as fractions (percentages) of the pressure at the turbine inlet and the condensing pressure. Thus, the pressure at the turbine exit (point 7) is the pressure in the condenser (point 1) plus the specified pressure drop in the condenser and the pressure drop on the vapor side of the regenerator, if a regenerator is present. Likewise, the pressure at the pump exit is calculated from the turbine inlet pressure (point 6) plus the specified pressure drop in the vaporizer.

Calculation of the pressures at the remaining state points required some modeling approximations. As a first approximation, pressure drops in the liquid phase were neglected, and all pressure drops were assumed to occur in those portions of the cycle where the fluid is superheated vapor or boiling or condensing. (Supercritical cycles are discussed below.) This assumption allows the properties of the saturated liquid to be used to calculate enthalpy changes for the compressed liquid after the pump, or if subcooling occurs in the condenser.

As a result of this first assumption, the pressure at the pump-inlet ($p_{1'}$) is equal to the pressure (p_1) of the saturated liquid in the condenser, and the pressures of the compressed liquid at points 2, 3, and 4 are equal. Also, the total pressure drop in the vaporizer ($p_6 - p_4$) is applied in two parts; the first part to boiling region ($p_5 - p_4$) and the second to the superheat region ($p_6 - p_5$). The specification of p_5 requires a model to

apportion the total pressure drop into these two parts. In the code, it was assumed that the ratio of these two pressure drops are equal to the ratio of the heat transfer in these two sections of the vaporizer:

$$r = \frac{p_6 - p_5}{p_5 - p_4} = \frac{Q_{\text{sup}}}{Q_{\text{sat}}} = \frac{h_6 - h_5}{h_5 - h_4} \quad (1)$$

where Q_{sat} and Q_{sup} are the heat transfer rates in the boiling (saturated) region and the superheat region. As described above, p_4 and p_6 are known. In Eq. 1, h_5 is unknown and is approximated in the code using the average of the enthalpies for the saturated vapor evaluated at p_4 and p_6 . Figure A-3 shows a sketch of the state-points used in this averaging process. Point 5a is saturated vapor on the p_4 isobar. Point 5b is saturated vapor at p_6 . The code approximates the enthalpy at point 5 by

$$h_{5'} = \frac{h_{5a} + h_{5b}}{2}, \quad (2)$$

which is used to modify Eq. 1 to

$$r = \frac{(h_{6'} - h_{5'})}{(h_{5'} - h_4)}, \quad (3)$$

which gives;

$$p_5 = \frac{(p_6 + r \cdot p_4)}{(1 + r)}. \quad (4)$$

At this point, the above process could be repeated iteratively; to re-evaluate r from Eq. 1 using the calculated value for p_5 to calculate a better estimate for h_5 . This is not done in the code since the pressure drop calculation for the vaporizer is at best an approximation, and the slight improvement in determining p_5 is not felt to be warranted. Given p_5 , the temperature T_5 and the enthalpy h_5 are calculated by interpolation of the input data for the saturated vapor.

The evaluation of the state point pressures for the low pressure fluid is done similar to the vaporizer, with consideration given to the possible use of a regenerator. The total pressure drop is set by user specified values for the pressure drop in the condenser, and the regenerator (if used);

$$\Delta p = (p_7 - p_1) = \Delta p_c + \Delta p_r . \quad (5)$$

The magnitudes of these pressure drops are specified as fractions of p_1 , which define the pressures p_7 and p_8 (if a regenerator is used). Similar to the vaporizer, this total Δp is apportioned proportional to the heat transferred in the superheat region and the heat transfer by the condensing fluid;

$$r = \frac{(p_7 - p_9)}{(p_9 - p_1)} = \frac{Q_{\text{sup}}}{Q_{\text{sat}}} = \frac{(h_7 - h_9)}{(h_9 - h_1)} . \quad (6)$$

In Eq. 6 h_9 is unknown and is approximated as the average of the enthalpies of the saturated vapor at p_8 and at p_1 , similar to the approximation for h_5 described above. Using this average for h_9 in Eq. 6 yields

$$p_9 = \frac{(p_7 + r p_1)}{(1 + r)} . \quad (7)$$

As for the vaporizer, this process could be repeated iteratively to refine the value of h_9 , using the calculated value of p_9 . This is also not done in the code. Given p_9 , then T_9 and h_9 are calculated by interpolation of the input data for the saturated vapor.

Pressure drops in the vaporizer are specified as a fraction of the turbine inlet pressure, which may change for various cases, and in particular for calculating off-design performance. For example, for a turbine inlet pressure of 800 psia, an 80 psi drop through the vaporizer would be calculated if the user specified 0.1 for the vaporizer pressure drop factor. For multiple cases and off-design calculations, this pressure drop factor remains fixed, but the pressure drops are recalculated for each different cycle. Because the pressure in the vaporizer is relatively high, rather significant pressure drops can occur in the system, which can have rather significant effects on the various state-point enthalpies. Thus, it was deemed necessary to calculate these pressure changes for each different cycle.

For supercritical cycles, the pressure drop in the vaporizer is treated differently. Since no distinct boiling and superheat regions can be defined, the total pressure drop for the vaporizer is applied between state points 6 and 3, with $p_3 = p_2$ if a regenerator is used.

2.2 CYCLE STATE POINT ENTHALPY VALUES

The code calculates the properties of the fluid at the various state points using tabulated thermodynamic property data for the working fluid. The input formats for this tabulated data are defined in Section 4. A conventional Rankine cycle analysis is performed, using the conventional definitions for the efficiencies of the turbine and pump (assumed constant). As described above, all the cycle pressures are set by input data and code models for pressure drops. To calculate cycle performance and determine heat exchanger sizes, it is necessary to determine the enthalpies and temperatures of the various points.

At point 1, h_1 and T_1 are determined by interpolation of the input saturated liquid data at p_1 . If the liquid is subcooled in the condenser, T_1 is calculated by subtracting the input value of the subcooling temperature drop. The enthalpy at 1' is determined using a calculated specific heat value. The code evaluates

$$C_p = \frac{(h_{i+1} - h_i)}{(T_{i+1} - T_i)} \quad (8)$$

from the input data for the saturated liquid, where the values T_1 and T_{i+1} encompass or include the saturation temperature at p_1 . Using this specific heat gives

$$h_{1'} = h_1 - C_p (T_1 - T_{1'}) \quad (9)$$

The specific volume at point 1' is then calculated, interpolating the input property data for the saturated liquid, at the temperature $T_{1'}$.

The enthalpy at the pump exit is calculated from

$$h_2 = h_{1'} + \eta_p (h_{2s} - h_{1'}) \quad (10)$$

where η_p is the input pump efficiency, and $(h_{2s} - h_{1'})$ is the isentropic work required to pump the liquid from p_1 to p_2 . This quantity is evaluated as

$$(h_{2s} - h_{1'}) = v_{1'} (p_2 - p_1) \quad (11)$$

where the determination of $v_{1'}$ was described above. The temperature and

enthalpy at p_4 are calculated from interpolation of the saturated liquid data.

The enthalpy and entropy at the turbine inlet are determined by interpolation of the superheated input data at p_6, T_6 . The enthalpy at the turbine exit is given as

$$h_7 = h_6 - \eta_T (h_6 - h_{7s}) \quad (12)$$

where η_T is the turbine efficiency and $(h_6 - h_{7s})$ would be the enthalpy change if the working fluid expanded isentropically to p_7 . The code evaluates h_7 (and T_7) by interpolation of input property data along an isobar at p_7 . This interpolation includes provision for cases where state points 7 and 7s may be in the wet region. Extrapolation for h_7 is also possible, if the turbine exit conditions are outside the range of the input property data.

Regenerator effectiveness for a counter-flow heat exchanger is defined in terms of the limiting case where an effectiveness of unity corresponds to the situation where the outlet temperature of the hot stream equals the inlet temperature of the cold stream. Regenerator effectiveness is defined as the ratio of the actual temperature change of the hot stream divided by the theoretical maximum temperature change:

$$\epsilon_R = \frac{T_7 - T_8}{T_7 - T_2} \quad (13)$$

If T_8 could approach T_2 in the limit, then the effectiveness would approach unity. Assuming a constant specific heat (C_p) for the superheated vapor at the turbine exit, the regenerator effectiveness is also given as

$$\epsilon_R = \frac{C_p (T_7 - T_8)}{C_p (T_7 - T_2)} = \frac{h_7 - h_8}{h_7 - h_2}, \quad (14)$$

where h_2 is the enthalpy of the superheated vapor at p_8 evaluated at the pump outlet temperature T_2 . Given T_2 and T_7 as described above and a user-specified ϵ_R , the temperature T_8 at the exit of the regenerator is evaluated from Eq. 13. The enthalpy h_8 is obtained from Eq. 14 by evaluating h_2 at T_2 by interpolation of property data along the isobar at p_8 . Given h_7 and h_8 , the heat regenerated is calculated which yields the enthalpy at state point 3.

2.3 CYCLE MASS FLOW RATE AND PINCH-POINT

The Rankine cycle described above is defined per unit mass flow of the working fluid. To calculate the system power and size of the components, this unit cycle must be matched to the source gas stream. If the mass flow rate (\dot{m}_g) and the inlet and outlet temperatures (T_{gin} and T_{gout}) of the source stream were known, then the mass flow rate of the working fluid could be determined from the total enthalpy change of the gas stream:

$$\dot{m}_f = \frac{\dot{m}_g C_{pg} (T_{gin} - T_{gout})}{(h_6 - h_3)} \quad (15)$$

where C_{pg} is the assumed constant specific heat of the gas stream (assuming $T_3 < T_{gout}$). Once the mass flow rate of the working fluid is determined, the sizes of the various heat exchangers can be determined.

As a practical matter, it is not always possible to specify the outlet temperature of the gas stream, and the pinch-point temperature difference between the gas stream and the working fluid must be considered. As shown in Fig. A-2, as heat is extracted from the gas stream, the temperature of the gas stream decreases. At some point (shown as point X on Fig. A-2), the temperature difference between the gas stream and the cycle working fluid has its minimum value, which is known as the pinch-point. This temperature difference must be greater than zero, and to achieve reasonable sizes for the heat exchangers in the vaporizer, a large pinch-point temperature difference is often required.

In the code, this pinch-point problem and matching the Rankine cycle to the gas source stream are treated together in an iterative process. For a given gas inlet temperature and flow rate, the outlet temperature of the gas stream is an unknown. The code uses the user specified minimum gas outlet temperature to calculate an initial estimated mass flow rate for the working fluid from Eq. 15. This estimated mass flow rate sets estimated values for the total heat transferred in the various sections of the vaporizer which, in turn, specifies the gas stream temperature at the various points in the vaporizer. Given these estimated gas temperatures and the cycle temperatures, their differences are compared to the user specified minimum pinch-point temperature difference. If all the temperature differences are above the pinch-point, then the calculation is complete and the cycle can be operated

with the gas stream exiting at the minimum gas temperature. If any temperature difference (gas to cycle) is less than the minimum pinch-point temperature difference, then the exiting gas temperature is increased, and this iterative process is repeated, stopping when the exiting gas temperature is at the lowest level consistent with the minimum allowable gas stream outlet temperature.

Referring to Fig. A-2, the iteration process described above can be considered equivalent to a rotation of the gas stream temperature line, with the point T_{gin} fixed. The shape of the line changes for different iterative steps, but it is relatively easy to determine where the pinch point occurs and to estimate the required change in T_{gout} . In checking for the pinch-point, temperature differences are calculated at the obvious cycle points (6, 4, and 3 or 2). In some cycles (e.g., supercritical or for fluids with a large variation in the liquid specific heat), the pinch-point may occur between the gas and the compressed liquid. The code tests for these conditions, using input data for the enthalpy of the saturated liquid, in the region between points 2 and 4.

3. OPTIONAL CALCULATION MODES

The ANL/RBC code can calculate cycle performance in one of three optional modes. Examples for these modes are given in Sections 5.1 through 5.3. In the first (Mode 1), turbine inlet conditions are spaced over a pressure-temperature grid, defined by the user from the maximum and minimum turbine inlet pressures and temperatures, and the pressure and temperature grid intervals. In the second (Mode 2), calculations are done for a number of cycles (≤ 100) where the user specifies the turbine inlet temperature(s) and pressure(s) and other system parameters. In the third (Mode 3), off-design calculations are performed for a user-specified number of off-design conditions, for a single cycle configuration. For Mode 3, the user specifies the design-point cycle conditions for a single case, and a number of off-design conditions where the mass flow and/or inlet temperature of the source gas stream are different from the design point. In this mode, the code calculates the component sizes (heat-exchangers and vaporizer) for the design point and uses these components for the off-design cases. These three modes are

mutually exclusive; only one mode may be specified for a single computer run.

In any of the modes, the user must specify the overall cycle operating conditions and a number of input quantities. Table B-1 lists the cycle parameters/options (with their FORTRAN variable names), which are assumed to be fixed for any single computer run. These include such things as the working fluid, the condensing temperature, the coolant (air or water), the coolant inlet and outlet temperature limits, the specific heat of the waste gas stream, the turbine and pump efficiencies, the pressure drop coefficients, and the heat transfer coefficients used to size the heat exchanger components.

In addition, the user must specify the turbine inlet temperature and pressure, the source gas inlet temperature, and gas mass flow rate for each of the cases to be calculated. The input of these quantities will vary, depending on which calculational mode is selected.

4. WORKING FLUID PROPERTY DATA INPUT

The thermodynamic properties of the working fluid are input to the code using four different input files, described below. These files supply the following data: saturation pressures, temperatures and enthalpies of the saturated liquid and vapor for the pressure range of the Rankine cycles; high pressure superheat values for temperatures, enthalpies and entropies for the range of turbine inlet pressures; low pressure superheat values for temperatures, enthalpies and entropies for the range of turbine exit pressures; and condensing temperatures and other properties for the range of condenser pressures. These files are specified for ranges of pressures, which must encompass the operating pressures for the cycle state points. Properties for the various cycle state points are calculated by interpolation of the input data, with error messages if a cycle point falls outside the range of the input data or the code's interpolation/extrapolation routines. For conditions at the turbine exit, the code will extrapolate the given input data, if necessary.

4.1 SATURATION TEMPERATURES AND ENTHALPIES

Saturation temperature and enthalpy data for the saturated liquid and vapor must be supplied in tabular form for saturation pressures which encompass the lowest temperature for the calculation set (T_1) and the maximum cycle pressure, or the critical pressure if super-critical cycles are included. These values are read from Input File 35 with an unformatted FORTRAN READ statement. This file must contain as a first record (e.g., card) the integer number of saturation states being input, followed by the property data entered as pressure, temperature, liquid enthalpy and vapor enthalpy, (p_s, T_s, h_f, h_g) using one record for each pressure. Table B-2 lists these data for RC-1, used for the example problems described in this report. For this case, the number of saturation points is given as 18, followed by the 18 records giving p_s, T_s, h_f and h_g . Since an unformatted READ is used, the format of the numeric values is not important, except that the four property values must be separated by blanks or commas, with only four values per record. Because the unformatted READ of the first record stops after reading the first integer number, FORTRAN ignores subsequent characters in this record. Thus, the file shown in Table B-2 includes an identifying label on the first record, which is ignored in reading the data. This feature of the unformatted READ provides a convenient way to label and identify the various files, and records in a file.

