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COMPUTER PROGRAM FOR THERMODYNAMIC ANALYSIS OF OPEN-CYCLE MULTISHAFT POWER SYSTEM WITH MULTIPLE REHEAT AND INTERCOOL

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16. Abstract

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COMPUTER PROGRAM FOR THERMODYNAMIC ANALYSIS OF OPEN-CYCLE MULTISHAFT POWER SYSTEM WITH MULTIPLE REHEAT AND INTERCOOL

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SUMMARY

This report presents a computer program for the thermodynamic analysis of an open-cycle multishaft power system with multiple intercooling and reheating capability. The program can compute specific power output, specific fuel consumption, and cycle efficiency for power systems having any number of shafts up to a maximum of five. On each shaft there can be any number of compressors and turbines up to a maximum of five each, along with any specified number of intervening intercoolers and reheaters. A recuperator can be included in the system. Turbine coolant flow can be accounted for. The combustion-gas thermodynamic properties are valid for any fuel consisting of hydrogen and/or carbon only. The program should be used with maximum temperatures no higher than about 2000 K (3600° R) because molecular dissociation is not included in the stoichiometry.

This report presents a description of the general open-cycle system that can be analyzed, the analysis method, and a complete description of the computer program. The description of the computer program includes a detailed explanation of input and output including an illustrative example, a discussion of the main program and each of the subprograms, the dictionary of program variables, and the program listing.

INTRODUCTION

Open-cycle systems for ground power-production applications, both stationary and propulsive, are currently being studied at the Lewis Research Center. One of the first phases in the analysis of any power cycle is the determination of the thermodynamic performance as a function of the cycle variables. Such cycle analyses are performed most readily by computer. Therefore, a computer program was written to perform the thermodynamic analysis of open-cycle power systems.

The computer program can be used to analyze power systems having any number of shafts up to a maximum of five. On each shaft there can be any number of compressors and turbines up to a maximum of five each, along with intervening intercoolers and reheat combustors. A recuperator can be included in the system, and turbine coolant flow can be accounted for. Any fuel consisting entirely of hydrogen and/or carbon can be used. The program should be used with maximum temperatures no higher than about 2000 K (3600° R) because molecular dissociation is not included in the stoichiometry.

This report presents a description of the general open-cycle system that can be analyzed, the analysis method, and a complete description of the computer program. The computer program description includes a detailed explanation of input and output including a sample case, a discussion of the main program and each of the subprograms, a program listing, and a dictionary of program variables.

SYSTEM ANALYSIS AND DESCRIPTION

An example two-shaft power system is used to show the type of analysis that can be performed by the computer program being described in this report. The general open-cycle power system that can be analyzed is then described.

Example-System Analysis

An example of a power system that can be analyzed using the computer program described herein is the two-shaft open-cycle power system with intercooling and reheating that is shown schematically in figure 1 and thermodynamically on a temperature-entropy diagram in figure 2. Air enters the low-pressure compressor and is partially compressed. The air is then cooled within the intercooler. Since heat is generated during compression and compressor work is proportional to temperature, the use of intercooling serves to reduce the total compression work required for a given pressure ratio. The cooled air is then further compressed in the high-pressure compressor and heated in the combustor by the burning of fuel. Partial expansion occurs in the high-pressure turbine, which drives the high-pressure compressor, and heating again occurs, this time in the reheater. Since turbine work is proportional to temperature, the use of reheating increases the total work obtained for a given expansion. Final expansion to atmospheric pressure then occurs in the low-pressure turbine, which drives both the low-pressure compressor and the generator.

The computer program described in this report can be used to analyze such a power system to determine cycle efficiency as a function of turbine-inlet temperature and compressor pressure ratio. The improvements in cycle efficiency resulting from the use of intercooling and reheating can also be determined. Cycle efficiency computed by the program is plotted against turbine-inlet temperature in figure 3 for a system with one intercooling and one reheating (fig. 1), a system with one intercooling only, and a simple system (no intercooling and no reheating). For these three systems an increase in turbine-inlet temperature from 1090 to 1370 K (1500° to 2000° F) increases cycle efficiency by about 20 to 25 percent; a further increase from 1370 to 1650 K (2000° to 2500° F) increases cycle efficiency by another 10 to 15 percent. Operation at higher turbine-inlet temperatures, therefore, results in significant improvements in cycle efficiency.

The improvements in cycle efficiency resulting from intercooling and reheating are also indicated in figure 3. At a temperature of 1370 K (2000° F) as an example, the use of one intercooling alone increases the efficiency from 39 to 43 percent and the addition of one reheating along with the intercooling increases efficiency to 45 percent. For a plant of fixed power output, this corresponds to about a 10-percent reduction in fuel consumption with intercooling and about 5-percent additional reduction in fuel consumption with the reheating added. At other temperatures, the benefits are about the same magnitude with efficiency reaching about 50 percent at 1650 K (2500° F). The reductions in fuel cost associated with such improvements in efficiency must be considered against the additional capital cost of the plant. Additional intercoolings and reheatings can be used to yield further improvements in cycle efficiency. The incremental improvements, however, become smaller and smaller as additional intercool and reheat steps are added. The optimum number of intercoolers and reheaters to be used will depend on a detailed economic analysis for a given plant.

In order to realize the benefits associated with the use of intercooling and reheating, the system must operate at greater pressure ratios than the simple cycle. This is indicated in figure 4, where cycle efficiencies for the simple system and for a system with one intercooling and one reheating are plotted against pressure ratio at a turbine-inlet temperature of 1370 K (2000° F), as an example. For the simple cycle the optimum pressure ratio is 30, and efficiency decreases markedly if the pressure ratio is less than 20 or greater than 40. For the cycle with intercooling and reheating, the optimum pressure ratio is about 120. However, the curve is very flat in the region of maximum efficiency, and it is possible to operate at a pressure ratio of about 75 without a significant decrease in efficiency. This pressure ratio of 75 is still considerably higher than that for the simple cycle. Thus, with intercooling and reheating, not only will additional heat exchangers be required, but also additional stages will be required for the turbomachinery.

General-System Description

The example system just discussed is only one of many possible variations for open-cycle power systems. The computer program presented in this report can be used to analyze open-cycle power systems having different numbers and types of components. Figure 5(a) shows schematically a system having the maximum number of components that can be included in the analysis; figure 5(b) shows a system having the minimum number of components that must be included. Any system intermediate between these two can be analyzed. The size of the maximum system was selected on the basis of it being large enough to include all cases of possible interest.

In figure 5(a) the system capability includes an inlet, a series of compressors and intercoolers, a recuperator, a primary burner, a series of turbines and reheaters, and a diffuser. There can be as many as five shafts. On each shaft there can be as many as five compressors with any specified number of intervening intercoolers and five turbines with any specified number of intervening reheaters. Output power can be obtained from each shaft. Part of the compressor exit flow can be used as turbine coolant or lost through recuperator leakage. The turbine coolant, which can be directed to any or all of the turbines, rejoins the primary flow at the exit of the turbine being cooled.

Any liquid or gaseous fuel consisting entirely of hydrogen and/or carbon can be used. A fuel boost pump or compressor, with intercooling if desired, can be provided with the required drive power taken from the system output.

The subscripts shown for the compressors, intercoolers, burners, and turbines correspond to the double subscript notation used in the program. The first subscript refers to the component number, and the second subscript refers to the shaft number. An understanding of the proper order of subscripts is necessary to correctly prepare program input. Specific directions for properly specifying input-variable subscripts are given in the section Description of Input and Output.

METHOD OF ANALYSIS

The equations used for the open-cycle power system thermodynamic analysis are presented in this section. Equations are presented for the thermodynamic properties of the gas, analysis of the fluid state changes in each component, and computation of the system performance in terms of specific power output, specific fuel consumption, and cycle efficiency. The calculation logic for combining the components into the desired system is discussed as needed. All symbols used in the analysis are defined in appendix A.

Thermodynamic Properties

To perform a cycle thermodynamic analysis, it is necessary to relate enthalpy change and constant-pressure entropy change to the gas temperature change and composition. This is done herein as follows: The heat capacity c_p of each component of the general combustion gas is expressed as a polynomial function of temperature. Then, from the stoichiometry associated with the reaction of 1 mass unit of air plus associated inlet humidity with f mass units of fuel of composition CH_x, a single equation for the combustion-gas heat capacity is obtained. Finally, the enthalpy and constant-pressure entropy changes are obtained as

$$\Delta h = \int_{T_1}^{T_2} c_p \, dT \tag{1}$$

and

$$\Delta \varphi = \int_{T_1}^{T_2} \frac{c_p}{T} \, dT \tag{2}$$

The equations for Δh and $\Delta \varphi$ as functions of initial T_1 and final T_2 temperatures, fuel-air ratio f, fuel composition (function of x), and absolute humidity of the inlet air are derived in appendix B. These equations are valid over a temperature range of 200 to 2000 K (360° to 3600° R). A maximum temperature of 2000 K (3600° R) was chosen because the combustion stoichiometry does not include molecular dissociation, which starts to appear at about this temperature. The basic assumption inherent in these thermodynamic equations, as well as in most of the analysis, is that the gas obeys the ideal gas law.

For brevity in the analysis to follow, equation (B7) for Δh and equation (B12) for $\Delta \varphi$ will be denoted as

$$\Delta h = H(T_1, T_2, f) \tag{3}$$

and

$$\Delta \varphi = \Phi(T_1, T_2, f) \tag{4}$$

Since the fuel composition and inlet-air absolute humidity have singular values for any given system analysis, they were not included as arguments of these functions.

Components

The equations used to analyze the flow through the inlet, compressors, intercoolers, burners, turbines, diffuser, recuperator, and fuel system are presented in this section.

Inlet. - Since this is a ground-based power system, inlet total and static conditions were assumed equal. The inlet component would probably be some type of air filter. Therefore, for the flow leaving the inlet

$$T_1' = T_0 \tag{5}$$

$$p_1' = p_0 r_I \tag{6}$$

$$w_1 = 1 + m \tag{7}$$

The ambient static temperature T_0, ambient static pressure p_0, inlet pressure recovery r_I, and inlet absolute humidity m are program inputs.

Compressor. - The compressors and intercoolers are analyzed in flow sequence. The inlet conditions to the first compressor are those from the inlet component as specified by equations (5) to (7). For any subsequent compressor, the inlet conditions are the exit conditions from the component, either a compressor or an intercooler, immediately upstream. The mass flow rate remains constant at w_1 throughout the compressors and intercoolers.

For any compressor

$$p'_{C,ex} = p'_{C,in} r_C \tag{8}$$

where the pressure ratio r_C for each compressor is specified by the input variables. Either an overall efficiency $\eta_{C,o}$ or a polytropic efficiency $\eta_{C,p}$ can be specified for the compressor. With overall efficiency, an ideal exit temperature $T'_{C,ex,id}$ is found by iteration from

$$\Phi\left(T'_{C,in}, T'_{C,ex,id}, 0\right) = \frac{R}{J} \ln r_C \tag{9}$$

Compressor specific work is then found from the efficiency definition

$$\Delta h'_C = \frac{H\left(T'_{C,in}, T'_{C,ex,id}, 0\right)}{\eta_{C,o}} \tag{10}$$

and compressor exit temperature from

$$H\left(T'_{C,in}, T'_{C,ex}, 0\right) = \Delta h'_C \tag{11}$$

With polytropic efficiency, the compressor exit temperature is found from

$$\Phi\left(T'_{C,in}, T'_{C,ex}, 0\right) = \frac{1}{\eta_{C,p}} \frac{R}{J} \ln r_C \tag{12}$$

and compressor specific work from

$$\Delta h'_C = H\left(T'_{C,in}, T'_{C,ex}, 0\right) \tag{13}$$

For each shaft, the compressor specific works are summed in order to obtain the turbine power required to drive the compressors on that shaft:

$$P_{C,j} = w_1 \sum \Delta h'_{C,j} \tag{14}$$

Intercooler. - The inlet conditions to each intercooler are the exit conditions from the compressor immediately upstream. The exit temperature from each intercooler is specified as program input, and the exit pressure is determined from the input pressure recovery r_{INT}

$$p'_{INT,ex} = p'_{INT,in} r_{INT} \tag{15}$$

The heat rejected in each intercooler can be found as

$$\Delta h'_{INT} = H\left(T'_{INT,ex}, T'_{INT,in}, 0\right) \tag{16}$$

Recuperator cold side. - Entering the recuperator cold side is the last (highest pressure) compressor exit flow having temperature T'_2 and pressure p'_2. Some of this compressor-exit flow is bled off for turbine coolant or to account for a leakage loss such as in a rotary recuperator. The mass flow rate entering the recuperator is then

$$w_2 = w_1 - w_l - \sum w_{T,c} \tag{17}$$

The leakage flow w_l and the coolant flow $w_{T,c}$ required for each turbine are specified by the program input. The recuperator cold-side exit pressure is determined from the input value of pressure recovery $r_{R,\,cold}$:

$$p_3' = p_2' r_{R,\,cold} \tag{18}$$

At this point in the analysis it is necessary to enter an iteration loop. The recuperator cold-side exit temperature T_3' cannot be determined until the hot-side inlet temperature T_6' is known. The value of T_6' depends on the turbine flow rate, which in turn depends on the fuel added in the primary burner (B_{11}), which in turn depends on the temperature T_3'. Since the fuel flow is small as compared with the air flow, convergence is rapid. As a first estimate,

$$T_{3,\,est}' = T_2' + \frac{\eta_R}{2}\left(T_4' - T_2'\right) \tag{19}$$

where the primary burner exit temperature T_4' is a program input. The remainder of the recuperator analysis is presented later in proper sequence.

Burner. - The burners and turbines are analyzed in flow sequence. Gas entering the primary burner comes from the cold side of the recuperator, and gas entering any reheat burner comes from the turbine immediately upstream. In the general case, gas enters the burner with temperature $T_{B,\,in}'$, pressure $p_{B,\,in}'$, and mass flow rate $w_{B,\,in}$ having a composition corresponding to a fuel-air ratio of $f_{B,\,in}$. For the primary burner, $T_{B,\,in}' = T_3'$, $p_{B,\,in}' = p_3'$, $w_{B,\,in} = w_2$, and $f_{B,\,in} = 0$. Gas leaves the burner with temperature $T_{B,\,ex}'$, which is a program input, and pressure $p_{B,\,ex}'$, which is determined from the input value of pressure recovery r_B

$$p_{B,\,ex}' = p_{B,\,in}' r_B \tag{20}$$

and with flow

$$w_{B,\,ex} = w_{B,\,in} + w_{f,\,B} \tag{21}$$

where $w_{f,\,B}$ is the fuel flow added to this particular burner. The associated fuel-air ratio is

$$f_{B,\,ex} = \frac{w_{f,\,B,\,ex}}{w_{air,\,B}} = \frac{w_{f,\,B,\,in} + w_{f,\,B}}{w_{air,\,B}} = f_{B,\,in} + f_B \tag{22}$$

where $w_{f,\,B,\,in}$ is the amount of fuel added in previous burners and $w_{air,\,B}$ is the burner air flow (fraction of original inlet air that exists in the flow in this burner).

The fuel flow $w_{f,\,B}$ is found from a burner energy balance, which can be expressed with respect to a reference temperature T_r as

$$w_{f,B}H_f\left(T_r, T'_f\right) + \eta_B w_{f,B}\,\Delta h_{cb} + w_{B,in}H\left(T_r, T'_{B,in}, f_{B,in}\right) = w_{B,ex}H\left(T_r, T'_{B,ex}, f_{B,ex}\right) \tag{23}$$

The heat of combustion Δh_{cb} must be that at the reference temperature T_r and is a program input along with the burner efficiency η_B. The fuel enthalpy term H_f is a polynomial expression defined by equations (C2) and (C4) of appendix C. Fuel temperature T'_f is either the fuel inlet temperature $T'_{f,in}$ or the fuel-compressor exit temperature $T'_{f,C,ex}$ as obtained from equation (C8). The right-hand side (RHS) of equation (23) can be expressed in the form of equation (B9)

$$\mathrm{RHS} = w_{B,ex}\left(\frac{1}{1 + f_{B,ex} + m}\right)\left[(1 + m)H\left(T_r, T'_{B,ex}, 0\right) + f_{B,ex}I\left(T_r, T'_{B,ex}\right)\right] \tag{24}$$

Substituting for $f_{B,ex}$ from equation (22), equating the constant air flow in terms of inlet and exit conditions such that

$$w_{air,B} = \frac{w_{B,ex}}{1 + f_{B,ex} + m} = \frac{w_{B,in}}{1 + f_{B,in} + m} \tag{25}$$

and expressing $w_{f,B}$ as

$$w_{f,B} = f_B w_{air,B}$$

yield for equation (24)

$$\mathrm{RHS} = w_{B,in}\left(\frac{1}{1 + f_{B,in} + m}\right)\left[(1 + m)H\left(T_r, T'_{B,ex}, 0\right) + f_{B,in}I\left(T_r, T'_{B,ex}\right)\right] + w_{f,B}I\left(T_r, T'_{B,ex}\right) \tag{26}$$