In the code, these data are used for several purposes. The enthalpy values for liquid and vapor are used to calculate the heat transfer and component sizes in the vaporizer. The liquid enthalpy and saturation temperatures at low pressure are used to calculate a liquid specific heat, which is used to calculate the temperature rise across the pump. If sub-cooling occurs at the condenser, this specific heat is used to calculate the enthalpy of the sub-cooled liquid. The liquid enthalpies and saturation temperatures are used in the pinch-point calculations, to determine if the pinch-point occurs in the vaporizer. Because of these varied uses, the range of this input data should include the lowest pressure to be encountered in a calculation set (p_s at condenser exit at T_1), up to at least the highest pressure (p_6 at the turbine inlet) for sub-critical cycles. For super-critical cycles, this input file should stop at p_c, T_c with $h_f = h_g$ at the critical point.

4.2 CONDENSER PROPERTY VALUES

The code requires an input file containing property data for a range of pressures corresponding to the pressure at the condenser exit. These data are the pressure, temperature, liquid specific volume, liquid enthalpy, vapor enthalpy, liquid entropy and vapor entropy (p_s , T_s , v_f , h_f , h_g , s_f , and s_g). Some of these data may duplicate data supplied for the saturation properties described in Section 4.1, so the user should be careful that these data are consistent. The decision to specify these condenser conditions separately from the saturation data was based on several factors. Entropy values at saturation are not needed for all uses of saturation data, only for condensing if the working fluid becomes wet. Likewise, only a few low pressure condensing states are needed in most computer runs, but saturation enthalpies are required over a wide range of pressures. Thus, it was decided to retain these separate specifications of saturation data, to provide the data needed for the desired range of condenser conditions, without extracting these values from those specified for the larger range of saturation conditions.

These data for condenser properties must be supplied on Input File 65, starting first with a single integer record specifying the number of condenser states provided ($NCND \leq 20$). This record is followed by $NCND$ records, each containing the seven values of saturation properties p_s , T_s , v_f , h_f , h_g , s_f , and s_g , corresponding to each condensing pressure p_s . These data are all read unformatted, with the seven numerical values separated by blanks or commas. Table B-3 shows an example of this file for RC-1, for four saturation pressures ranging from 4.72 psia to 10.15 psia.

4.3 HIGH PRESSURE SUPERHEAT PROPERTIES

The code requires properties for the superheated vapor, representative of turbine inlet conditions. The required data values are the pressure, temperature, enthalpy and entropy of the superheated vapor. These data must be defined on a grid in p - T coordinates, consisting of a fixed number of temperature points (NT), on a fixed number of isobars (NP), as shown in Fig. A-4. For each pressure p_i , there must be data values for enthalpy and entropy for each of the temperatures T_j . The data must be grouped in order of increasing temperatures for each pressure. The values for the various pressures must be provided in order of increasing pressures. The intervals between subsequent

pressures are arbitrary. The temperature intervals are also arbitrary, but must be the same for all pressures. The code interpolates property data for turbine-inlet conditions from this input data. Thus, this data file must encompass the range of expected turbine-inlet conditions, but the actual turbine-inlet state points are not required.

This input file must start with the two interger numbers for the number of pressure lines (NP) and the number of temperatures (NT) as the first record. This must be followed by NT records for the first pressure, with each record containing four values representing p, T, h and s for a single point for the superheated vapor. For each of the pressures, a full set of NT records must be provided. Therefore, this entire file will consist of $NP*NT+1$ records; the first giving the sizes of the data grid, and the remainder giving the data for each point in the p-T grid. These values are all read from Input File 45, unformatted, so subsequent data values on a given record need only be separated by blanks or commas. Table B-4 gives an abbreviated example of this input file for RC-1, for 5 pressures with 31 temperature values for each for a total of 155 data points. (The code contains a fixed dimension limiting $NP*NT \leq 200$).

This input format for the properties of the superheated vapor is redundant, in the sense that the equal pressures and temperatures are repeated on the various records. This was done for ease of identifying and checking the various records. With this format, any given record is clearly identified.

4.4 LOW PRESSURE SUPERHEAT PROPERTIES

The code requires property values of low pressure superheated vapor, which must encompass the turbine exit pressures. These data are read using the same format as the high pressure superheat data described above; on a given p-T grid with an equal number of data points along each isobar, at the same temperature values for each isobar.

The input file starts with a first record containing two integer values specifying the number of isobars (NP) and the number of temperature values (NT). This is followed by $NP*NT$ records specifying the pressure, temperature enthalpy and entropy of the vapor. Table B-5 gives an example of this input file for RC-1, for two pressures at $p = 5$ and 10 psia, with twenty (20)

temperatures for each pressure, ranging from $T = 100$ F to $T = 560$ F.

In using these data, the code generates tables of property values on isobars at the turbine exit pressure and at the regenerator exit pressure. These tables are generated by interpolation/extrapolation of the input data, so that the actual cycle pressures may be different from the input data. Also, the code checks these calculated values against the saturation temperature at a given pressure, and discards any property values for temperatures less than the saturation temperature. Thus, dummy values may be included in this input file for temperatures below saturation if the p-T mesh extends into the wet region, which may be required to provide a full rectangular mesh of p-T values.

5. EXAMPLE PROBLEM RUNS

This section describes the input and (partial) output for Example runs of the ANL/RBC code in each of the three operational modes described in Section 3. The cases run are all cycles patterned after the RC-1 Organic Rankine Bottoming Cycle for an adiabatic diesel engine, designed by Thermo Electron Corp. (TECO), (Ref. 2) and described below. Input for Mode 1 calculations are presented for nine different sets of turbine inlet pressures and temperatures, using the mesh generating capability of the code. Input for Mode 2 calculations were made for these same nine cases with the different turbine inlet conditions, input for each case. An example of Mode 3 calculations is presented for the TECO design-point and eight off-design conditions having different values for the diesel exhaust temperature and mass flow rate, resulting from different load conditions for the diesel engine.

For all these runs, the thermodynamic property data were the same. The formats of the input files for these property data are described in detail in Section 4. As input files, these data files must be assigned to FORTRAN Input Units 35, 45, 55 and 65. The code reads these files consecutively and completely, so they may be combined into one continuous source file if desired. The code reads input data which define the cycle and problem(s) from input Files 15 and 25. For any mode of operation (Mode 1, 2 or 3), the data read from File 15 would be the same and define cycle parameters such as working

fluid, coolant type and temperature, component efficiencies, pressure drop factors, etc. The data read from File 25 define the calculational mode and specific cycle operating conditions such as turbine inlet temperature and pressure and gas temperatures and flow rates for off-design calculations. Thus the data in File 25 may be different for different computer runs.

Figure A-5 (from Ref. 2) shows a schematic diagram of the TECO RC-1 organic Rankine system with the vaporizer heated from the exhaust stream of an adiabatic diesel engine. The design selected by TECO was a super-critical cycle, with a regenerator after the turbine exit. Figure A-6 (from Ref. 2) shows T-s diagram of the design-point cycle. For this cycle, turbine inlet conditions were set at $p = 800$ psia and $T = 750\text{F}$. Pump inlet conditions were set at $p = 7.01$ psia and $T = 135\text{F}$. The pressure drops in the system were set as follows: 70 psi for the vaporizer, 10 psi for the liquid side of the regenerator, 0.5 psi for the condenser and 0.5 psi for the vapor side of the regenerator.

As discussed in Section 2.1, the pressure drop model in ANL/RBC does not include pressure drops for the liquid portions of the cycle. For the ANL/RBC model of this cycle, these liquid pressure drops were included in the vapor segments, resulting in cycle state points which differ slightly from those used by TECO, and result in some differences in the calculated performance. For the low-pressure portion of the cycle, condensation at 7.01 psia corresponds to a saturation temperature of 140F. Thus, the pressure at the end of the condensing section (p_1) of the condenser was set at 7.01 psia and sub-cooling of 5F was specified to obtain the pump inlet conditions specified by TECO. As discussed in Section 2.1, the pressure drops in the condenser and the vapor side of the regenerator are specified in terms of percentage factors of the pump inlet pressure. Thus, to get $\Delta p = 0.5$ psi with $p_1 = 7.01$ psia, pressure drop factors of 0.07133 were used for the condenser and regenerator, giving $p_8 = 7.51$ psia and $p_7 = 8.01$ psia. On the high pressure side, TECO specified a total pressure drop of 80 psi, with 10 psi in the regenerator and 70 psi in the vaporizer. For the ANL/RBC model the pump outlet pressure (p_2) was set at 880 psia, using a pressure drop factor of 0.100 for the vaporizer. Because of the assumption of no pressure drop in the liquid, this same value of 880 psia exists at the liquid outlet of the regenerator, and along the liquid portion in the vaporizer. (Because this is a super-critical

cycle, this $p = 880$ psia is assumed to exist through the psuedo phase change at the critical temperature).

TECO specified air coolant for the condenser, with an air inlet temperature of 80F and an outlet temperature of 120F. Also, the exhaust gas stream was specified with a gas inlet temperature of 1240F and a mass flow rate of 2886 lb/hr. These same values were used in the ANL/RBC model. The TECO model specified turbine, pump and mechanical efficiencies of 0.765, 0.500 and 0.926, respectively, and a regenerator effectiveness of 0.600. These efficiency values were used in the ANL/RBC model, but the regenerator effectiveness was changed slightly. Using the TECO value of 0.600 for the regenerator effectiveness resulted in a calculated cycle mass flow rate which differed slightly from the TECO value of 4350 lb/hr. This difference was attributed to the small differences in the calculated enthalpy values at the turbine exit and the enthalpy values of the liquid after the pump. Changing the value of the effectiveness to 0.60535 resulted in the same mass flow rate for the working fluid as calculated by TECO, and this was used as a basis of comparison.

5.1 MODE 1 EXAMPLE

The input data for Input File 15 define the overall system parameters and fixed cycle conditions. These data are read in free format and the input was designed for interactive user responses to computer prompts at the terminal. Table B-6 lists a terminal display of this input file during execution, listing the prompts/questions from the code (typed in upper-case) and the user input responses. The prompts are self-explanatory and most of the numerical input data values have been described above. The input includes four indicator values, used to select whether cost functions are to be included in the calculations, whether a regenerator is to be included, and whether the coolant is air or water. The input includes the name of the fluid, which is used only for print-out in a page heading and should be 16 or less characters. ~~The input includes five values for heat transfer coefficients;~~ three for the three sections of the vaporizer and one each for the condenser and regenerator. All five of these must be provided, even if no regenerator is used. The numerical values in this input are all read in free format and decimal points are not required. Where more than one value is requested, these must be separated by blanks or commas.

In the data shown in Table B-6, the heat transfer coefficients were all specified as unity. TECO's calculated results presented the various heat exchanger sizes in terms of UA values, not the actual A values. ANL/RBC calculates heat exchanger areas from calculated UA values using the input values of U. Using unity for the coefficients U results in fictitious area values which are numerically equal to the UA values for the heat exchangers. This was done for this example problem so that the heat exchanger results calculated from ANL/RBC could be directly compared to the UA values reported by TECO. This comparison is discussed below in this Section.

Table B-7 presents this same input data, separated from the computer prompts and with identifying labels added for each line, for a case where these input data were not supplied interactively from a keyboard terminal. If the input for File 15 is not provided from the terminal keyboard, then a file containing the data in Table B-7 would be required as an input file, and could be set-up and retained for multiple computer runs. Because the code uses unformatted reads, the information in the identifying labels is ignored. Thus, if a permanent file copy of Table B-7 (with the identifying labels) is created, it can be easily edited and used for different problem cases, and serves as very convenient documentation of the input required for File 15.

Table B-8 presents a listing of the computer prompts and input for File 25. This input includes the calculation mode, (Mode 1), which specifies that turbine inlet conditions are to be generated over a specified p-T mesh. The next input specifies the ranges and intervals for this mesh; 750F to 850F in steps of 50°F, and 700 psia to 900 psia in steps of 100 psi (9 cases over this mesh). The code automatically generates these turbine inlet conditions and proceeds with the cycle calculations (9 cases for this example). As with the input for File 15, this File 25 input is read using a free format and can be obtained from a pre-defined data file rather than from the terminal. Table B-9 shows a listing of this input file, without the input prompts, which could be used if File 25 was pre-prepared and not supplied from the terminal. As discussed above for File 15, the identifying labels after the input data will be ignored and this pre-prepared table can be used as documentation of File 25 for Mode 1, and edited as required.

Tables B-10 and B-11 present samples of the code output for two of these cases; $T_6 = 750F$, $p_6 = 800$ psia (which is the TECO design point) and $T_6 =$

850F, $p_6 = 900$ psia. The output summaries includes the cycle power and mass flow, heat transfer rates, component sizes, and temperatures at various points in the system. The output is labeled with explanatory descriptions and ends with state point property table listing the temperature, pressure and enthalpy at each of the ten state points in the cycle, defined in Section 2.

For purposes of comparison and verification, Table B-12 lists selected values of the results for the design-point, along with the corresponding values reported by TECO. As can be seen, the overall agreement is quite good. As noted earlier, the regenerator effectiveness was adjusted slightly to make the mass flow rates of the ANL calculations agree with the TECO value. The calculated enthalpy at the turbine exit differs slightly, which is attributed to probable differences in the interpolation methods used to calculate the working fluid properties from the input data. The calculated power and the heat exchanger UA values appear to be in acceptable agreement.

The actual areas required for the heat exchangers can be determined from the calculated UA values, if the heat transfer coefficients are known. For the vaporizer, for example, the heat transfer is limited by the gas side heat transfer coefficient. Reference 1 presents typical values of U for these conditions in the range of 5-6 Btu/hr/ft²/F. Using this value and the $(UA)_B$ value of 3.69×10^3 Btu/hr from Table B-12, results in a vaporizer area of 671 ft². TECO did not report their value of vaporizer area, so no direct comparison is possible.

5.2 MODE 2 EXAMPLE

As an example of Mode 2 calculations, input for the (9) nine cases discussed above is presented, where the values for the turbine inlet temperature and pressure for each case are supplied on File 25. The format for the input data for the fluid properties (Files 35, 45, 55 and 65) is unchanged. Also, the input data for File 15 are not changed. Thus, the only difference is File 25.

For this example the File 25 data must specify Mode 2, the number of cases to be run (9 in this example) and the turbine inlet temperature and pressure for each case. Table B-13 shows a listing of the terminal display including prompts and user responses for this case. As for the other files, these values are read in free format, decimal points are not required, data

must be separated by blanks or commas and this file may be prepared in advance and supplied from a source other than the terminal. Table B-14 shows a listing of this input file (without the computer prompts) and with descriptive identifying labels after the input values (which would be ignored in the unformatted READ), for a case where these input data were pre-prepared and not supplied from a terminal. As for the other modes, these identifying labels will be ignored by the unformatted READ, and documents File 25, Mode 2, and can be edited to produce an input file for other runs.

As a further example of this Mode 2 operation, this p-T mesh was extended to calculate more cycle conditions. The data for File 25 were expanded to run cycle calculations for turbine inlet temperatures ranging from 600F to 1000F in increments of 50F, and for turbine inlet pressures ranging from 500 psia to 900 psia in increments of 100 psia. For these calculations, all the parameters for the TECO system were fixed and only the turbine inlet conditions were varied. Figures A-7 through A-10 show some of the calculated results, giving the cycle power, efficiency, exhaust stack exit temperature and the required UA for the vaporizer. (The curves shown are not smoothed; rather they are straight-line segments between points at 50F increments.) The curves for 900 psia and 800 psia have discontinuities in slope for turbine temperatures in the range 650-750F. These occur because the minimum gas temperature (300F) was reached for the low turbine inlet temperatures, as shown in Fig. A-9. For the higher turbine inlet temperatures, the pinch-point $\Delta T_p = 30F$ was reached, usually at the regenerator exit, which limits the amount of heat which can be extracted from the gas stream. This is illustrated by the relatively high stack temperatures shown in Fig. A-9, for the higher turbine inlet temperatures.