In accordance with equation (B9), equation (26) can be expressed as

$$\mathrm{RHS} = w_{B,in}H\left(T_r, T'_{B,ex}, f_{B,in}\right) + w_{f,B}I\left(T_r, T'_{B,ex}\right) \tag{27}$$

Now, substituting equation (27) back into equation (23), combining terms, and rearranging yield

$$w_{f,B} = \frac{w_{B,in} H\left(T'_{B,in}, T'_{B,ex}, f_{B,in}\right)}{H_f\left(T_r, T'_f\right) + \eta_B \Delta h_{cb} - I\left(T_r, T'_{B,ex}\right)} \tag{28}$$

Turbine. - Flow into any turbine comes either from a burner or from another turbine. The exact nature of the turbine calculation depends on which shaft the turbine is on. For a multishaft system the drive power for all shafts other than the low-pressure shaft ($j \neq n_{sh}$) is

$$P_{T,j} = P_{C,j} K_P \tag{29}$$

where $P_{C,j}$ is obtained from equation (14) and K_P is a factor (program input) to allow for output power from the shaft. With the shaft power $P_{T,j}$ known, the power P_T for each turbine is obtained from program input. Turbine specific work is then determined as

$$\Delta h'_T = \frac{P_T}{w_{T,in}} \tag{30}$$

and turbine exit temperature from

$$H\left(T'_{T,ex}, T'_{T,in}, f_{T,in}\right) = \Delta h'_T \tag{31}$$

Either an overall efficiency $\eta_{T,o}$ or a polytropic efficiency $\eta_{T,p}$ can be specified for each turbine. With overall efficiency, the turbine ideal work is obtained as

$$\Delta h'_{T,id} = \frac{\Delta h'_T}{\eta_{T,o}} \tag{32}$$

and turbine ideal exit temperature from

$$H\left(T'_{T,ex,id}, T'_{T,in}, f_{T,in}\right) = \Delta h'_{T,id} \tag{33}$$

Turbine exit pressure is then

$$p'_{T,ex} = p'_{T,in} \exp\left[\frac{J}{R} \Phi\left(T'_{T,in}, T'_{T,ex,id}, f_{T,in}\right)\right] \tag{34}$$

With polytropic efficiency, turbine exit pressure is

$$p'_{T,ex} = p'_{T,in} \exp\left[\frac{J}{R\eta_{T,p}} \Phi\left(T'_{T,in}, T'_{T,ex}, f_{T,in}\right)\right] \tag{35}$$

For a single-shaft system and for the low-pressure shaft of a multishaft system, the pressure ratio across the shaft is determined from the last turbine exit pressure

$$p_5' = p_0\left(\frac{p_7'}{p_0}\right)\frac{1}{r_{R,\mathrm{hot}}r_D} \tag{36}$$

where the recuperator-exit total-to-static pressure ratio p_7'/p_0, the recuperator hot-side pressure recovery $r_{R,\mathrm{hot}}$, and the diffuser pressure recovery r_D are program inputs. The individual turbine inlet and exit pressures $p_{T,\mathrm{in}}'$ and $p_{T,\mathrm{ex}}'$ are then obtained from the input pressure ratio distribution. With polytropic efficiency specified, turbine exit temperature $T_{T,\mathrm{ex}}'$, specific work $\Delta h_T'$, and power P_T are determined from equations (35), (31), and (30), respectively. With overall efficiency specified, turbine specific work $\Delta h_T'$ is determined from equations (34), (33), and (32) in that order. Turbine exit temperature $T_{T,\mathrm{ex}}'$ and power P_T are then determined from equations (31) and (30), respectively.

For the analysis model, it is assumed that the coolant flow for each turbine bypasses that turbine and then mixes with the exit flow from that turbine. The coolant does not contribute to either turbine work or loss. To make any better assumption would require detailed turbine design information. If such were available, the turbine efficiency could be adjusted to account for effects of the coolant flow. It is assumed that the total pressure $p_{T,\mathrm{ex},m}'$ after mixing is equal to the turbine exit total pressure $p_{T,\mathrm{ex}}'$. The mixed total flow rate is equal to

$$w_{T,\mathrm{ex},m} = w_{T,\mathrm{in}} + w_{T,c} \tag{37}$$

and the air flow is

$$w_{\mathrm{air},T,\mathrm{ex},m} = w_{\mathrm{air},T,\mathrm{in}} + w_{T,c}\left(\frac{1}{1+m}\right) \tag{38}$$

The fuel-air ratio is then

$$f_{T,\mathrm{ex},m} = f_{T,\mathrm{in}}\left(\frac{w_{\mathrm{air},T,\mathrm{in}}}{w_{\mathrm{air},T,\mathrm{ex},m}}\right) \tag{39}$$

The total temperature $T_{T,\mathrm{ex},m}'$ after mixing is found from a heat balance for the mixing process:

$$w_{T,\mathrm{ex},m}H\left(T_c', T_{T,\mathrm{ex},m}', f_{T,\mathrm{ex},m}\right) = w_{T,\mathrm{in}}H\left(T_c', T_{T,\mathrm{ex}}', f_{T,\mathrm{in}}\right) \tag{40}$$

The coolant temperature T'_c is either the last-compressor exit temperature T'_2 or some input value.

Diffuser. - A diffuser is included in the system to allow for a loss when diffusing the high-velocity turbine-exit flow to the low velocity desired in the recuperator. The diffuser-exit total pressure is determined from the input value of pressure recovery r_D

$$p'_6 = p'_5 r_D \tag{41}$$

All other variables retain the same values as at the exit of the last turbine.

Recuperator. - The recuperator cold-side flow w_2 was defined by equation (17) and the cold-side exit pressure p'_3 by equation (18). The hot-side flow is the diffuser-exit flow w_6, and the hot-side exit total pressure p'_7 is determined by the input value of pressure recovery $r_{R,\,hot}$

$$p'_7 = p'_6 r_{R,\,hot} \tag{42}$$

The cold-side exit total temperature T'_3, which was initially estimated using equation (19), can now be computed using the recuperator effectiveness definition:

$$H\left(T'_2, T'_3, 0\right) = \eta_R H\left(T'_2, T'_6, 0\right) \tag{43}$$

If the computed value of T'_3 does not agree with the initial estimate or previously computed value, the calculation loops back to the primary burner for another iteration. After a satisfactory value of T'_3 is found, the hot-side exit total temperature is obtained from a recuperator heat balance:

$$w_6 H\left(T'_7, T'_6, f_6\right) = w_2 H\left(T'_2, T'_3, 0\right) \tag{44}$$

If there is a recuperator leakage flow, such as in a rotary recuperator, the recuperator hot-side exit throughflow mixes with the leakage to give an exit flow rate of

$$w_8 = w_7 + w_l \tag{45}$$

The mixed temperature T'_8 is then obtained from a heat balance for the mixing process:

$$w_8 H\left(T'_2, T'_8, f_8\right) = w_7 H\left(T'_2, T'_7, f_7\right) \tag{46}$$

Overall Performance

The net shaft output power is

$$P_{sh,net} = \sum_{j=1}^{n_{sh}} (P_{T,j} - P_{C,j}) - w_{f,tot}\,\Delta h'_{f,C} \tag{47}$$

where the fuel-compression specific work $\Delta h'_{f,C}$ is obtained from equation (C9). The net plant output power is

$$P_{net} = \eta_{cv} P_{sh,net} \tag{48}$$

where the conversion efficiency η_{cv} reflects a generator, gearbox, or other device.

The specific fuel consumption is

$$SFC = \frac{3600\ w_{f,tot}}{P_{net}} \tag{49}$$

and the cycle efficiency is

$$\eta_{cy} = \frac{P_{net}}{w_{f,tot}\,\Delta h_{cb}} \tag{50}$$

DESCRIPTION OF INPUT AND OUTPUT

This section presents a detailed description of the program input, normal output, and error messages. The input and corresponding printed output for an example power system are included for illustrative purposes.

Input

A general description of the program input is given and then followed by an illustrative example.

General input. - The data and option indicators are input in data records having the NAMELIST name INPUT. The variables and indicators that compose INPUT along with descriptions, units, and special remarks are presented in the list to follow. Either SI units or U.S. customary units may be used with this program. In this list the symbolism (X(J), J = 1, N) means that X is a singly subscripted variable having N values (X(1) to X(N)) to be entered into the program unless otherwise indicated. Similarly, the symbolism ((X(I, J), I = 1, N) I = 1, M) means that X is a doubly subscripted variable having N×M Values to be entered into the program unless otherwise indicated.

The single subscript refers to the shaft number. The first of the double subscripts refers to the component number on each shaft, and the second subscript refers to the shaft number. The order of subscripting is shown in figure 5(a). All subscripted variables are dimensioned to allow for a maximum value of 5 for each subscript.

Values for some of the variables in the input list are internally preset by the program before reading the input. These internally preset values are used by the program if alternate values are not specified by the input. Thus, if a preset value is appropriate, that particular variable does not have to be specified in the input. These internally preset values are shown in the input list that follows:

Variable	Description	Preset value
TS0	ambient temperature, K (°R)	518.7
PS0	ambient pressure, N/cm^2 (psia)	14.696
W	ambient air absolute humidity	0.0
R10	inlet total pressure recovery	1.0
NSHAFT	number of shafts	1
(NCOMP(J), J=1, NSHAFT)	number of compressors on each shaft	1 (for J=1 only)
((ETAC(I, J), I=1, NCOMP(J)) J=1, NSHAFT)	compressor efficiency (See IETAC and KPOLY. Only ETAC(1, 1) need be input if IETAC=0.)	---
IETAC	compressor efficiency value indicator: 0 - all ETAC(I, J)=ETAC(1, 1) 1 - each ETAC(I, J) must be input	0
KPOLY	compressor and turbine efficiency type indicator: 0 - overall (isentropic) efficiency 1 - polytropic efficiency	1
RCMIN	minimum value of overall compression ratio	---
RCDEL	increment in overall compression ratio	---
RCMAX	maximum value of overall compression ratio (Calculations made at increments of RCDEL for each compression ratio starting at RCMIN and ending at RCMAX.)	---

Variable	Description	Preset value
(RCSHSP(J), J=1, NSHAFT)	shaft compression ratio factor, fractional power of overall compression ratio (Sum of RCSHSP(J) must equal 1.0.)	1.0 (for J=1 only)
((RCCOSP(I, J), I=1, NCOMP(J)) J=1, NSHAFT)	compressor compression ratio factor for each shaft, fractional power of shaft compression ratio (Sum of RCCOSP(I, J) must equal 1.0 for each J.)	1.0 (for I=1, J=1 only)
((ICOOL(I, J), I=1, NCOMP(J)) J=1, NSHAFT)	intercooling indicator: 0 - no intercooling 1 - intercooling	0 (for all I, J)
((RINT(I, J), I=1, NCOMP(J)) J=1, NSHAFT)	intercooler total pressure recovery (Input only for those I, J having ICOOL(I, J)=1. See IRINT. Only RINT(1, 1) need be input if IRINT=0.)	---
IRINT	intercooler total pressure recovery value indicator: 0 - all RINT(I, J)=RINT(1, 1) 1 - each RINT(I, J) must be input	0
((TINT(I, J), I=1, NCOMP(J)) J=1, NSHAFT)	intercooler exit temperature, K (^{O}R) (Input only for those I, J having ICOOL(I, J)=1. See ITINT. Only TINT(1, 1) need be input if ITINT=0.)	---
ITINT	intercooler exit temperature value indicator: 0 - all TINT(I, J)=TINT(1, 1) 1 - each TINT(I, J) must be input	0
WLAOWA	recuperator leakage flow, fraction of inlet flow	0.0
(NTURB(J), J=1, NSHAFT)	number of turbines on each shaft	1 (for J=1 only)
((IBURN(I, J), I=1, NTURB(J)) J=1, NSHAFT)	reheating indicator: 0 - no reheating 1 - reheating	1 (for I=1, J=1 only) 0 (for all other I, J)

Variable	Description	Preset value
((ETAB(I, J), I=1, NTURB(J)) J=1, NSHAFT)	burner efficiency (Input only for those I, J having IBURN(I, J)=1. See IETAB. Only ETAB(1, 1) need be input if IETAB=0.)	---
IETAB	burner efficiency value indicator: 0 - all ETAB(I, J)=ETAB(1, 1) 1 - each ETAB(I, J) must be input	0
((RBURN(I, J), I=1, NTURB(J)) J=1, NSHAFT)	burner total pressure recovery (Input only for those I, J having IBURN(I, J)=1. See IRBURN. Only RBURN(1, 1) need be input if IRBURN=0.)	---
IRBURN	burner total pressure recovery value indicator: 0 - all RBURN(I, J)=RBURN(1, 1) 1 - each RBURN(I, J) must be input	0
((TTI(I, J), I=1, NTURB(J)) J=1, NSHAFT)	burner exit (turbine inlet) temperature, K ($^{\circ}$R) (Input only for those I, J having IBURN(I, J)=1. See ITTI. Only TTI(1, 1) need be input if ITTI=0.)	---
ITTI	burner exit temperature value indicator: 0 - all TTI(I, J)=TTI(1, 1) 1 - each TTI(I, J) must be input	0
HVF	lower heating value of fuel at temperature TR, J/kg (Btu/lb)	18 640.
TR	reference temperature for fuel heating value, K ($^{\circ}$R)	760.
HOC	mass ratio of hydrogen to carbon in fuel	0.16786
ITF	indicator for fuel temperature entering burner: 0 - fuel enters burner at temperature TR 1 - fuel enters burner at temperature TF $\geq$10 - fuel enters burner at temperature calculated from fuel compression work (Second digit indicates number of intercools back to TFIN during fuel compression. In this case fuel compression power is subtracted from gross shaft power output.)	0

le	Description	Preset value
	temperature of fuel entering burner K (^{o}R) (Input only when ITF=1.)	---
	constant A_f in fuel heat capacity equation (eq. (C1)), J/(kg)(K) (Btu/(lb)(^{o}R)) (Input only when ITF $>$ 0.)	---
BF	constant B_f in fuel heat capacity equation (eq. (C1)), J/(kg)(K^2) (Btu/(lb)($^{o}R^2$)) (Input only when ITF $>$ 0.)	---
CF	constant C_f in fuel heat capacity equation (eq. (C1)), J/(kg)(K^3) (Btu/(lb)($^{o}R^3$)) (Input only when ITF $>$ 0.)	---
TFIN	temperature of fuel entering fuel compressor, K (^{o}R) (Input only when ITF $\geq$ 10.)	---
PRFIN	ratio of pressure of fuel entering fuel compressor to ambient pressure (Input only when ITF $\geq$ 10.)	1.0
ETACF	fuel compressor polytropic efficiency (Input only when ITF $\geq$ 10.)	---
MWF	fuel molecular weight (Input only when ITF $\geq$ 10.)	---
((ETAT(I, J), I=1, NTURB(J)) J=1, NSHAFT)	turbine efficiency (See IETAT and KPOLY. Only ETAT(1, 1) need be input if IETAT = 0.)	---
IETAT	turbine efficiency value indicator: 0 - all ETAT(I, J)=ETAT(1, 1) 1 - each ETAT(I, J) must be input	0
(POWFAC(J), J=1, NSHAFT-1)	output power factor for all shafts other than low-pressure shaft (J=NSHAFT), ratio of total shaft power to compressor power (Not used when NSHAFT=1.)	1.0 (for all J)
((TSPLIT(I, J), I=1, NTURB(J)) J=1, NSHAFT)	turbine work factor for each shaft (For shafts other than low-pressure shaft, TSPLIT specifies power of each turbine as fraction of shaft power; for low-pressure shaft (J=NSHAFT), TSPLIT	1.0 (for I=1, J=1 only)

Variable	Description	Preset value
	specifies pressure ratio for each turbine as fractional power of shaft pressure ratio. Sum of TSPLIT(I, J) must equal 1.0 for each J.)	
((WCAOWA(I, J), I=1, NTURB(J)) J=1, NSHAFT)	turbine coolant flow, fraction of inlet flow	0.0 (for all I, J)
ITCOOL	turbine coolant temperature indicator: 0 - turbine coolant temperature equals last compressor exit temperature 1 - turbine coolant temperature equals input TCOOL	0
TCOOL	turbine coolant temperature, K (°R) (Input only when ITCOOL=1.)	---
R65	turbine exit diffuser total pressure recovery	1.0
ER	recuperator effectiveness	0.0
R32	recuperator cold-side total pressure recovery	1.0
R76	recuperator hot-side total pressure recovery	1.0
RSTEX	cycle exit static-to-total pressure ratio	1.0
ETAETA	shaft power conversion efficiency	1.0
TTOL	temperature tolerance for iterative calculations, K (°R)	0.1
KOUT	output indicator: 0 - output for each cycle point consists of overall performance only 1 - output for each cycle point consists of overall performance plus all internal temperatures, pressures, and flow rates	0
IU	units indicator: 1 - SI units 2 - U.S. customary units	2

Input data for NAMELIST input begins with a $ in the second location on a new line, immediately followed by the NAMELIST name, which is INPUT for this program, immediately followed by one or more blank characters. Any combination of three types of data items may then follow. The data items must be separated by commas. If more than one line is needed for the input data, the last item on each line, except the last line, must be a number followed by a comma. The first location on each line should always be left blank since it is ignored. The end of a group of data items is signaled by a $ anywhere except in the first location of a line. The form that data items may take is:

(1) Variable name = constant, where the variable name may be an array element or a simple variable name. Subscripts must be integer constants.