The power curves, shown in Fig. A-7, have positive slope for the high turbine temperatures, primarily because the Rankine cycle efficiency increases with increasing temperature. However, as the turbine temperature is decreased the exhaust stack temperature is lowered, resulting in more energy being extracted from the gas stream. This increased energy extraction more than compensates for the reduced cycle efficiency, resulting in the flattening of the power curves in the range 800-850F, and the negative slope for lower temperatures. Thus for example the net power for turbine inlet temperatures of 700F is essentially the same as that at 1000F, and the TECO design point of

750F is probably nearly optimal. Figure A-10 shows the required UA for the vaporizer. Below 700F, the slope is affected by the minimum gas temperature of 300F. Above 700F, these curves show that the vaporizer UA is essentially the same for all the turbine inlet pressures. This is a consequence of the fact that the enthalpy of the RC-1 working fluid is a rather weak function of the pressure. Thus, for a fixed turbine inlet temperature, changing the pressure has only a slight effect on the enthalpy changes of the working fluid in the vaporizer, resulting in only minor changes in the log-mean temperature differences.

5.3 MODE 3 EXAMPLE

As an example of Mode 3, input is presented for this cycle, operating at 8 off-design points. In Mode 3, calculations are performed for a single Rankine cycle system; first for the design-point, and then for a user specified number of off-design conditions. As in the other modes, the input formats for File 15 and the property data (Files 34, 45, 55 and 65) are unchanged.

The data for File 25 includes the mode number, the number of off-design cases, the values for the turbine inlet temperature and pressure for the design-point, and then the off-design values for source gas stream inlet temperature and mass-flow rate for each off-design point. Table B-15 shows a listing of a terminal display of the prompts and responses for this input, for a case of 8 off-design points, which are representative of various part-load conditions for the diesel engine. As for the other cases, this File 25 data is read in free format, and this file may be supplied from a prepared datafile. Table B-16 shows a listing of this input file pre-prepared for input not from the terminal, with identifying labels added for documentation.

6. USER DEFINED COST FUNCTIONS

This section describes a module of subroutines developed to allow the user to define cost functions for use with the ANL/RBC code. Section 6.1 contains a description of the definitions and conventions used in generating cost functions and the structured ways in which functions may be combined.

Section 6.2 contains a description of the input/output and use of this module, either as a stand-alone program to generate an input file for the ANL/RBC code, or optionally as part of the code. Section 6.3 presents four examples of the usage of this module to generate actual cost functions, along with input/output listings of actual computer runs for the example problems.

6.1 COST FUNCTION DEFINITIONS AND CONVENTIONS

This section describes the function definitions and conventions used to define cost functions for use with the ANL/RBC code. The original ANL/RBC code had fixed cost correlations for specific components of large fixed-station power plants. In planning to modify this code for other applications, several factors became apparent. First, not all potential systems use the same components. For example, some systems utilize air-cooled condensers while others utilize water-cooled condensers. Likewise, components may be packaged differently, which could affect how costs are determined. An example of this is the Modular Condenser/Regenerator used by TECO for their RC-1 Rankine Bottoming Cycle for an Adiabatic Diesel Engine. Other factors may be how much detail is known (or required) about component costs and how sub-components are to be grouped together. To accommodate these variations, a cost-function module was developed which is quite general and allows considerable flexibility in defining cost variables and their functional relations, where the user is able to define/select cost variables and the functional relationships between the dependent and independent variables. This procedure starts with a initial list of independent variables, defined by NAME and used by VALUE in the ANL/RBC code. This initial independent variable list is given in Table B-17, listing the FORTRAN variable names used in the code and their physical definitions. As discussed below, this initial list of independent variables is expanded to include the NAME and subsequent VALUE of each new dependent variable defined by the user. This allows the addition of new cost variables and the construction of very general cost functions.

A set of Functional Forms was established relating a single dependent variable to a single independent variable. These Functional Forms are:

1: Linear $y = a + bx$

2: Quadratic $y = a + bx + cx^2$

- | | |
|---------------------|----------------------------|
| 3: Cubic | $y = a + bx + cx^2 + dx^3$ |
| 4: Mixed/Hyperbolic | $y = a + bx + \frac{c}{x}$ |
| 5: Power | $y = cx^n$ |

These five forms are identified in the code as Type 1-5, respectively. The user must select the Functional Form Type to be used for a given function, select the NAME of the independent variable (from the list of variable names), and define a NAME for the dependent variable (up to 24 characters, with all variables treated as real FORTRAN variables, not integer, regardless of name).

Numerical data for the constants for a given equation can be supplied in two optional ways. For Option 1, the user must provide actual numerical values for the constants in the selected equation. Thus, for Option 1, if Type 2 is specified, the user must supply values for the constants a, b, and c in the quadratic form. Zero values for any constants are acceptable.

The code also includes the provision (Option 2) to calculate the required constants by least-squares curve fitting to input data points. For this option the user must provide the number of data points (≤ 10) and the values of the data points, as x,y pairs. The minimum number of data pairs required depends on the functional form selected and is equal to the number of constants in the equation. Thus, a linear form or a power form requires a minimum of two points, and the quadratic and hyperbolic require a minimum of three points. Using these input data points, the code generates the constants required for the specified Functional Form.

In providing data for several equations, each equation is processed separately so that different Types and Modes may be used for different equations. The code has been structured so that when the NAME of a dependent variable is defined for an equation, this new variable NAME is added to the list of available NAMES of independent variables, and may be used as an independent variable in subsequent definitions. This allows the user to link definitions together and to build-up more complicated functions if needed. For example, consider the case where the user has several cost functions that depend on the square of the power. An equation could be defined (using the arbitrary name PSQRD) for the dependent variable, with POWER (from Table X-1) as the name of the independent variable. Specifying Type 2 with the constants

a=0, b=0, and c=1 would generate the variable named PSQRD which would have the numerical value of the square of the power. This new variable PSQRD could then be used in subsequent definitions as an independent variable, and would pass the value of the square of the power to the resulting calculations.

A variation of the PSQRD example discussed above demonstrates the ability to supply the NAMES and VALUES of new variables for constants which had not been anticipated/included in the programmed list of variables (Table B-17). In Section 6.3 an example for a rather complicated cost-function for the cost of organic working fluids will be described. This is a function of a number of calculated variables and two which are not: the molecular weight of the fluid and the fluid cost per gallon. Each of these variable NAMES (FMW and CGAL as used in Sec. 6.3) can be introduced as newly defined dependent variables, by specifying Type 1 for an arbitrary independent variable (e.g., POWER), and specifying "b" = 0 for the coefficient and setting "a" equal to the numerical value being introduced. Doing this for both the molecular weight and the fluid cost per gallon would generate newly defined independent variables names FMW and CGAL, with the numerical values of the constants "a" used to generate each function.

This concept of linking variables and equations was extended to allow two independent variables to be combined either as a linear combination or a scaled product. Two independent variables x_i and x_j can be combined to give y_n defined either as

$$y_n = \alpha_1 x_i + \alpha_2 x_j \quad (\text{Linear Combination Type 6})$$

or

$$y_n = \beta x_i \cdot x_j \quad (\text{Scaled Product Type 7})$$

where the constants α_1 , α_2 , or β are user supplied. These Functional Forms are defined as Type 6 and Type 7 in the code. These operations allow the user to combine variables in a wide variety of ways. The additive form allows the user to define functions of several independent variables. The multiplication form allows products of different independent variables (and division if Type 4 is specified in defining x_i or x_j). These combinations may be nested, or

repeated, so that very general and complicated functional forms may be generated.

While the ability to link various functional forms together allows a great variety of functional forms to be generated, it also provides a mechanism to handle special situations for new or unusual components or data which could not be anticipated or generally programmed into the ANL/RBC. For example, Ref. 1 presents cost functions for pumps defined by two linear functions of flow rate (Q) for two different fixed values of pump-head (H). For the cycle the cost is to be derived by linear interpolation between these cost functions, using the actual pump-head and flow rates calculated from the Rankine cycle analysis. This interpolation over pump-head can be defined and treated as follows:

Assume the two given cost functions are:

$$C_1 = a_1 + b_1 Q \quad \text{for a given value of } H_1$$

$$C_2 = a_2 + b_2 Q \quad \text{for a given value of } H_2$$

then the interpolated cost for $H_1 < H < H_2$ is

$$C = C_1 + (C_2 - C_1) \cdot \frac{(H - H_1)}{(H_2 - H_1)}$$

Assuming that the Functions C_1 and C_2 have been defined as discussed previously (e.g., Type 1, MDOTF as the independent variable using the known values for the numerical constants a_1 , b_1 , a_2 , b_2), then the above interpolation can be constructed by defining 3 intermediate functions:

$$F_1 = \text{HEAD} - H_1 \quad (\text{Type 1, } x = \text{HEAD, } a = -H_1, b=1)$$

$$F_2 = C_2 - C_1 \quad (\text{Type 6, } \alpha_1 = 1, \alpha_2 = -1)$$

$$F_3 = \beta F_1 \cdot F_2 \quad (\text{Type 7, } \beta = 1/(H_2 - H_1))$$

which can be combined to give the interpolated cost

$$C = C_1 + F_3$$

(Type 6, $\alpha_1 = 1$, $\alpha_2 = 1$)

Thus, without actually having this interpolation routine in the FORTRAN code, it could be included in the cost evaluation through this process of linking several variables together. Many other combinations can be made, so it should be possible to build up cost functions for many situations not included in the ANL/RBC coding (see Example 4, Sec. 6.3).

In the above discussion, intermediate functions were introduced which are not actual costs, and their values should not be included in a total cost evaluation. This is handled in the code by a computer prompt question during input, "Is this variable to be included in the total cost? (Y/N)." A response of YES (or Y) results in inclusion of this equation as an actual cost. A response of NO (or N) flags the variable as an intermediate variable, and its value and name will not be included in the final cost summary.

6.2 COST FUNCTION INPUT/OUTPUT

This section describes usage and the input/output options of the Cost Function Module. Actual sample input/output listings for four example cases are included in Appendix B. This code module was designed around interactive use as a stand-alone program, with input from a terminal keyboard and output to a terminal display, with an output file written on a peripheral device for later use in the ANL/RBC code. Usage will be described first as an interactive terminal session, for stand-alone operation, with the user responding to prompts and questions as display at the terminal. Optional input/output methods are described later.

To use this module, the user must have a set of functions (equations), and the necessary numerical data (described in Section 6.2). These functions (equations) should be numbered in sequence starting with 1, with the total number limited to 30. As described in Section 6.2, each of these equations must have a dependent variable name, at least one independent variable name, a function form Type number (1-7), and numerical data to define the function using either Option 1 or 2. The computer will display a series of prompts/questions, to which the user responds.

This sequence starts with a display INPUT DATA FOR EQUATION #1, followed by **** TYPE DEPENDENT VARIABLE ****. The user should type the name assigned

for the dependent variable for Equation 1. (Dependent variable names can be any character string including blanks and punctuation, up to 12 characters long. These names may be descriptive and will be included in the final Cost Summary produced by the code.) The computer will then prompt with **** TYPE EQUATION FORM (1-7) ****, and the user should input the Type value. The computer will then prompt with the message **** TYPE DATA INPUT OPTION: 1 = INPUT CONSTANTS, 2 = CURVE-FIT ****, and the user should type the selected option. The computer will then prompt with **** TYPE INDEPENDENT VARIABLE ****. The user should respond with the name of the independent variable, which must be typed exactly. If Option 1 is selected, the computer will prompt with the functional form for the specified Type and request numerical values for the individual constants. For example, if a quadratic form ($y = a + bx + cx^2$) is specified the computer would display:

FUNCTIONAL FORM FOR "dependent variable name"

$$Y = A + B*X + C*X**2.$$

**** TYPE COEFFICIENT A **** ,

and the user should type the numerical value of the constant term a. this process is repeated for all the constants required for the specified functional form. (The input of these constants is also free-format using any FORTRAN designation for a real constant. A decimal point is not required.)

If the equation had been specified for input as Option 2, then the user will be prompted to provide the input data values for curve-fitting. The computer will prompt

**** INPUT DATA FOR CURVE-FIT ****

**** TYPE # OF DATA POINTS **** ,

the terminal prompt will appear and the user should type the number of data points available for this function. This must be an integer value ≤ 10 , and is input in free-format. After this the computer will prompt

**** TYPE X,Y PAIRS FOR N DATA POINTS **** ,

followed by a ? for each x,y pair. The user should type the x and y values

for each data point. (These constants are input in free-format, separated by blanks or a comma, and the decimal point is not required.)

At the end of the above steps for a given equation, the computer will prompt

**** IS THIS VARIABLE TO BE INCLUDED IN TOTAL COST? Y/N **** ,

and the user should respond YES (or Y) or NO (or N) starting in the first typing position. As described in Section 6.2, some equations may be defined as intermediate variables and their names and values are not part of the final Cost Summary. These variables should be excluded by answering NO (or N). After responding to this last prompt, the code increments the equation number and repeats the above sequence for the next equation. This input loop is terminated by typing DONE as the name of the dependent variable. As described in Section 6.2, functions may be defined as combinations of two independent variables (Types 6 and 7). In such cases, the prompts are somewhat different, but self-explanatory. Independent variable names must be typed exactly, and numerical constants are in free-format.

Upon completion of this terminal input process, an output file is written (on logical unit 36). This is an exact copy of the terminal input and is generated for an alternate input file to the RBC code, to eliminate the need to type all the input information each time if multiple computer runs are to be made. An option has been provided in the input module to read the input from a source other than the terminal keyboard. When the input module is executed, it first prompts the user for the input source with the question **** IS THE INPUT FROM THE KEYBOARD? (Y/N) ****. If the user responds by typing YES (or Y), then input from the terminal keyboard is to be provided, as described above. If the response is NO (or N), input is to come from another device (defined as FORTRAN unit 75 in the code). Thus, the output file generated on unit 36 during one execution may be used as an input file on unit 75 for subsequent runs, eliminating the need to type all the input information for each computer run. Also, this file may be modified independently, for example to change variable names or numerical constants.

The description above applies to execution of the input module as a stand-alone program which generates a data file (on unit 36) for input to the

ANL/RBC code. Actually, this input module has been incorporated in the RBC code, with variables and data in shared COMMON blocks, and after input of the cost function data the code can proceed with a Rankine cycle analysis. To allow for usage without proceeding, an option has been provided to stop after the above input process has been completed. The computer will prompt with the question **** DO YOU WANT TO CONTINUE FOR RBC ANALYSIS? (Y/N) ****. If the user responds with YES (or Y), the computer will proceed with the RBC analysis. If the response is NO (or N) the computer will stop. It should be noted that this last response is not included in the file generated on Unit 36. In testing the response to this prompt, the computer will accept an end-of-file as equivalent to a yes. Thus, if the input is being read (on Unit 75) from a previously prepared file, the computer will proceed into the RBC analysis unless a NO (or N) is added to the end of this file.