(2) Array name = set of constants separated by commas where k*constant may be used to represent k consecutive values of a constant. The number of constants must be equal to or less than the number of elements in the array. This results in the set of constants being placed in consecutive array elements, starting with the first element of the array.

(3) Subscripted variable = set of constants separated by commas where, again, k*constant may be used to represent k consecutive values of a constant. This results in the set of constants being placed in consecutive array elements, starting with the element designated by the subscripted variable.

Illustrative example. - The cycle being used as the illustrative example for input and output is shown in figure 6. It is a two-shaft recuperated system with four intercoolers and three reheaters. The arrangement of components along with the proper subscripts for each component are shown in figure 6. Also shown in the figure are all temperatures, pressures, flows, and component performance parameters required as program input. The fuel is a gas composed of 80 percent (by volume) methane and 20 percent ethane. The fuel properties required as program input are found in any appropriate reference book. It is desired to compute cycle thermodynamic performance for overall compression ratios of 5 to 100 in increments of 5.

The program input for this illustrative example is presented in table I. It is assumed that the user is familiar with the rules for NAMELIST input, some of which were presented previously, and with the order of array storage. A FORTRAN instruction or reference manual should be consulted for complete information of this type. Each line of the input form shown in table I represents one data card. The output corresponding to this sample input is described in the following section.

Output

The program output consists of a description of the input and the computed results. This section presents normal output. Error message output is described in the next section.

Table II presents the output that corresponds to the input shown in table I for the illustrative example. The first part of the output is the description of the input, which is in narrative form. The first line gives the number of shafts and the ambient temperature and pressure. The next line presents the inlet and diffuser pressure recoveries and the exit static-to-total pressure ratio. The third line gives the recuperator effectiveness and pressure recoveries. The next three lines present all the fuel-related input.

All input parameters associated with the intercoolers, compressors, burners, and turbines are then presented in shaft groupings. For each shaft the top line presents the shaft number, number of compressors, fraction of overall compression, and number of turbines. There is a line for each compressor, giving its fraction of shaft compression and its efficiency. If there is an intercooler preceding the compressor, there is a line of output preceding the compressor line and giving the intercooler exit temperature and pressure recovery. Then there is a line for each turbine on the shaft, giving the turbine power or expansion fraction and the turbine efficiency. If there is a burner preceding the turbine, there is a line of output preceding the turbine line and giving the burner exit temperature, efficiency, and pressure recovery. If the turbine is cooled, there is a line of output giving the amount of coolant flow. After this information is presented for each shaft, there is finally a line of output giving the shaft-power conversion efficiency and specifying the nature of the turbomachinery efficiencies.

After presentation of all the input information, the computed results are then printed. Since KOUT = 0 (preset value not altered by input), the computed results that are printed include the overall performance only. There is one line of results output for each compression ratio. The results output includes the compression ratio, specific power output (both in kW and hp), specific fuel consumption, cycle efficiency, and fuel-compression power.

If the input had specified that KOUT = 1, the results output would include all internal temperatures, pressures, and flow rates in addition to the overall performance. An example of this detailed output is shown in table III, which gives the results output for a compression ratio of 50. There is one line of output for each compressor and each turbine as well as for each side of the recuperator. The lines of output are in flow sequence. For the compressors and turbines, the shaft and component numbers are given, followed by a "NO" or "YES" to specify whether there is an intercooler preceding the compressor or a burner preceding the turbine. Then, the next five columns give the inlet flow, pressure, and temperature, and the exit pressure and temperature for each component. For the turbines the temperature and flow after coolant mixing are given in the next two columns. This same information is provided for mixing of any leakage flow in the recuperator. The last column gives the specific work for each compressor and turbine. The overall performance is presented to the right of the table of detailed output.

Error Messages

The program contains five output messages indicating the nonexistence of a solution satisfying the specified input requirements. These messages are presented in this section, and their causes are discussed.

(1) COMPRESSOR EXIT TEMP (XXXX.X) GREATER THAN TURBINE INLET TEMP (XXXX.X) - This message is caused by the computed exit temperature T_2' from the last compressor (C_{11}) being greater than the primary burner (B_{11}) exit temperature T_4'. It indicates that the overall compression ratio is too high and/or the burner exit temperature is too low. After the message is printed, the program calls for another data set.

(2) TURBINE-SYSTEM EXIT PRESSURE (XXX.XX) GREATER THAN TURBINE EXIT PRESSURE PTTO(I, J)=XXX.XX - This message is caused by the exit pressure for any turbine in the system being less than the available pressure p_5' at the last turbine exit. It indicates that the overall compression ratio is too low for the cycle to be self-sustaining in view of the compressor and turbine inefficiencies and the pressure losses in the other components. If the compression ratio is not particularly low, one of the input efficiencies or pressure recoveries could be excessively low. After the message is printed, the program increments the overall compression ratio to the next higher value and proceeds with the new calculation.

(3) RECUPERATOR HOT GAS INLET TEMP (XXXX.X) COLDER THAN COLD GAS INLET TEMP (XXXX.X) - This message is caused by the last turbine exit temperature T_5' being lower than the last compressor exit temperature T_2' with a recuperator in the system. It indicates that the overall compression ratio is too high to provide a temperature potential for recuperation. After the message is printed, the program calls for another data set.

(4) TURBINE POWER LESS THAN COMPRESSOR POWER ON SHAFT J - This message is caused by the turbine power for the low-pressure shaft (J=NSHAFT) being less than the power required to drive the compressors on that shaft. The basic causes for this condition are the same as for error message (2), as is the program operation sequence.

(5) OXYGEN USED UP IN BURNER I ON SHAFT J - This message is caused by the fuel-air ratio in the flow leaving a burner being greater than the stoichiometric fuel-air ratio. It indicates that all the oxygen in the inlet air was used up before all the required burning occurred. This can be caused by overall compression ratio being too low or burner-exit temperature being too high. After the message is printed, the program increments the overall compression ratio and proceeds with the new calculation.

PROGRAM DESCRIPTION

This computer program consists of main program MULTI, subroutine FUEL, and a set of combustion-gas thermodynamic-property subprograms containing the six functions CP, H, T2H, S, T2S, and HF and subroutine THERMO. The entire program is written in IBM 7090/7094 FORTRAN IV language. In this section, the functions of the main and subprograms are described, the program variables are defined, and the program listing is presented.

Main Program MULTI

Main program MULTI performs all input and output operations, all logic associated with the shaft and component arrangements, and all computations except those directly using the thermodynamic properties of the fuel and of the combustion gas.

Program variables. - The variables used in MULTI are defined as follows:

ABSBF	absolute value of BF
ABSCF	absolute value of CF
AF	constant A_f in eq. (C1)
BF	constant B_f in eq. (C1)
CF	constant C_f in eq. (C1)
DELHC(I, J)	compressor specific work
DELHF	fuel compression specific work
DELHIN(I, J)	intercooler heat removal per pound of flow
DELHSH(J)	sum of compressor specific work for shaft J
DELHT(I, J)	turbine specific work
DHID	turbine ideal specific work
DHL	recuperator leakage mixing heat balance term
DHM	turbine coolant mixing heat balance term
DHR	recuperator heat balance term
DLHC	overall sum of compressor specific work
ER	recuperator effectiveness
ETAB(I, J)	burner efficiency
ETAC(I, J)	compressor efficiency