6.3 EXAMPLE COST FUNCTION INPUTS

This section describes, by four examples, the use of this code module to generate cost functions for the ANL/RBC code. These examples, taken from Ref. 1 are for costs of components for large (> 500 kW) fixed station systems, and the numerical cost values are not appropriate for transportation sized systems (< 50 kW). However, these functional forms are available and documented and can be used to illustrate the usage of this code capability. For the smaller systems, different numerical values would be appropriate, but the input process to the code would be the same.

The first example is a shell and tube regenerator with the cost (\$) given as a function of the regenerator heat transfer area (A_R in ft^2) by

$$C_R = 43.16 (A_R)^{.85} .$$

For this example, the Functional Form is the exponential form, (Type 5), and it was assumed that the numerical values of the coefficient and exponent are to be input, using Option 1. The dependent variable is the regenerator cost, which for this illustration was named REGENERATOR. The independent variable is the regenerator area which is one of the predefined variables (AREGEN) in Table B-17.

During input the user would respond to a series of prompts with 5 for the

Functional Form, 1 for the data input option, REGENERATOR for the dependent variable name, AREGEN for the independent variable name, 43.16 for the coefficient and .85 for the exponent. This series of prompts and responses is illustrated in Table B-18, which is a printout of this part of the prompting and input from an actual run of the ANL/RBC code.

As a second example, this same function was input using Option 2, with numerical data points, rather than using the known constants as illustrated above. Assume the user has the following table of cost data, with the assumption that $C_R = K(A_R)^n$.

$x = A_R$	$y = C_R$
1000.	15,313.75
1500.	21,615.19
2000.	27,603.04

(These values were generated from the original cost function, and for this functional form only two data points are required. The use of seven significant figures is only to illustrate that the curve-fitting procedure can reproduce the original constants.)

In the input for this illustration, the dependent variable was named REG2 and the user response was 5 for the Functional Form, 2 for the input option, 3 for the number of data points in this example, and then the three x,y pairs of data values, from the table above. Table B-19 is a printout of the execution for this mode, which includes the printing of the coefficients A(2) and A(3) calculated from a least squares fit of the data. For the power form A(2) is the log (10) of the coefficient and A(3) is the exponent. Since the three data points fit the function exactly, the calculated constants agree with those in the original functional form.

A third example, Ref. 1 cites the cost of axial flow turbines (> 500 kW) as

$$C_t = 31167 + 23.58 P - 3.66 \times 10^{-3} P^2$$

where P is the power. Assume the user specifies a quadratic form $y = a + bx + cx^2$, has three data points,

x = P	y = C
500	42,042
1000	51,087
1500	58,302

(which fit the original equation to the nearest \$1). For this component, the independent variable was POWER, which is one of the predefined variables in Table B-17. The dependent variable was the turbine cost, which was named TURBINE for this example. This case was input with Functional Form 3, Option 2, the number of data points as 3 and the three x,y pairs from the table above. Table B-20 lists a printout for this case, where the coefficients A(2), A(3), and A(4) differ slightly from those in the original equation because of slight round-off in the arithmetic.

The fourth example is more complicated, chosen to illustrate how a very general cost function can be generated as a function of several variables, using the capabilities incorporated in the code module EQNS and intermediate variables defined by the user. Reference 1 presents a development of a function for calculating the cost of the working fluid, as a product of the unit cost (\$/gal) and the working fluid inventory (gal). As described in Ref. 1, the fluid volume is a function of the size of the economizer section of the boiler, the size of the regenerator, the flow rate of the working fluid and the fluid molecular weight, given as

$$V_F = 0.02 A_{sub} + 0.08 A_{reg} + 1.2 Q + 414 Q/M$$

(for the geometries considered in Ref. 1), where V_F is the volume of working fluid, A_{sub} is the surface area of the economizer section of the boiler, A_{reg} is the surface area of the regenerator, Q is the volume flow rate of the working fluid and M is the molecular weight. The fluid cost is then given as

$$C_F = C_g \cdot V_F$$

where C_g is the unit cost of the fluid. This cost function consists of a linear combination of three variables, as well as a term with the ratio of two variables, all multiplied by a final variable.

A cost function for the fluid was built-up by defining 4 intermediate functions and combining them, using the addition and multiplication capabilities of the code module EQNS. The above expression for fluid cost can be generated by the following steps:

- (1) $f_1 = 0.02 A_{\text{sub}} + 0.08 A_{\text{reg}}$: Linear Combination (Type 6)
- (2) $f_2 = 1.2 + 414/M$: Hyperbolic Function (Type 4)
- (3) $f_3 = f_2 \cdot Q$: Product Combination (Type 7)
- (4) $f_4 = f_1 + f_3$: Linear Combination (Type 6)
- (5) $C_F = C_g \cdot f_4$: Product Combination (Type 7)

The independent variables in Steps 1 and 3 are the predefined variables from Table B-17 (ASUB, AREGEN, and MDOTF). The independent variables in Steps 2 and 5 (M and Cg) are not in Table B-17, and it is assumed that these have been pre-defined as the variables FMW and CGAL as described previously in Section 6.2. For simplicity, the dependent variable names for the above functions were labeled F1,....F4 and FLUID, the last being the final fluid cost (Step 5). Each of these intermediate functions (Steps 1 through 4) was defined separately, specifying the appropriate Functional Form, and supplying the numerical coefficients as required when prompted. At Step 3, when the Product Operation is specified (Type 7) the computer will prompt for the names of the variable factors. The responses for Step 3 should be MDOTF and F2 (either order). Similarly at Step 4, when the Addition Operation is specified (Type 6) the computer will ask for the variable terms, and the responses should be F1 and F3. Completion of these five steps will produce the desired cost function, for this rather complicated form. Table B-21 presents a printout of this entire process, for this example. It should be noted that only the last step (5) produces an actual dollar cost. Thus, for Steps 1-4, the "cost" should not be included in the Total Cost, which is accomplished by responding NO to the question "Should This Variable Be Included in the Total Cost?". For Step 5, the response is YES.

In building-up a function in this process, the independent variable can be any variable from the predefined list or any variable that has been defined by a previous functional definition. Thus, in the above example, Steps 1 and 2 can be done in any order, but Step 3 must come after the definition of F2. Likewise, Step 4 must come after the definitions of F1 and F3. Also, once an intermediate function has been defined for a given component, it remains in the list of variables and can be used for subsequent components if desired.

REFERENCES

1. T. J. Marciniak, J. L. Krazinski, J. C. Bratis, H. M. Bushby, and E. H. Buyco, "Comparison of Rankine-Cycle Power Systems: Effects of Seven Working Fluids," ANL/CNSV-TM-87 (June 1981).
2. L. DiNanno, F. DiBella, and M. Koplow (Thermo Electron Corporation), "An RC-1 Organic Rankine Bottoming Cycle for an Adiabatic Diesel Engine," DOE/NASA/0302-1, NASA CR-168256, TE4322-251-83 (Dec. 1983).

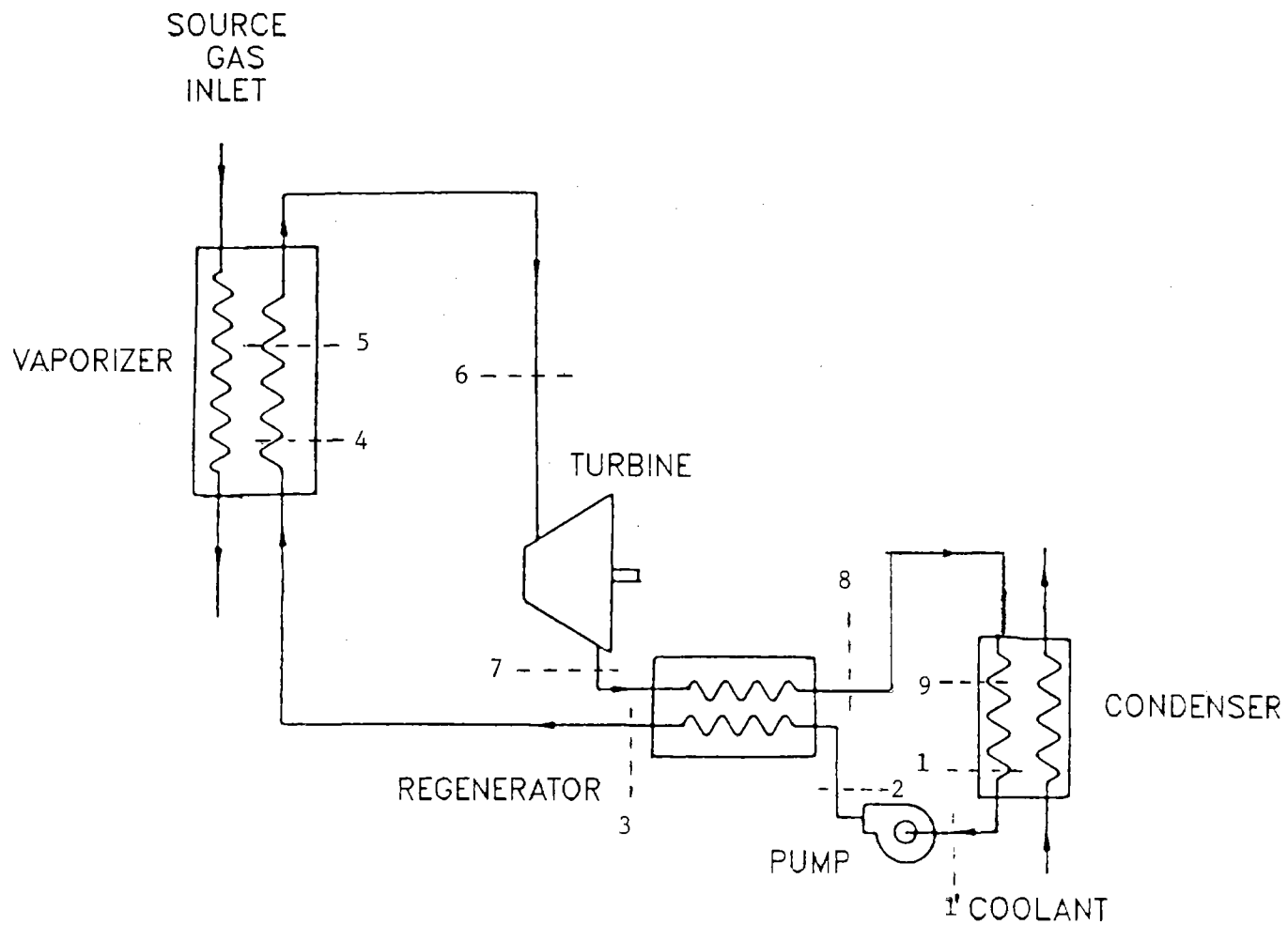


Fig. A-1. Schematic Diagram of Rankine Bottoming Cycle Model for ANL/RBC
(Numerals refer to state-points on Fig. A-2.)