ETACF	fuel compressor efficiency
ETACY	cycle efficiency
ETAETA	shaft power conversion efficiency
ETAT(I, J)	turbine efficiency
EXP1	data statement word EXPAN for output use
EXP2	data statement word SION for output use
FA	fuel-air ratio
FBOA(I, J)	fuel-air ratio addition in burner
FLPOKW	fuel compression power
FOATI(I, J)	fuel-air ratio at turbine inlet
FOATOM(I, J)	fuel-air ratio after turbine coolant mixing
FOA5	fuel-air ratio at station 5
FOA6	fuel-air ratio at station 6
FOA7	fuel-air ratio at station 7
FOA8	fuel-air ratio at station 8
FSTOIC	stoichiometric fuel-air ratio
FUELPO	fuel compression power
H	function defined by eq. (B7), see Combustion-Gas Thermodynamic Property Subprograms
HF	function defined by eq. (B10), see Combustion-Gas Thermodynamic Property Subprograms
HFF	fuel enthalpy relative to reference temperature
HOC	mass ratio of hydrogen to carbon in fuel
HVF	lower heating value of fuel
I	dummy index
IBURN(I, J)	reheating indicator, see Input section
IC	compressor number index
ICOOL(I, J)	intercooling indicator, see Input section
IETAB	burner efficiency value indicator, see Input section
IETAC	compressor efficiency value indicator, see Input section

IETAT	turbine efficiency value indicator, see Input section
IRBURN	burner total-pressure recovery value indicator, see Input section
IRINT	intercooler total-pressure recovery value indicator, see Input section
IS	shaft number index
IT	turbine number index
ITCOOL	turbine coolant temperature indicator, see Input section
ITF	burner-inlet fuel temperature indicator, see Input section
ITINT	intercooler-exit temperature value indicator, see Input section
ITTI	burner-exit temperature value indicator, see Input section
IU	units indicator, see Input section
J	dimensional constant
JJ	turbine number index for last turbine on shaft
JJJ	number of turbines on shaft number NSHAFT
KOUT	output indicator, see Input section
KPOLY	compressor and turbine efficiency indicator, see Input section
L	dummy index turbine number index
M	dummy index
MINUS	data statement word for minus sign for output use
MW	combustion-gas molecular weight function, eq. (B15)
MWF	fuel molecular weight
N	index for number of turbines on shaft
NCOMP(J)	number of compressors on each shaft
NS	number of shafts minus one
NSHAFT	number of shafts
NTURB(J)	number of turbines on each shaft
OFF	data statement word NO for output use
ON	data statement word YES for output use
OVHP	net output power
OVPOKW	net output power

PHP	data statement word HP for output use
PKW	data statement word KW for output use
PLUS	data statement word for plus sign for output use
PNC2	data statement word N/CM2 for output use
POWFAC(J)	shaft output power factor, see Input section
POWSH(J)	total power for each shaft except for shaft number NSHAFT
POWT(I, J)	shaft power for each turbine
POWTSH	total power for shaft number NSHAFT
POW1	data statement word POW for output use
POW2	data statement word ER for output use
PSI	data statement word PSIA for output use
PRFIN	ratio of fuel inlet pressure to ambient pressure
PRSH	total turbine expansion ratio for shaft number NSHAFT
PRT(I, J)	expansion ratio for each turbine on shaft number NSHAFT
PSC	value of function Φ in eq. (9) or (12)
PST	value of function Φ in eq. (34) or (35)
PS0	ambient pressure
PT	total pressure
PTCI(I, J)	compressor inlet total pressure
PTCO(I, J)	compressor exit total pressure
PTTI(I, J)	turbine inlet total pressure
PTTO(I, J)	turbine exit total pressure
PTTOM(I, J)	turbine exit total pressure after coolant mixing
PT0	total pressure at station 0
PT1	total pressure at station 1
PT2	total pressure at station 2
PT3	total pressure at station 3
PT5	total pressure at station 5
PT6	total pressure at station 6
PT7	total pressure at station 7

PT8	total pressure at station 8
QF	total heat input to cycle
R	gas constant
RBURN(I, J)	burner total pressure recovery
RBURNT	product of all RBURN(I, J) for shaft number NSHAFT
RC	overall compression ratio
RCCOSP(I, J)	compressor compression ratio factor for each shaft, see Input section
RCDEL	increment in overall compression ratio
RCMAX	maximum value of overall compression ratio
RCMIN	minimum value of overall compression ratio
RCOMP(I, J)	compression ratio for each compressor
RCSHFT(J)	compression ratio for each shaft
RCSHSP(J)	shaft compression ratio factor, see Input section
RINT(I, J)	intercooler total pressure recovery
RSTEX	cycle-exit static-to-total pressure ratio
R10	inlet total pressure recovery
R32	recuperator cold-side total pressure recovery
R65	diffuser total pressure recovery
R76	recuperator hot-side total pressure recovery
S	function defined by eq. (B12), see Combustion-Gas Thermodynamic Property Subprograms
SFC	specific fuel consumption
SHPOBT	net output shaft power
SIGNBF	output word set equal to PLUS or MINUS as appropriate
SIGNCF	output word set equal to PLUS or MINUS as appropriate
TCOOL	turbine coolant temperature
TEST	value used to test for maximum compression ratio
TF	temperature of fuel entering burner
TFIN	temperature of fuel entering fuel compressor
TINT(I, J)	intercooler-exit temperature

TPK	data statement word K for output use
TPK1	data statement word KELV for output use
TPK2	data statement word IN for output use
TPR	data statement word R for output use
TPR1	data statement word RANK for output use
TPR2	data statement word INE for output use
TR	reference temperature for fuel heating value
TSPLIT(I, J)	turbine work factor for each shaft, see Input section
TS0	ambient temperature
TT	total temperature
TTCI(I, J)	compressor-inlet total temperature
TTCO(I, J)	compressor-exit total temperature
TTCOID(I, J)	compressor-exit ideal total temperature
TTI(I, J)	burner-exit temperature
TTOL	temperature tolerance for iterative calculations
TTTI(I, J)	turbine-inlet total temperature
TTTO(I, J)	turbine-exit total temperature
TTTOID(I, J)	turbine-exit ideal total temperature
TTTOM(I, J)	turbine-exit total temperature after coolant mixing
TT0	total temperature at station 0
TT1	total temperature at station 1
TT2	total temperature at station 2
TT3	total temperature at station 3
TT3PRE	previous value of total temperature at station 3
TT5	total temperature at station 5
TT6	total temperature at station 6
TT7	total temperature at station 7
TT8	total temperature at station 8
TYPEF	output word set equal to TYPEFP or TYPEFI as appropriate
TYPEFP	data statement word POLY for output use

TYPEFI	data statement word ISEN for output use
T2H	temperature satisfying function H value, see Combustion-Gas Thermodynamic Property Subprograms
T2S	temperature satisfying function S value, see Combustion-Gas Thermodynamic Property Subprograms
W	ambient air absolute humidity
WAIRT	airflow rate
WAIR2	airflow rate at station 2
WAIR5	airflow rate at station 5
WAIR6	airflow rate at station 6
WAIR7	airflow rate at station 7
WAIR8	airflow rate at station 8
WARTOM(I, J)	airflow rate at turbine exit after coolant mixing
WBTU	data statement word BTU for output use
WCAOWA(I, J)	coolant flow fraction to each turbine
WCAWA	total coolant flow fraction
WF(I, J)	fuel flow rate to each burner
WFTOT	total fuel flow rate
WGM	data statement word GM for output use
WJLS	data statement word JLS for output use
WKG	data statement word KG for output use
WLAOWA	recuperator leakage flow fraction
WLB	data statement word LB for output use
WT	gas flow rate
WTI(I, J)	gas flow rate at turbine inlet
WTOM(I, J)	gas flow rate at turbine exit after coolant mixing
W0	gas flow rate at station 0
W1	gas flow rate at station 1
W2	gas flow rate at station 2
W3	gas flow rate at station 3

W5	gas flow rate at station 5
W6	gas flow rate at station 6
W7	gas flow rate at station 7
W8	gas flow rate at station 8
X1	output word set equal to POW1 or EXP1 as appropriate
X2	output word set equal to POW2 or EXP2 as appropriate
X3	output word set equal to TPR1 or TPK1 as appropriate
X4	output word set equal to TPR2 or TPK2 as appropriate
X5	output word set equal to TPR or TPK as appropriate
X6	output word set equal to PPSI or PNC2 as appropriate
X7	output word set equal to WLB or WKG as appropriate
X8	output word set equal to PHP or PKW as appropriate
X9	output word set equal to WLB or WGM as appropriate
X10	output word set equal to WBTU or WJLS as appropriate
YN	output word set equal to ON or OFF as appropriate