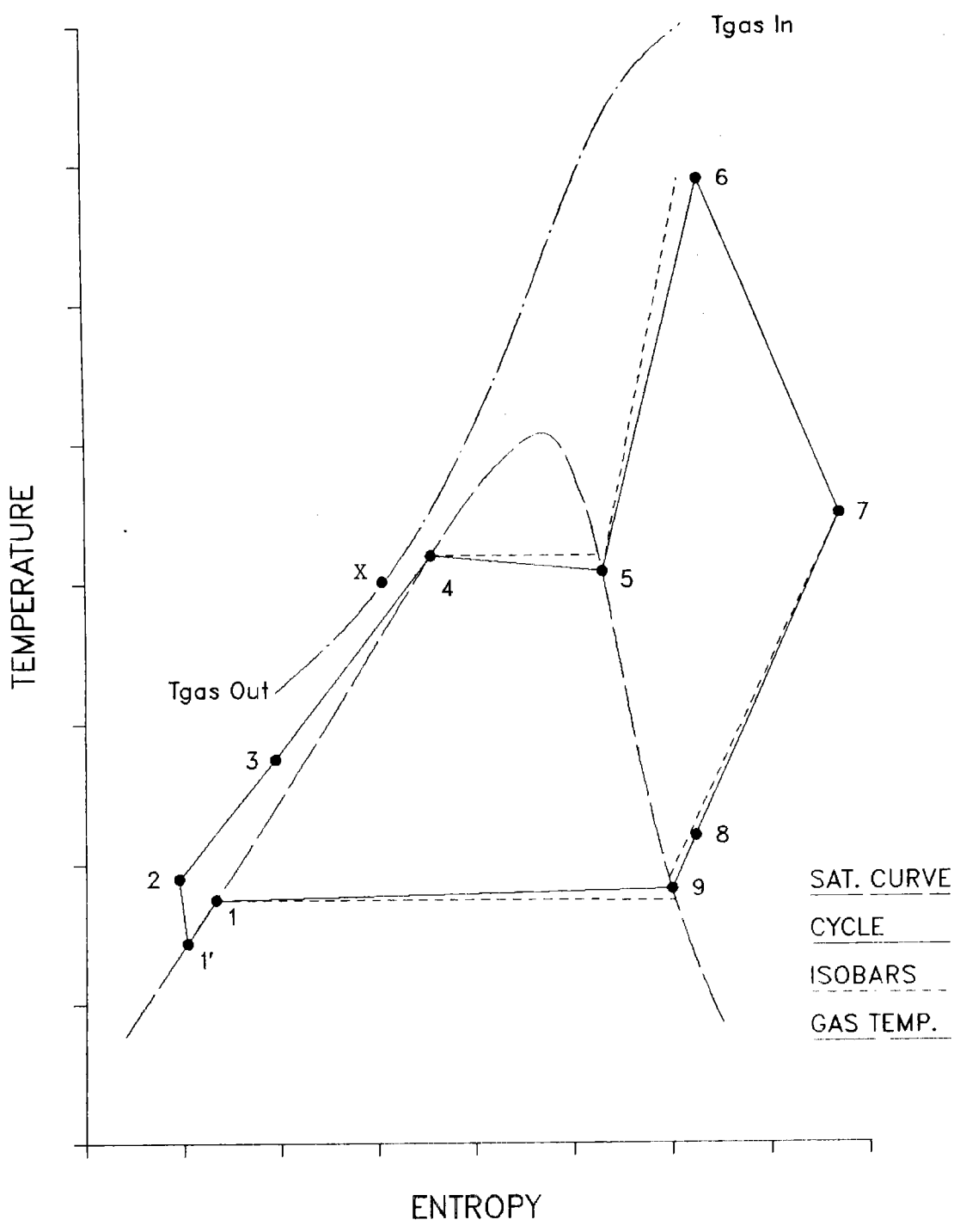


Fig. A-2. Temperature-entropy Diagram of Rankine Bottoming Cycle

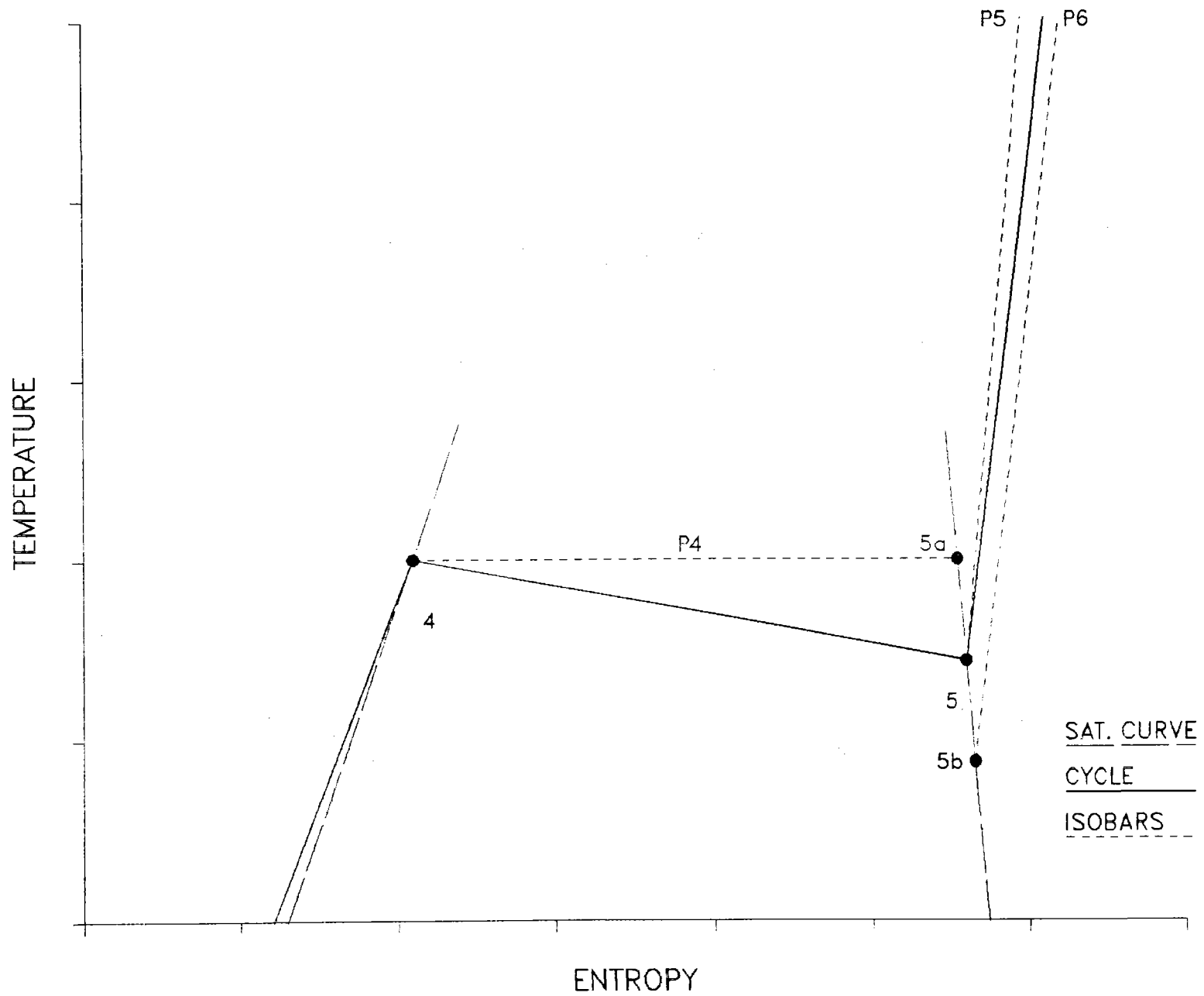


Fig. A-3. Expanded T-s Diagram Illustrating Approximation of Saturation Pressure in Heat Exchangers

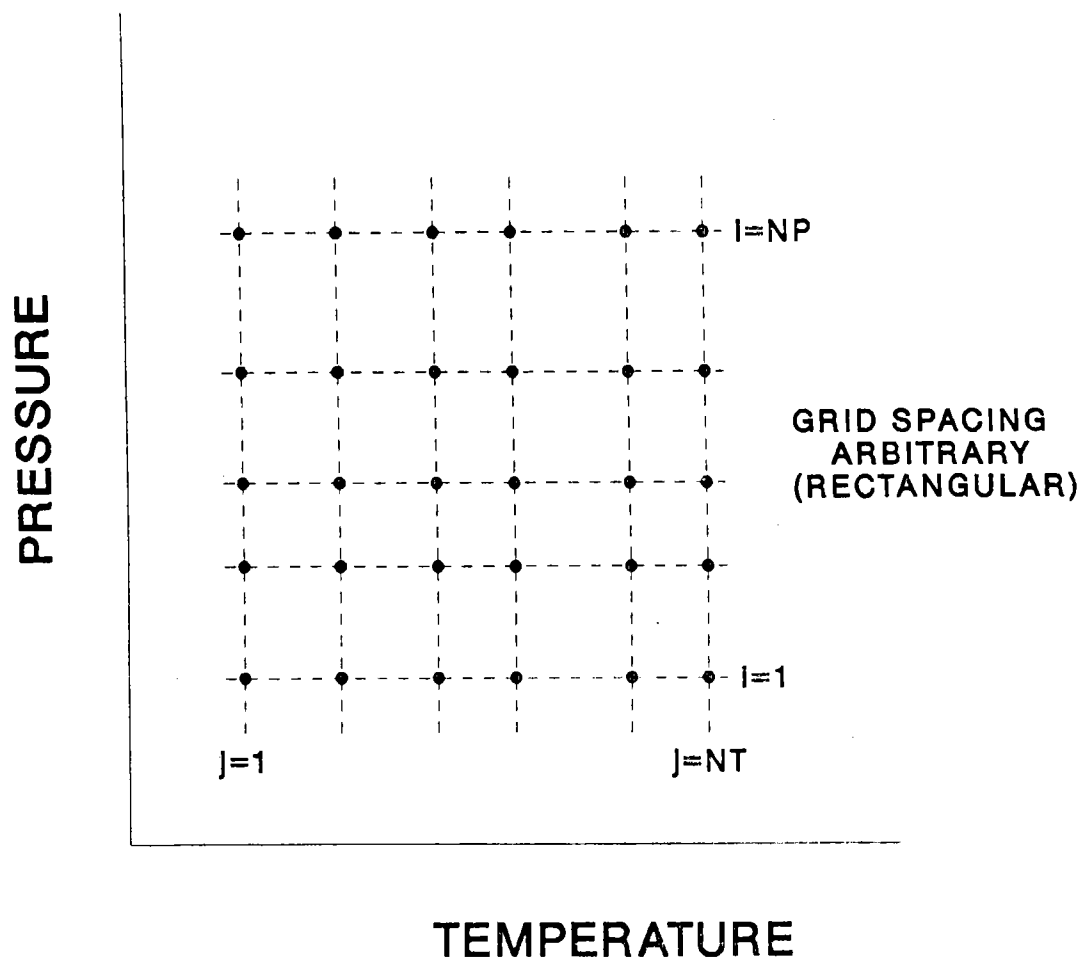


Fig. A-4. Pressure-temperature Grid for Definition of Properties of Superheated Vapor

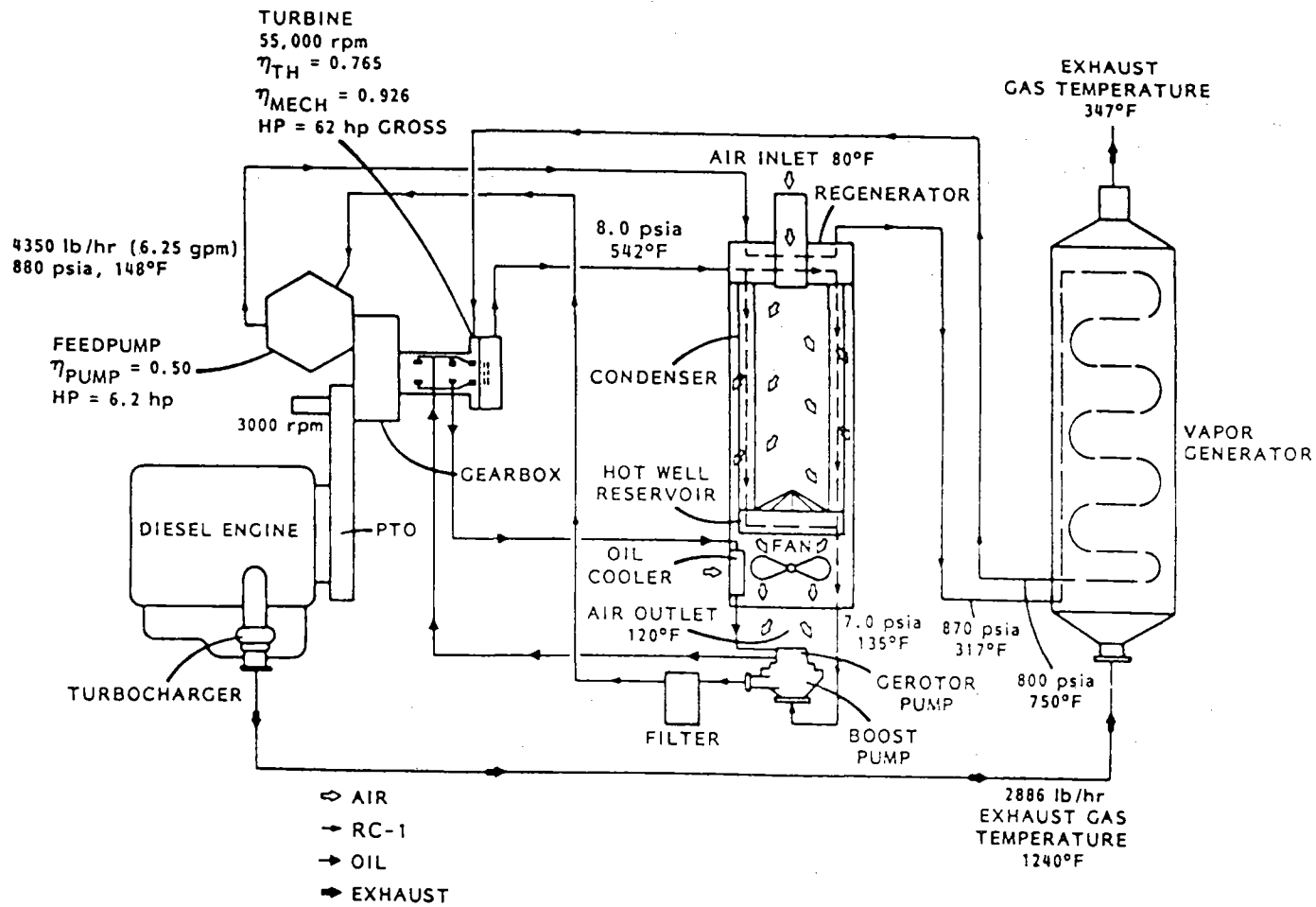


Fig. A-5. Schematic Diagram of Example RC-1 Rankine Bottoming Cycle (from Ref. 2)

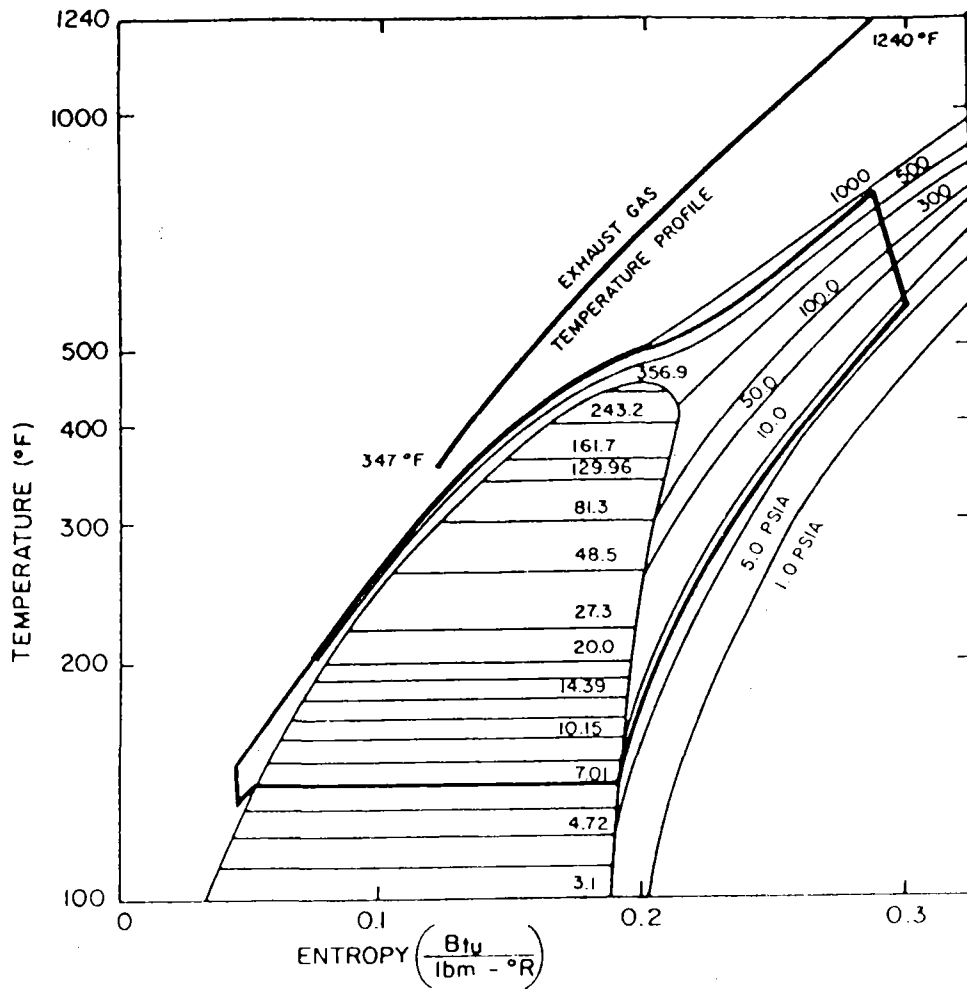


Fig. A-6. Temperature-entropy Diagram of Example RC-1 Rankine Bottoming Cycle (from Ref. 2)

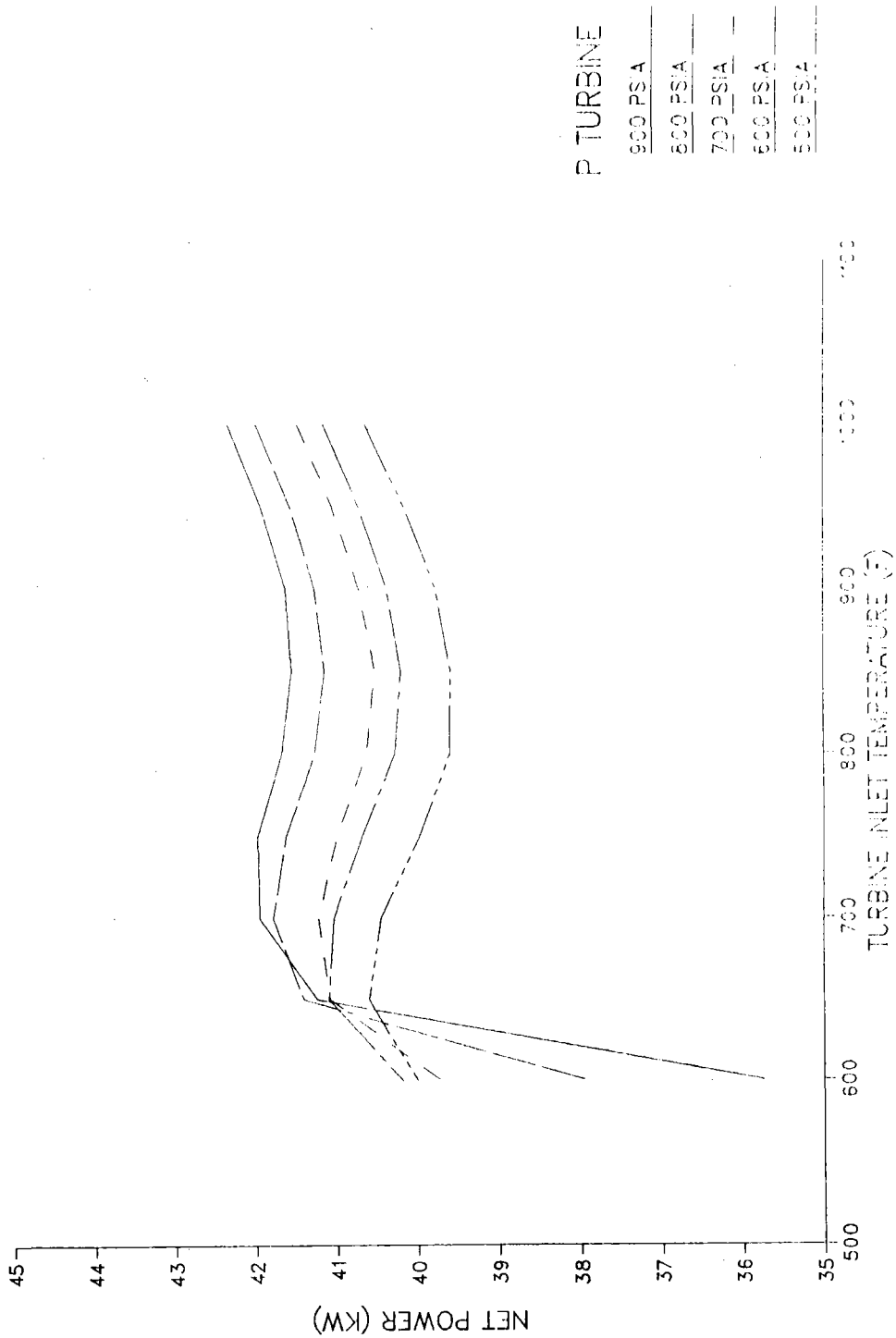


Fig. A-7. Power vs. Turbine Inlet Temperature for TECO RC-1 Bottoming Cycle

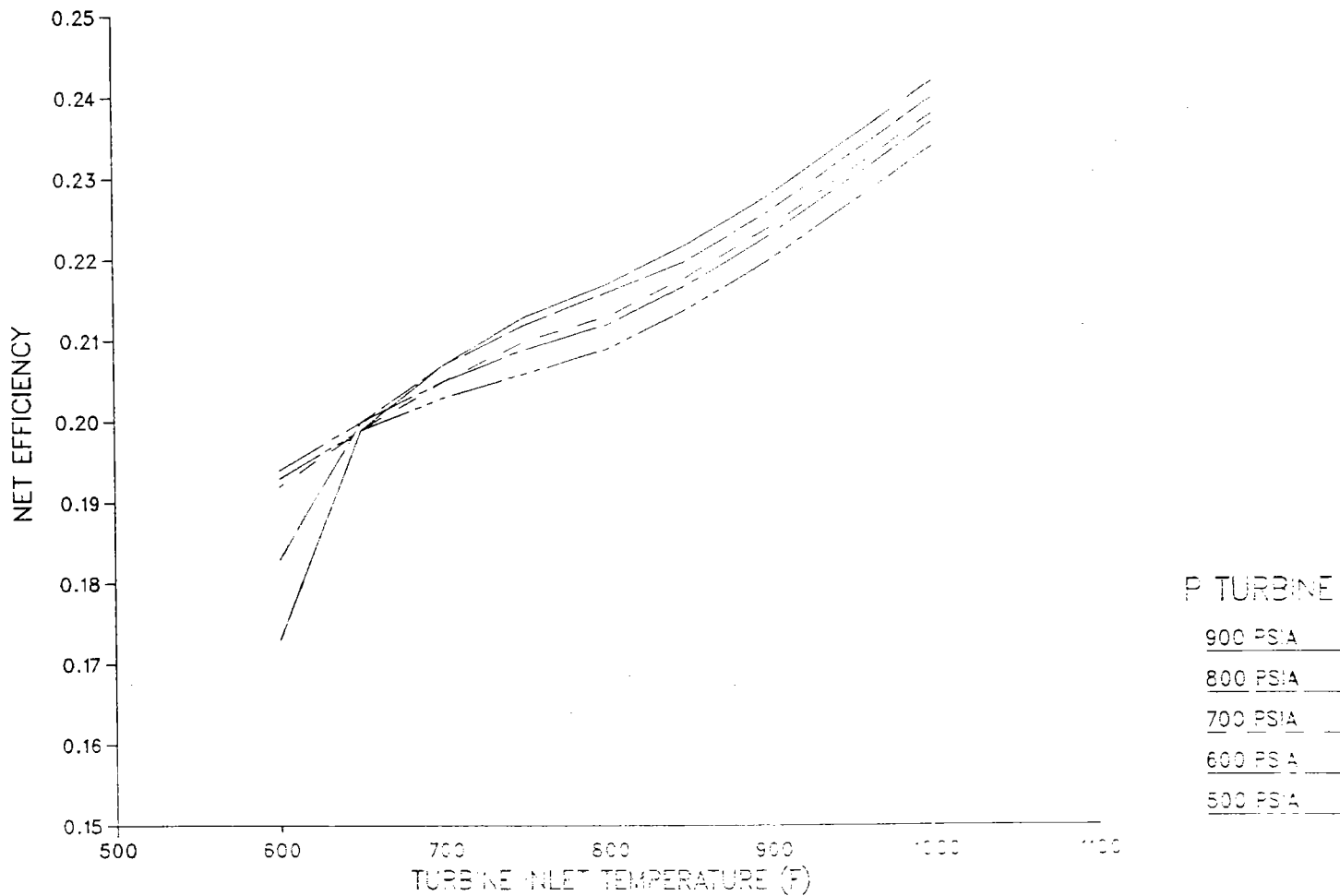


Fig. A-8. Efficiency vs. Turbine Inlet Temperature for TECO RC-1 Bottoming Cycle

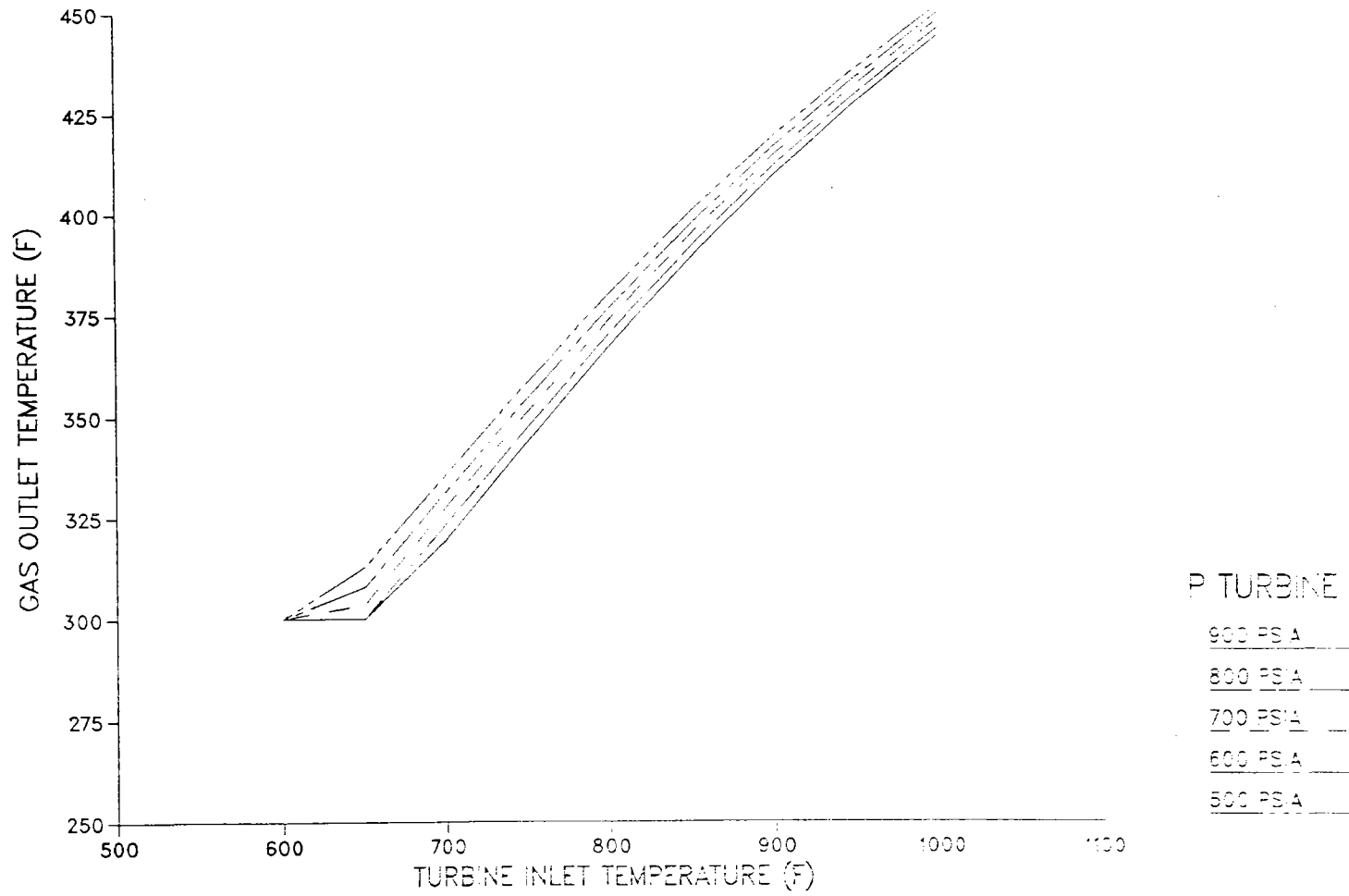


Fig. A-9. Exhaust Stack Temperature vs. Turbine Inlet Temperature for
TECO RC-1 Bottoming Cycle

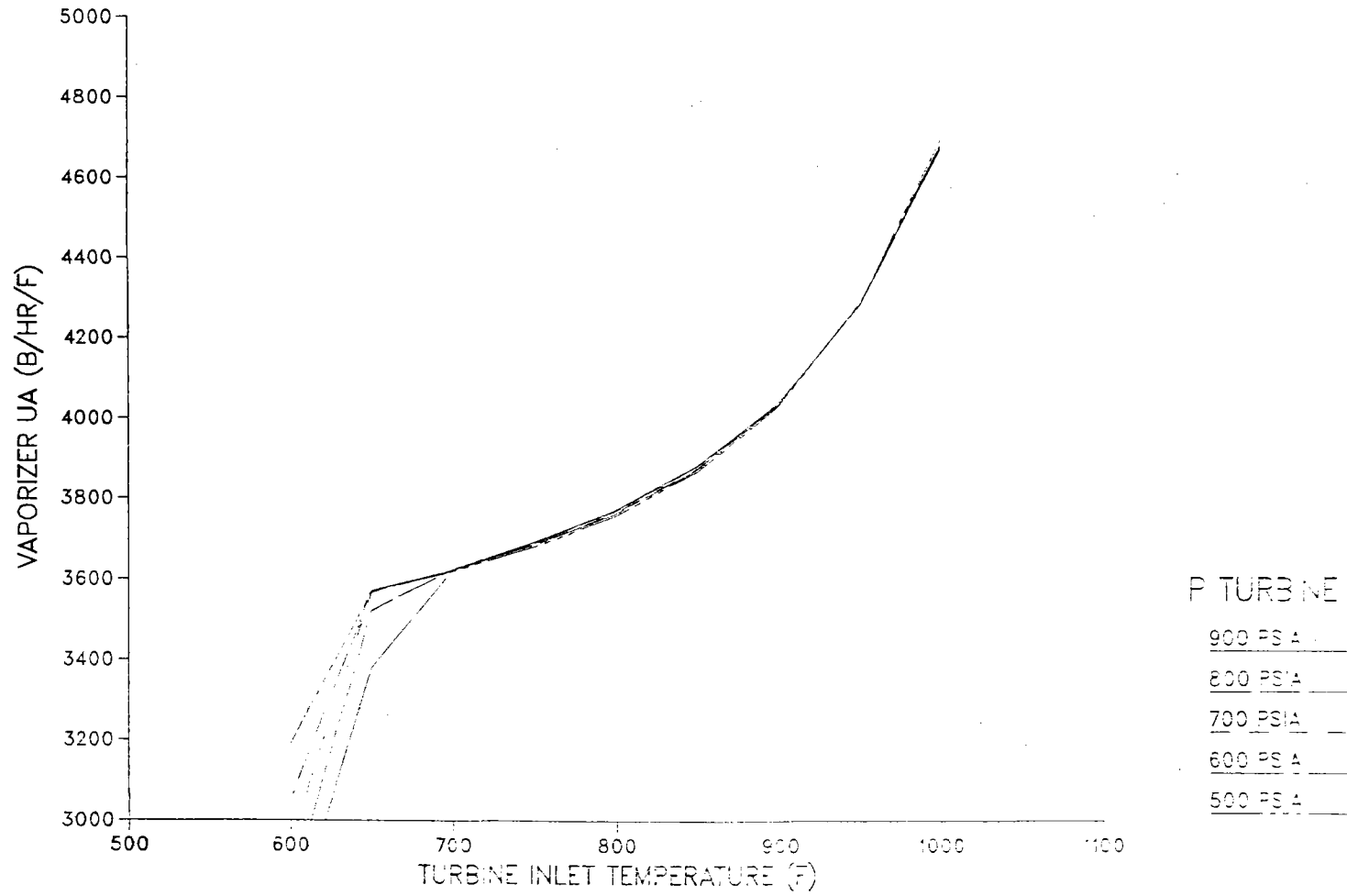


Fig. A-10. Vaporizer UA vs. Turbine Inlet Temperature for TECO RC-1 Bottoming Cycle

Table B-1. Cycle Variables Fixed for Each Computer Run

FORTRAN Name	Definition	Note
CPGAS	Specific heat of source gas (B/lb)	
DTSUB	Sub-cooling temperature drop at condenser (F)	
FLUID	Name of working fluid	
EMECH	Mechanical efficiency of Rankine system	
EPUMP	Pump efficiency	
ETURB	Turbine efficiency	
EREGEN	Regenerator effectiveness	2
FFB	Boiler pressure drop factor (decimel < 1)	
FFC	Condenser pressure drop factor (decimel < 1)	
FFR	Regenerator pressure drop factor (decimel < 1)	
ICOOL	Indicator for coolant (1=Air, 2=Water)	
MDOTG	Mass flow-rate of source gas (lb/hr)	3
TCOND	Saturation temperature in condenser (F)	
TGIN	Source gas inlet temperature (F)	3
TGMIN	Minimum outlet gas temperature (F)	
TPMIN	Minimum pinch-point temperature difference (F)	
UCOND	Condenser U value (B/hr/ft sq/F)	
UREGEN	Regenerator U Value (B/hr/ft sq/F)	
UVAP1	Economizer U value (B/hr/ft sq/F)	
UVAP2	Vaporizer U value (B/hr/ft sq/F)	
UVAP3	Superheater U value (B/hr/ft sq/F)	

NOTES: 1. All cost-function data fixed for each run.
 2. For Mode 3, effectiveness will vary from input value.
 3. For Mode 3, variable input values are used.