Program listing. - The FORTRAN listing for main program MULTI is as follows:

```
C
C     THERMODYNAMIC CYCLE ANALYSIS FOR MULTISHAFT POWER SYSTEM WITH
C     MULTIPLE INTERCOOLS AND REHEATS
C
      COMMON/CFUEL/AF,BF,CF,TFIN,TF,ETACF,ITF,RC,HFF,TR,DELHF,MWF,PRFIN
      COMMON HOC,TTOL,W
      REAL J,MW,MWF,MINUS
      DIMENSION WCAOWA(5,5),ICOOL(5,5),IBURN(5,5),RCCCSP(5,5),TSPLIT(5,5
     1),RBURN(5,5),TTCO(5,5),PTCO(5,5),TINT(5,5),TTCI(5,5),PTCI(5,5),
     2RINT(5,5),DELHIN(5,5),RCOMP(5,5),TTCOID(5,5),DELHC(5,5),ETAC(5,5),
     3TTI(5,5),TTTOM(5,5),PTTOM(5,5),WTOM(5,5),WARTOM(5,5),FOATOM(5,5),
     4PTTI(5,5),TTTI(5,5),FBOA(5,5),ETAB(5,5),FOATI(5,5),WF(5,5),WTI(5,5
     5),POWT(5,5),DELHT(5,5),ETAT(5,5),TTTOID(5,5),PTTO(5,5),PRT(5,5),
     6TTTO(5,5),POWFAC(5),NCOMP(5),NTURB(5),RCSHSP(5),RCSHFT(5),DELHSH(5
     7),POWSH(5)
C
      NAMELIST/INPUT/TSO,PSO,R10,ETAC,WCAOWA,ER,R32,HVF,TR,ETAB,RINT,
     1RBURN,TTI,ETAT,ETAETA,W,ICOOL,IBURN,ITCOOL,IETAC,IETAT,IETAB,
     2POWFAC,NSHAFT,NCOMP,NTURB,RCSHSP,RCCOSP,TSPLIT.ITTI,ITINT,HOC,R65,
     3R76,TTOL,TINT,RCMIN,RCDEL,RCMAX,TCOOL,TF,AF,BF,CF,ETACF,MWF,TFIN,
     4IRBURN,IRINT,ITF,KOUT,KPOLY,WLACWA,PRFIN,RSTEX,IU
      MW(F)=(1.0+F+W)/(.034522+(F/(1.0+HOC))*(.24802*HOC)+W/18.016)
      R(F)=1545./MW(F)
      DATA PLUS,MINUS/1H+,1H-/
      DATA POW1,POW2,EXP1,EXP2/5H  POW,5HER   ,5HEXPAN,5HSION /
      DATA TYPEFP,TYPEFI/5H POLY,5H ISEN/
```

```
      DATA ON,OFF/5H   YES,5H    NO/
      DATA TPR1,TPR2,TPK1,TPK2,TPR,TPK/4HRANK,3HINE,4HKELV,3HIN ,1HR,1HK
     1/,WGM,WBTU,WJLS/2HGM,3HBTU,3HJLS/
      DATA PPSI,PNC2/6H PSIA ,6H N/CM2/
      DATA WLB,WKG/2HLB,2HKG/,PHP,PKW/2HHP,2HKW/
C
C     INITIALIZATION
C
      TS0=518.7
      PS0=14.696
      W=0.0
      ETAETA=1.0
      R10=1.
      DO 72 L=1,5
      DO 71 M=1,5
      WCAOWA(L,M)=0.0
      ICOOL(L,M)=0
   71 IBURN(L,M)= 0
   72 POWFAC(L)=1.0
      NSHAFT=1
      NCOMP(1)= 1
      NTURB(1)= 1
      RCSHSP(1)=1.
      RCCOSP(1,1)= 1.
      TSPLIT(1,1)= 1.
      IBURN(1,1)= 1
      ITTI=0
      ITINT=0
      ITCOOL=0
      IETAC=0
      IETAT=0
      IETAB=0
      IRINT=0
      IRBURN=0
      KOUT=0
      KPOLY=1
      WLAOWA=0.0
      ITF=0
      ER=0.0
      R32=1.
      HOC=.16786
      HVF=18640.
      TR=760.
      PRFIN=1.0
      R65=1.
      R76=1.
      RSTEX=1.
      IU=2
      J=778.
      TTOL=.1
    1 IF(IU.EQ.2) GO TO 73
      TS0=TS0/1.8
      DO 76 I=1,NSHAFT
      II=NCOMP(I)
      DO 74 L=1,II
   74 TINT(L,I)=TINT(L,I)/1.8
      IJ=NTURB(I)
      DO 75 L=1,IJ
   75 TTI(L,I)=TTI(L,I)/1.8
```

```
   76 CONTINUE
      HVF=HVF*1055.87/.45359237
      TR=TR/1.8
      TF=TF/1.8
      AF=AF*1055.87/.45359237*1.8
      BF=BF*1055.87/.45359237*1.8*1.8
      CF=CF*1055.87/.45359237*1.8*1.8*1.8
      IF(ITF.GE.10) TFIN=TFIN/1.8
      IF(ITCOOL.EQ.1) TCOOL=TCOOL/1.8
   73 READ (5,INPUT)
      X3=TPR1
      X4=TPR2
      X5=TPR
      X6=PPSI
      X7=WLB
      X8=PHP
      X9= WLB
      X10= WBTU
      IF(IU.EQ.2) GO TO 7
      X3=TPK1
      X4=TPK2
      X5=TPK
      X6=PNC2
      X7=WKG
      X8=PKW
      X9= WGM
      X10= WJLS
    7 TEST=RCMAX+.1*RCDEL
      FSTOIC=.2314*(1.+HOC)/(2.6644+7.9365*HOC)
      IF(ITF.EQ.0) TF=TR
      JJJ=NTURB(NSHAFT)
      WCAWA=0.0
      RBURNT=1.0
      DO 13 M=1,NSHAFT
      L=NCOMP(M)
      IF(L.EQ.0) GO TO 12
      DO 11 I=1,L
      IF(ICOOL(I,M).EQ.0) GO TO 11
      IF(ITINT.EQ.0) TINT(I,M)=TINT(1,1)
      IF(IRINT.EQ.0) RINT(I,M)=RINT(1,1)
   11 IF(IETAC.EQ.0) ETAC(I,M)=ETAC(1,1)
   12 N=NTURB(M)
      DO 13 I=1,N
      WCAWA=WCAWA+WCAOWA(I,M)
      IF(IBURN(I,M).EQ.0) GO TO 13
      IF(IETAB.EQ.0) ETAB(I,M)=ETAB(1,1)
      IF(IRBURN.EQ.0) RBURN(I,M)=RBURN(1,1)
      IF(M.EQ.NSHAFT) RBURNT=RBURNT*RBURN(I,M)
      IF(ITTI.EQ.0) TTI(I,M)=TTI(1,1)
   13 IF(IETAT.EQ.0) ETAT(I,M)=ETAT(1,1)
C
C     WRITE INPUT VALUES
C
      WRITE (6,1000) NSHAFT,TS0,X3,X4,PS0,X6,R10,R65,
     1RSTEX,FR,R32,R76,WLAOWA,HVF,TR,X3,X4,HOC
 1000 FORMAT(1H1,I1,54H-SHAFT POWER SYSTEM OPERATING AT AMBIENT CONDITIO
     1NS OF,F8.2,5H DEG ,A4,A3,4H AND,F8.3,A6/   31H INLET TOTAL PRESSU
     2RE RECOVERY=,F5.3,54H,     TURBINE EXHAUST DIFFUSER TOTAL PRESSURE
     3RECOVERY=,F5.3,29H,  EXIT STAT/TOT PRESS RATIO=,F5.3,
```

```
     3               /27H RECUPERATOR EFFECTIVENESS= ,F5.3,36H, COLD SIDE
     4TOTAL PRESSURE RECOVERY=,F5.3,35H, HOT SIDE TOTAL PRESSURE RECOVER
     5Y=,F5.3,14H, BYPASS FLOW=,F6.4
     5/20H FUEL HEATING VALUE=,F9.0,3H AT,F6.0,5H DEG ,A4,A3,     12H, H
     6/C RATIO=,F7.5)
      IF(ITF.GE.10) GO TO 42
   41 WRITE (6,1010) TF,X3,X4
 1010 FORMAT(1H+,65X,23H, FUEL ENTERS BURNER AT,F6.0,5H DEG ,A4,A3/)
      IF(ITF.EQ.0) GO TO 43
   42 SIGNBF=PLUS
      SIGNCF=MINUS
      IF(BF.LT.0.0) SIGNBF=MINUS