Table B-2. RC-1 Saturation Properties Input Data

18 :RC-1 SATURATION PROPERTIES (FILE35)

7.01	140.00	26.42	109.90
10.15	160.00	31.76	113.10
14.39	180.00	37.23	116.40
20.00	200.00	42.83	119.80
27.81	220.00	48.58	123.20
36.66	240.00	54.47	126.60
48.48	260.00	60.51	130.00
63.20	280.00	66.71	133.30
81.32	300.00	73.09	136.70
103.38	320.00	79.65	140.00
129.96	340.00	86.44	143.10
161.66	360.00	93.51	146.20
199.17	380.00	100.90	149.00
243.21	400.00	108.90	151.50
294.71	420.00	117.80	153.50
356.92	440.00	128.80	153.80
402.73	445.00	142.00	142.00
411.00	456.00	142.00	142.00

Pres.	Temp.	H-liq	H-vap
psi	F	Btu/lb	Btu/lb

Table B-3. RC-1 Condenser Conditions Input Data

4 :RC-1 CONDENSER CONDITIONS (FILE65)

4.72	120.0	.01098	21.23	106.70	0.	0.
7.01	140.0	.01135	26.42	109.90	0.	0.
8.01	146.4	.01147	28.12	110.90	0.	0.
10.15	160.0	.01174	31.76	113.10	0.	0.

Pres.	Temp.	V-liq	H-liq	H-vap	S-liq	S-vap
psi	F	cf/lb	---Btu/lb---		--Btu/lb/F--	

Table B-4. RC-1 High-pressure Superheat Input

Pres.	Temp.	H-vap	S-vap	
psi	F	Btu/lb	Btu/lb F	
5 31 :RC-1 HIGH-PRESSURE SUPERHEAT DATA (FILE45)				
100.0	400.0	157.8	.2296	:
100.0	420.0	162.3	.2348	:
100.0	440.0	166.9	.2401	:
100.0	460.0	171.6	.2452	:
100.0	480.0	176.4	.2503	:
100.0	500.0	181.2	.2553	:
100.0	520.0	186.0	.2604	:
----	BREAK		----	31 ENTRIES @ 20F
100.0	880.0	282.1	.3435	:
100.0	900.0	287.9	.3478	:
100.0	920.0	293.7	.3521	:
100.0	940.0	299.5	.3562	:
100.0	960.0	305.4	.3604	:
100.0	980.0	311.3	.3645	:
100.0	1000.	317.3	.3687	-----
300.0	400.0	108.9	.1647	:
300.0	420.0	117.8	.1745	:
300.0	440.0	158.7	.2208	:
----	BREAK		----	31 ENTRIES @ 20F
300.0	940.0	297.1	.3424	:
300.0	960.0	303.0	.3467	:
300.0	980.0	309.0	.3509	:
300.0	1000.	315.0	.3592	-----
500.0	400.0	108.9	.1647	:
500.0	420.0	117.8	.1745	:
500.0	440.0	128.8	.1862	:
----	BREAK		----	31 ENTRIES @ 20F
500.0	940.0	294.4	.3353	:
500.0	960.0	300.5	.3396	:
500.0	980.0	306.6	.3439	:
500.0	1000.	312.6	.3481	-----
700.0	400.0	108.9	.1647	:
700.0	420.0	117.8	.1745	:
700.0	440.0	128.8	.1862	:
----	BREAK		----	31 ENTRIES @ 20F
700.0	960.0	298.1	.3352	:
700.0	980.0	304.3	.3395	:
700.0	1000.	310.4	.3438	-----
900.0	400.0	108.9	.1647	:
900.0	420.0	117.8	.1745	:
900.0	440.0	128.8	.1862	:
----	BREAK		----	31 ENTRIES @ 20F
900.0	960.0	295.8	.3308	:
900.0	980.0	302.0	.3352	:
900.0	1000.	308.2	.3395	:

Table B-5. RC-1 Low-pressure Superheat Input

2 20 :RC-1 LOW SUPERHEAT PROPERTIES (FILE55)

5.0	100.	16.17	0.0344
5.0	140.	109.80	0.1963
5.0	160.	113.40	0.2018
5.0	180.	116.90	0.2073
5.0	200.	120.50	0.2128
5.0	220.	124.20	0.2183
5.0	240.	127.90	0.2238
5.0	260.	131.80	0.2291
5.0	280.	135.60	0.2345
5.0	300.	139.60	0.2398
5.0	320.	143.70	0.2451
5.0	340.	147.90	0.2503
5.0	360.	152.10	0.2556
5.0	400.	160.70	0.2659
5.0	420.	165.10	0.2710
5.0	440.	169.60	0.2760
5.0	480.	178.80	0.2860
5.0	500.	183.60	0.2910
5.0	520.	188.30	0.2959
5.0	560.	198.00	0.3056
10.0	100.	16.17	0.0344
10.0	140.	26.42	0.0532
10.0	160.	113.10	0.1937
10.0	180.	116.60	0.1992
10.0	200.	120.20	0.2048
10.0	220.	123.90	0.2102
10.0	240.	127.70	0.2157
10.0	260.	131.60	0.2211
10.0	280.	135.50	0.2265
10.0	300.	139.50	0.2318
10.0	320.	143.50	0.2371
10.0	340.	147.70	0.2423
10.0	360.	151.90	0.2476
10.0	400.	160.60	0.2579
10.0	420.	165.00	0.2630
10.0	440.	169.50	0.2681
10.0	480.	178.70	0.2781
10.0	500.	183.40	0.2830
10.0	520.	188.20	0.2879
10.0	560.	197.90	0.2977

Pres.	Temp.	H-vap	S-vap
psi	F	Btu/lb	Btu/lb F

Table B-6. Interactive Input of System Conditions (FILE15)

ARE COST FUNCTIONS TO BE CALCULATED?
TYPE 1 FOR YES OR 0 FOR NO.
?
0
INPUT CONDENSER TEMPERATURE (F)
?
140
INPUT PUMP AND TURBINE AND MECHANICAL
EFFICIENCIES (RANGE = 0.0 TO 1.0)
?
.500 .765 .926
IS A REGENERATOR TO BE INCLUDED IF TURBINE EXIT IS SUPERHEATED ?
INPUT 0 FOR NO, OR EFFECTIVENESS (<.99)
?
.60535
TYPE 0 TO SPECIFY THE HEAT SOURCE MASS FLOW RATE
TYPE 1 TO SPECIFY THE SYSTEM POWER OUTPUT
?
0
INPUT THE HEAT SOURCE SPECIF HEAT (B/LB/F)
?
.26
INPUT THE HEAT SOURCE MASS FLOW RATE (LBM/HR)
?
2886
TYPE IN THE GAS INLET AND MINIMUM OUTLET HEAT TEMPERATURES (F)
?
1240 300
TYPE THE MINIMUM DESIGN PINCH POINT DELTA T (F)
?
30
INPUT COOLANT:
TYPE 1 FOR AIR, 2 FOR WATER
?
1
TYPE IN THE DESIRED INLET AND OUTLET COOLANT STREAM TEMPERATURES
?
80 120
TYPE PRESSURE DROP FACTORS: BOILER, CONDENSER, REGEN.
?
.1000 .07133 .07133
TYPE SUBCOOLING DELTA T, BELOW CONDENSING TEMP.
?
5.0
TYPE FLUID NAME
rc-1
TYPE 5 HEAT TRANSFER COEFFICIENTS
VAPORIZER: SUBCOOLED, BOILER, SUPERHEAT
REGENERATOR (EVEN IF NOT USED), AND CONDENSER
?
1. 1. 1. 1. 1.

Table B-7. Non-interactive Input of System Conditions (FILE15)

0					:INDICATOR FOR COST CALCULATIONS
140.0					:CONDENSING TEMPERATURE
.5000	.765	.926			:EFFICIENCIES; PUMP,TURBINE,MECH
.60535					:REGENERATOR EFFECTIVENES(0=NO)
0					:INDICATOR FOR MASS FLOW/POWER OPTION
.26					:GAS SPECIFIC HEAT
2886.					:GAS FLOW RATE
1240.	300.				:GAS TEMPERATURES; INLET & MIN.
30.					:MIN. PINCH POINT FOR DESIGN
1					:COOLANT INDICATOR 1=AIR,2=H2O
80.	120.				:COOLANT INLET & OUTLET TEMPS.
.1000	.07133	.07133			:PRESSURE DROP PERCENTAGES
5.0					:SUBCOOLING DELTA TEMP.
RC-1					:FLUID
1.	1.	1.	1.	1.	:HEAT EXCHANGER U VALUES

Table B-8. Interactive Input of Mode 1 Cases (FILE25)

TYPE MODE=1,2 OR 3
 ?
 1
 INPUT FOR A RANGE OF CASES
 TYPE MAXIMUM T6, MINIMUM T6 & MESH DELT
 ?
 850 750 50
 TYPE MAXIMUM P6, MINIMUM P6 & MESH DELP
 ?
 900 700 100

Table B-9. Non-interactive Input of Mode 1 Cases (FILE25)

1					:CALCULATION MODE
850	750	50			: T6; MAX, MIN, DELTA
900	700	100			: P6; MAX, MIN, DELTA

Table B-10. Sample Output - TECO RC-1 System Design Point

CASE NUMBER 8
DESIGN POINT

COND TEMP (FAHR) (CENT)	TURB TEMP (FAHR) (CENT)	TURB PRES (PSIA) (MPA)	COND PRES (PSIA) (MPA)	THERMAL EFFICIENCY (RANKINE) (CARNOT)	TURB WORK (BTU/LB OF WORKING FLUID)	PUMP WORK (BTU/LB OF WORKING FLUID)	HEAT ADDED (BTU/LB OF WORKING FLUID)	ENERGY REGEN (BTU/LB OF WORKING FLUID)
140.0	750.0	800.0	7.01	0.229				
60.0	398.9	5.514	0.048	0.508	38.891	-3.638	154.042	49.935

THE PINCH POINT DELTA T FOR THIS SYSTEM IS 30.00 F.
THE GAS TEMPERATURE AT THE PINCH POINT IS 346.98 F.
THE WORKING FLUID TEMPERATURE AT THE PINCH POINT IS 316.98 F.

CYCLE POWER= 41.62 KW NET

VAPORIZER CHARACTERISTICS
SUPERHEATER SECTION

SOURCE STREAM TEMPERATURES: INLET=1240.0F OUTLET= 714.2F
WORKING FLUID TEMPERATURES: OUTLET= 750.0F INLET= 456.0F
DUTY= 3.94548E+05 BTU/HR, HEAT TRANSFER U= 1.00 BTU/HR-FT**2-F, SURFACE AREA= 1.09051E+03 FT**2

ECONOMIZER SECTION

SOURCE STREAM TEMPERATURES: INLET= 714.2F OUTLET= 347.0F
WORKING FLUID TEMPERATURES: OUTLET= 456.0F INLET= 317.0F
DUTY= 2.75540E+05 BTU/HR, HEAT TRANSFER U= 1.00 BTU/HR-FT**2-F, SURFACE AREA= 2.59914E+03 FT**2
OVERALL HEAT TRANSFER U = 1.0 BTU/FT**2-HR-F
VAPORIZER DUTY = 6.70089E+05 BTU/HR
VAPORIZER SURFACE AREA = 3.68965E+03 FT**2

REGENERATOR CHARACTERISTICS

REGENERATOR EFFECTIVNESS = 0.605
TEMPERATURES OF HOT STREAM: INLET= 543.0F OUTLET= 321.3F
TEMPERATURES OF COLD STREAM: OUTLET= 317.0F INLET= 148.6F
DUTY= 2.17219E+05 BTU/HR, HEAT TRANSFER U= 1.00 BTU/HR-FT**2-F, SURFACE AREA= 1.09628E+03 FT**2

CONDENSER CHARACTERISTICS

WORKING FLUID TEMPERATURES: INLET= 321.3F OUTLET= 140.0F
COOLANT STREAM TEMPERATURES: OUTLET= 120.0F INLET= 80.0F
DUTY= 5.16736E+05 BTU/HR, HEAT TRANSFER U= 1.00 BTU/HR-FT**2-F, SURFACE AREA= 9.67041E+03 FT**2

OVERALL SYSTEM CHARACTERISTICS

MASS FLOW RATE OF THE WORKING FLUID = 4.35004E+03 LBM/HR
MASS FLOW RATE OF THE GAS STREAM = 2.88600E+03 LBM/HR
MASS FLOW RATE OF THE COOLANT STREAM = 5.27281E+04 LBM/HR
NET SYSTEM EFFICIENCY (INCLUDES TURBINE, PUMP, AND MECHANICAL LOSSES) = 0.212

CYCLE STATE POINT PROPERTIES

POINT=	1	1S	2	3	4	5	6	7	8	9
T=	140.00	135.00	148.63	316.98	456.00	456.00	750.00	542.96	321.31	142.60
P=	7.01	7.01	880.00	880.00	880.00	880.00	800.00	8.01	7.51	7.37
H=	26.42	25.08	28.72	78.66	142.00	142.00	232.70	193.81	143.87	110.32

Table B-11. Sample Output - TECO RC-1 System (T6=850,P6=900)

CASE NUMBER 1 DESIGN POINT								
COND TEMP (FAHR) (CENT)	TURB TEMP (FAHR) (CENT)	TURB PRES (PSIA) (MPA)	COND PRES (PSIA) (MPA)	THERMAL EFFICIENCY (RANKINE) (CARNOT)	TURB WORK (BTU/LB OF WORKING FLUID)	PUMP WORK (BTU/LB OF WORKING FLUID)	HEAT ADDED (BTU/LB OF WORKING FLUID)	ENERGY REGEN (BTU/LB OF WORKING FLUID)
140.0	850.0	900.0	7.01	0.240				
60.0	454.4	6.203	0.048	0.546	44.506	-4.096	168.604	63.915

THE PINCH POINT DELTA T FOR THIS SYSTEM IS 30.00 F.
 THE GAS TEMPERATURE AT THE PINCH POINT IS 388.83 F.
 THE WORKING FLUID TEMPERATURE AT THE PINCH POINT IS 358.83 F.

***** CYCLE POWER= 41.54 KW NET *****

VAPORIZER CHARACTERISTICS
 SUPERHEATER SECTION

SOURCE STREAM TEMPERATURES: INLET=1240.0F OUTLET= 635.7F
 WORKING FLUID TEMPERATURES: OUTLET= 850.0F INLET= 456.0F
 DUTY= 4.53432E+05 BTU/HR, HEAT TRANSFER U= 1.00 BTU/HR-FT**2-F, SURFACE AREA= 1.67063E+03 FT**2

ECONOMIZER SECTION

SOURCE STREAM TEMPERATURES: INLET= 635.7F OUTLET= 388.8F
 WORKING FLUID TEMPERATURES: OUTLET= 456.0F INLET= 358.8F
 DUTY= 1.85252E+05 BTU/HR, HEAT TRANSFER U= 1.00 BTU/HR-FT**2-F, SURFACE AREA= 2.21508E+03 FT**2
 OVERALL HEAT TRANSFER U = 1.0 BTU/FT**2-HR-F
 VAPORIZER DUTY = 6.38684E+05 BTU/HR
 VAPORIZER SURFACE AREA = 3.88571E+03 FT**2

REGENERATOR CHARACTERISTICS

REGENERATOR EFFECTIVNESS = 0.605
 TEMPERATURES OF HOT STREAM: INLET= 639.4F OUTLET= 365.9F
 TEMPERATURES OF COLD STREAM: OUTLET= 358.8F INLET= 150.3F
 DUTY= 2.42114E+05 BTU/HR, HEAT TRANSFER U= 1.00 BTU/HR-FT**2-F, SURFACE AREA= 9.81624E+02 FT**2

CONDENSER CHARACTERISTICS

WORKING FLUID TEMPERATURES: INLET= 365.9F OUTLET= 140.0F
 COOLANT STREAM TEMPERATURES: OUTLET= 120.0F INLET= 80.0F
 DUTY= 4.85608E+05 BTU/HR, HEAT TRANSFER U= 1.00 BTU/HR-FT**2-F, SURFACE AREA= 8.38370E+03 FT**2

OVERALL SYSTEM CHARACTERISTICS

MASS FLOW RATE OF THE WORKING FLUID = 3.78807E+03 LBM/HR
 MASS FLOW RATE OF THE GAS STREAM = 2.88600E+03 LBM/HR
 MASS FLOW RATE OF THE COOLANT STREAM = 4.95518E+04 LBM/HR
 NET SYSTEM EFFICIENCY (INCLUDES TURBINE, PUMP, AND MECHANICAL LOSSES) = 0.222

CYCLE STATE POINT PROPERTIES

POINT=	1	1s	2	3	4	5	6	7	8	9
T=	140.00	135.00	150.34	358.83	456.00	456.00	850.00	639.40	365.92	142.42
P=	7.01	7.01	989.99	989.99	989.99	989.99	899.99	8.01	7.51	7.34
H=	26.42	25.08	29.18	93.10	142.00	142.00	261.70	217.19	153.28	110.29

Table B-12. Comparison of ANL/RBC Results to TECO Results

Fixed Constraints:

$\dot{m}_g = 2886 \text{ lb/hr}$, $T_{g_{in}} = 1240\text{F}$, $C_{p_g} = .26$
 Turbine Inlet; $T_6 = 750\text{F}$, $p_6 = 800 \text{ psi}$, $h_1 = 232.67 \text{ B/lb}$
 Turbine Outlet; $p_7 = 8.01 \text{ psi}$

	TECO	ANL	
	$\epsilon_r = .60$.60535	
\dot{m}_F (lb/hr)	4350	4350	
Δh turbine (B/lb)	39.15	38.89	
Δh reg (B/lb)	49.868	49.94	
Net Power (hp)	55.75	55.79	
$Q_{boil} \times 10^{-5}$ (B/hr)	6.702	6.701	
$Q_{reg} \times 10^{-5}$ (B/hr)	2.169	2.172	
$Q_{cond} \times 10^{-5}$ (B/hr)	5.158	5.167	
$(UA)_B \times 10^{-3}$ (B/hrF)	3.691	3.690	
$(UA)_r \times 10^{-3}$ (B/hrF)	1.100	1.096	
$(UA)_C \times 10^{-3}$ (B/hrF)	9.970	9.670	
$(\Delta T)_{pinch}$ (F)	30	30	
<u>State Points</u>			
7	T	541.79	542.9
Turbine	p	8.01	8.01
Outlet	h	193.52	193.81
8	T	320.26	321.31
Regen.	p	7.51	7.51
Outlet	h	143.66	143.87
1'	T	135.00	135.00
Cond.	p	7.01	7.01
Outlet	h	25.08	25.08
2	T	148.62	148.63
Pump	p	880	880
Outlet	h	28.72	28.72
3	T	316.76	316.98
Regen.	p	870	880
Outlet	h	78.59	78.66

Table B-13. Interactive Input of Mode 2 Cases (FILE25)

```
TYPE MODE=1,2 OR 3
?
2
TYPE NCASE
?
9
TYPE TURBINE INLET T6 AND P6
?
750 700
TYPE TURBINE INLET T6 AND P6
?
750 800
TYPE TURBINE INLET T6 AND P6
?
750 900
TYPE TURBINE INLET T6 AND P6
?
800 700
TYPE TURBINE INLET T6 AND P6
?
800 800
TYPE TURBINE INLET T6 AND P6
?
800 900
TYPE TURBINE INLET T6 AND P6
?
850 700
TYPE TURBINE INLET T6 AND P6
?
850 800
TYPE TURBINE INLET T6 AND P6
?
850 900
```

Table B-14. Non-interactive Input of Mode 2 Cases (FILE25)

```
2           :CALCULATION MODE
9           :NUMBER OF CASES
750 700    :TURBINE INLET T6, P6
750 800    :           DITTO
750 900    :           DITTO
800 700    :           DITTO
800 800    :           DITTO
800 900    :           DITTO
850 700    :           DITTO
850 800    :           DITTO
850 900    :           DITTO
```


Table B-15. Interactive Input of Mode 3 Cases (FILE25)

```

TYPE MODE=1,2 OR 3
?
3
TYPE NUMBER OF OFF-DESIGN CASES
?
8
TYPE TURBINE INLET T6 AND P6
?
750 800
TYPE OFF DESIGN GAS INLET TEMP. AND FLOW RATE.
?
1134 2340
TYPE OFF DESIGN GAS INLET TEMP. AND FLOW RATE.
?
983 1860
TYPE OFF DESIGN GAS INLET TEMP. AND FLOW RATE.
?
791 1548
TYPE OFF DESIGN GAS INLET TEMP. AND FLOW RATE.
?
750 1152
TYPE OFF DESIGN GAS INLET TEMP. AND FLOW RATE.
?
1375 1950
TYPE OFF DESIGN GAS INLET TEMP. AND FLOW RATE.
?
1198 1650
TYPE OFF DESIGN GAS INLET TEMP. AND FLOW RATE.
?
1000 1368
TYPE OFF DESIGN GAS INLET TEMP. AND FLOW RATE.
?
800 1170

```

Table B-16. Non-interactive Input of Mode 3 Cases (FILE25)

3	:CALCULATION MODE
8	:NUMBER OF OFF-DESIGN POINTS
750. 800.	:DESIGN-POINT TURBINE TEMP. & PRES.
1134 2340	:OFF-DESIGN GAS INLET TEMP & FLOW RATE
983 1860	:
791 1548	: DITTO
750 1152	: DITTO
1375 1950	: DITTO
1198 1650	: DITTO
1000 1368	: DITTO
800 1170	: DITTO

Table B-17. Pre-defined Variable Names for Cost Functions

NAME	Definition in Cycle/Code
ACOND	Total heat-transfer area (sq ft) of condenser
AREGEN	Total heat-transfer area (sq ft) of regenerator
ASAT	Vaporizer area (sq ft) for saturated liquid (Boiler)
ASUB	Vaporizer area for sub-cooled liquid (Economizer)
ASUP	Vaporizer area (sq ft) for superheated vapor
AVAPOR	Total vaporizer heat-transfer area (Sum of 3 above)
MDOTF	Mass flow-rate of cycle working fluid (lb/hr)
MDOTG	Mass flow-rate of source gas stream (lb/hr)
POWER	Net power output of cycle (kw)
TGIN	Temperature of source gas at inlet (F)
TGOUT	Temperature of source gas at outlet (F)
T1 - T9	Working fluid temperatures (F) at state points 1-9
P1 - P9	Working fluid pressures (psia) at state points 1-9
H1 - H9	Working fluid enthalpies (B/lb) at state points 1-9
H1P	Working fluid enthalpy (B/lb) at pump inlet
T1P	Working fluid temperature (F) at pump inlet

Table B-18. Example Cost Function for REGENERATOR Cost

```

INPUT DATA FOR EQUATION # 1
**** TYPE DEPENDENT VARIABLE ****
regenerator
**** TYPE EQUATION FORM (1-7) ****
?
5
**** TYPE DATA INPUT OPTION ****
**** 1 FOR INPUT CONSTANTS, 2 FOR CURVE FIT ****
?
1
**** TYPE INDEPENDENT VARIABLE ****
aregen
FUNCTIONAL FORM FOR REGENERATOR
Y=C*X**E
**** TYPE COEFFICIENT C ****
?
43.16
**** TYPE COEFFICIENT E ****
?
.85
**** IS THIS VARIABLE TO BE INCLUDED IN TOTAL COST? Y/N ****
Y

```

Table B-19. Alternate Input of Cost Function Data Values

```

INPUT DATA FOR EQUATION # 2
**** TYPE DEPENDENT VARIABLE ****
reg2
**** TYPE EQUATION FORM (1-7) ****
?
5
**** TYPE DATA INPUT OPTION ****
**** 1 FOR INPUT CONSTANTS, 2 FOR CURVE FIT ****
?
2
**** TYPE INDEPENDENT VARIABLE ****
aregen
**** INPUT DATA FOR CURVE-FIT. ****
**** TYPE # OF DATA POINTS. ****
?
3
**** TYPE X,Y PAIRS FOR 3 DATA POINTS ****
?
1000 15313.75
?
1500 21615.19
?
2000 27603.04
CALCULATED COEFFICIENTS FOR COMPONENT # 2
0.0 1.63503D+00 8.50016D-01 0.0 0.0
**** IS THIS VARIABLE TO BE INCLUDED IN TOTAL COST? Y/N ****
n

```

Table B-20. Example Cost Function for TURBINE Cost

```
      INPUT DATA FOR EQUATION # 3
**** TYPE DEPENDENT VARIABLE ****
turbine
**** TYPE EQUATION FORM (1-7) ****
?
2
**** TYPE DATA INPUT OPTION ****
**** 1 FOR INPUT CONSTANTS, 2 FOR CURVE FIT ****
?
2
**** TYPE INDEPENDENT VARIABLE ****
power
**** INPUT DATA FOR CURVE-FIT. ****
**** TYPE # OF DATA POINTS. ****
?
3
**** TYPE X,Y PAIRS FOR 3 DATA POINTS ****
?
500  42042
?
1000 51087
?
1500 58302
      CALCULATED COEFFICIENTS FOR COMPONENT # 3
      0.0          3.11671D+04  2.35798D+01 -3.65988D-03  0.0
**** IS THIS VARIABLE TO BE INCLUDED IN TOTAL COST? Y/N ****
y

      INPUT DATA FOR EQUATION # 4
**** TYPE DEPENDENT VARIABLE ****
done
**** DO YOU WANT TO CONTINUE FOR RBC ANALYSIS (Y/N) ****
n
**** INPUT STOPPED AFTER COST-FUNCTION INPUT. ****
```

Table B-21. Example Cost Function for FLUID Cost

```
INPUT DATA FOR EQUATION # 3
**** TYPE DEPENDENT VARIABLE ****
f1
**** TYPE EQUATION FORM (1-7) ****
?
6
LINEAR COMBINATION OF TWO VARIABLES: Y=A1*X1+A2*X2
**** TYPE 1ST INDEPENDENT VARIABLE NAME ****
asub
**** TYPE COEFFICIENT FOR 1ST VARIABLE ****
?
.02
**** TYPE 2ND INDEPENDENT VARIABLE NAME ****
aregen
**** TYPE COEFFICIENT FOR 2ND VARIABLE ****
?
.08
**** IS THIS VARIABLE TO BE INCLUDED IN TOTAL COST? Y/N ****
n
INPUT DATA FOR EQUATION # 4
**** TYPE DEPENDENT VARIABLE ****
f2
**** TYPE EQUATION FORM (1-7) ****
?
4
**** TYPE DATA INPUT OPTION ****
**** 1 FOR INPUT CONSTANTS, 2 FOR CURVE FIT ****
?
1
**** TYPE INDEPENDENT VARIABLE ****
fmw
FUNCTIONAL FORM FOR F2
Y=A+B*X +C/X
**** TYPE COEFFICIENT A ****
?
1.2
**** TYPE COEFFICIENT B ****
?
0
**** TYPE COEFFICIENT C ****
?
414
**** IS THIS VARIABLE TO BE INCLUDED IN TOTAL COST? Y/N ****
n
INPUT DATA FOR EQUATION # 5
**** TYPE DEPENDENT VARIABLE ****
f3
**** TYPE EQUATION FORM (1-7) ****
?
7
```

(Table B-21. continued next page)

(Table B-21. continued)

```
SCALED PRODUCT OF TWO VARIABLES:  $Y=C*X1*X2$ 
**** TYPE 1ST INDEPENDENT VARIABLE NAME ****
f2
**** TYPE 2ND INDEPENDENT VARIABLE NAME ****
mdotf
**** TYPE COEFFICIENT C ****
?
1
**** IS THIS VARIABLE TO BE INCLUDED IN TOTAL COST? Y/N ****
n
    INPUT DATA FOR EQUATION # 6
**** TYPE DEPENDENT VARIABLE ****
f4
**** TYPE EQUATION FORM (1-7) ****
?
6
    LINEAR COMBINATION OF TWO VARIABLES:  $Y=A1*X1+A2*X2$ 
**** TYPE 1ST INDEPENDENT VARIABLE NAME ****
f1
**** TYPE COEFFICIENT FOR 1ST VARIABLE ****
?
1
**** TYPE 2ND INDEPENDENT VARIABLE NAME ****
f3
**** TYPE COEFFICIENT FOR 2ND VARIABLE ****
?
1
**** IS THIS VARIABLE TO BE INCLUDED IN TOTAL COST? Y/N ****
n
    INPUT DATA FOR EQUATION # 7
**** TYPE DEPENDENT VARIABLE ****
fluid
**** TYPE EQUATION FORM (1-7) ****
?
7
    SCALED PRODUCT OF TWO VARIABLES:  $Y=C*X1*X2$ 
**** TYPE 1ST INDEPENDENT VARIABLE NAME ****
cgal
**** TYPE 2ND INDEPENDENT VARIABLE NAME ****
f4
**** TYPE COEFFICIENT C ****
?
1
**** IS THIS VARIABLE TO BE INCLUDED IN TOTAL COST? Y/N ****
Y
    INPUT DATA FOR EQUATION # 8
**** TYPE DEPENDENT VARIABLE ****
done
**** DO YOU WANT TO CONTINUE FOR RBC ANALYSIS (Y/N) ****
n
**** INPUT STOPPED AFTER COST-FUNCTION INPUT. ****
```

Table B-22. Summary of FORTRAN Input/Output Files

#	Function	Remarks
5	Interactive Cost-function Input	Usually TERMINAL (see 75)
15	FILE15 Rankine System Data	TERMINAL or Pre-prepared
25	FILE25 Operating Conditions	TERMINAL or Pre-prepared
35	FILE35 Saturation Properties	Normally Pre-prepared
45	FILE45 High Superheat Data	Normally Pre-prepared
55	FILE55 Low Superheat Data	Normally Pre-prepared
65	FILE65 Condenser Properties	Normally Pre-prepared
75	Alternate Cost-function Input	Use Output from FILE36
6	Prompt Messages; Cycle Input	DUMMY for Non-interactive
16	Prompt Messages; Cost-function	DUMMY for Non-interactive
26	Cycle Analysis Output Results	PRINTER or Storage
36	Copy of Cost-function Input	Saved for later use as 75

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16. Abstract <p>This report describes, and is a User's Manual for, a computer code (ANL/RBC) which calculates cycle performance for Rankine bottoming cycles extracting heat from a specified source gas stream. The code calculates cycle power and efficiency and the sizes for the heat exchangers, using tabular input of the properties of the cycle working fluid. An option is provided to calculate the costs of system components from user defined input cost functions. These cost functions may be defined in equation form or by numerical tabular data. A variety of functional forms have been included for these functions and they may be combined to create very general cost functions. An optional calculation mode can be used to calculate the off-design performance of a system when operated away from the design-point, using the heat exchanger areas calculated for the design-point.</p>			
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