      IF(CF.GE.0.0) SIGNCF=PLUS
      ABSBF=ABS(BF)
      ABSCF=ABS(CF)
      WRITE (6,1020) AF,SIGNBF,ABSBF,SIGNCF,ABSCF
 1020 FORMAT(13H FUEL GAS CP=,F9.4,1X,A1,1PE11.4,5H * T ,A1,E11.4, 7H *
     1T**2)
      IF(ITF.LT.10) GO TO 43
      WRITE (6,1021) MWF,TFIN,PRFIN,ETACF
 1021 FORMAT(                                                       14H
     1 FUEL MOL WGT=,0PF7.3, 17H FUEL INLET TEMP=,F5.0,25H, FUEL INLET C
     2OMPRESSION=,F5.1,24H, FUEL COMPRESSION EFF.=,F5.3)
   43 DO 50 I=1,NSHAFT
      IS=NSHAFT+1-I
      L=NCOMP(IS)
      M=NTURB(IS)
      WRITE (6,1030) IS,L,RCSHSP(IS),M
 1030 FORMAT(7H0SHAFT ,I1,5H HAS ,I1,24H COMPRESSORS THAT SUPPLY,F7.4,26
     1H OF TOTAL COMPRESSION AND ,I1,9H TURBINES)
      IF(IS.LT.NSHAFT) WRITE (6,1040) POWFAC(IS)
 1040 FORMAT(1H+,81X,12HTHAT DELIVER,F7.4,25H * COMPRESSOR SHAFT POWER)
      IF(L.EQ.0) GO TO 46
      DO 45 LL=1,L
      IC=L+1-LL
      WRITE (6,1050)
 1050 FORMAT(1H )
      IF(ICOOL(IC,IS).NE.0)WRITE(6,1060)IC,TINT(IC,IS),X3,X4,RINT(IC,IS)
 1060 FORMAT(6X,24HFLOW ENTERING COMPRESSOR,I2,13H IS COOLED TO,F6.0,5H
     1DEG ,A4,A3,30H WITH TOTAL PRESSURE RECOVERY=,F5.3)
   45 WRITE (6,1070) IC,RCCOSP(IC,IS),ETAC(IC,IS)
 1070 FORMAT(6X,10HCOMPRESSOR,I2,9H PROVIDES,F7.4,38H OF SHAFT COMPRESSI
     1ON WITH EFFICIENCY=,F5.3)
   46 DO 50 IT=1,M
      WRITE (6,1050)
      IF(IBURN(IT,IS).NE.0)WRITE(6,1080)IT,TTI(IT,IS),X3,X4,ETAB(IT,IS),
     1RBURN(IT,IS)
 1080 FORMAT(6X,21HFLOW ENTERING TURBINE,I2,13H IS HEATED TO,F7.1,5H DEG
     1 ,A4,A3,29H WITH COMBUSTION EFFICIENCY =,F5.3,29H AND TOTAL PRESSU
     2RE RECOVERY=,F5.3)
      IF(IS-NSHAFT) 47,48,48
   47 X1=POW1
      X2=POW2
      GO TO 49
   48 X1=EXP1
      X2=EXP2
   49 WRITE (6,1090) IT,TSPLIT(IT,IS),X1,X2,ETAT(IT,IS)
 1090 FORMAT(6X,7HTURBINE,I2,9H PROVIDES,F7.4,10H OF SHAFT ,2A5,16HWITH
     1EFFICIENCY=,F5.3)
```

```
      IF(WCAOWA(IT,IS).EQ.0.0) GO TO 50
      WRITE (6,1100) IT,WCAOWA(IT,IS)
 1100 FORMAT(6X,7HTURBINE,I2,15H IS COOLED WITH,F7.4,24H OF COMPRESSOR E
     1XIT FLOW)
      IF(ITCOOL.NE.0) WRITE (6,1110) TCOOL,X3,X4
 1110 FORMAT(1H+,61X,9HCOOLED TO,F7.1,5H DEG ,A4,A3)
   50 CONTINUE
      TYPEF=TYPEFP
      IF(KPOLY.EQ.0) TYPEF=TYPEFI
      WRITE (6,1120) ETAETA,TYPEF
 1120 FORMAT(20H0OUTPUT POWER EQUALS,F7.4,15H OF SHAFT POWER,20X,31HTURB
     1OMACHINERY EFFICIENCIES ARE,A5,6HTROPIC)
      IF(KOUT.EQ.0) WRITE(6,2000) X7,X7,X8
 2000 FORMAT(8H1 PRESS.,6X,3HNET,8X,3HNET,8X,4HFUEL,7X,5HCYCLE,6X,4HFUEL
     1,18X,18HPOWER VALUES REFER /7H  RATIO,6X,5HPOWER,6X,5HPOWER,5X,8HC
     2ONSUMP.,6X,3HEFF,6X,5HPOWER,18X,7HTO ONE ,A2,8H PER SEC/14X,2HKW,9
     3X,2HHP,7X,A2,4H/HR/,A2,17X,2HKW,19X,17HOF INLET AIR FLOW)
      IF(IU.EQ.2) GO TO 16
      TSO=TSO*1.8
   17 DO 36 I=1,NSHAFT
      II=NCOMP(I)
      DO 21 L=1,II
   21 TINT(L,I)=TINT(L,I)*1.8
      IJ=NTURB(I)
      DO 37 L=1,IJ
   37 TTI(L,I)=TTI(L,I)*1.8
   36 CONTINUE
      HVF=HVF/1055.87*.45359237
      TR=TR*1.8
      TF=TF*1.8
      AF=AF/1055.87*.45359237/1.8
      BF=BF/1055.87*.45359237/1.8/1.8
      CF= CF/1055.87*.45359237/1.8/1.8/1.8
      IF(ITF.GE.10)  TFIN= TFIN*1.8
      IF(ITCOOL.EQ.1)  TCOOL=TCOOL*1.8
C
C     INLET CONDITIONS
C
   16 TTO= TSO
      PTO=PSO
      WO=1.+W
C
C     INLET
C
    5 TT1=TTO
      PT1=PTO*R10
      W1=WO
      RC=RCMIN
    6 CONTINUE
      DLHC=0.0
      CALL FUEL
C
C     START INTERCOOLER-COMPRESSOR LOOP
C
      DO 150 I=1,NSHAFT
      IS= NSHAFT+1-I
      RCSHFT(IS)= RC**RCSHSP(IS)
      DELHSH(IS)=0.0
      IF(I-1) 2,2,3
```

```
    2 TT=TT1
      PT=PT1
      GO TO 4
    3 TT=TTCO(1,IS+1)
      PT= PTCO(1,IS+1)
    4 L=NCOMP(IS)
      IF(L.EQ.0) GO TO 141
      DO 140 M=1,L
      IC=L+1-M
      IF(M.EQ.1) GO TO 131
      TT= TTCO(IC+1,IS)
      PT=PTCO(IC+1,IS)
C
C     INTERCOOLER
C
  131 IF(ICOOL(IC,IS).EQ.0) GO TO 132
      TTCI(IC,IS)= TINT(IC,IS)
      PTCI(IC,IS)= PT*RINT(IC,IS)
      DELHIN(IC,IS)= H(TTCI(IC,IS),TT,0.0)
      GO TO 133
  132 TTCI(IC,IS)= TT
      PTCI(IC,IS)= PT
      DELHIN(IC,IS)=0.0
C
C     COMPRESSOR
C
  133 RCOMP(IC,IS)=RCSHFT(IS)**RCCOSP(IC,IS)
      PTCO(IC,IS)= PTCI(IC,IS)*RCOMP(IC,IS)
      PSC=R(0.0)/J*ALOG(RCOMP(IC,IS))
      IF(KPOLY.EQ.1) GO TO 134
      TTCOID(IC,IS)=T2S(TTCI(IC,IS),0.0,PSC)
      DELHC(IC,IS)=H(TTCI(IC,IS),TTCOID(IC,IS),0.0)/ETAC(IC,IS)
      TTCO(IC,IS)=T2H(TTCI(IC,IS),0.0,DELHC(IC,IS))
      GO TO 140
  134 PSC=PSC/ETAC(IC,IS)
      TTCO(IC,IS)=T2S(TTCI(IC,IS),0.0,PSC)
      DELHC(IC,IS)=H(TTCI(IC,IS),TTCO(IC,IS),0.0)
  140 DELHSH(IS)= DELHSH(IS)+DELHC(IC,IS)
      GO TO 150
  141 TTCO(1,IS)=TT
      PTCO(1,IS)=PT
  150 DLHC=DLHC+DELHSH(IS)
      TT2=TTCO(1,1)
      IF(ITCOOL.EQ.0) TCOOL=TT2
      IF(TT2.GT.TTI(1,1)) GO TO 100
      PT2=PTCO(1,1)
C
C     BYPASS AIR
C
      W2=W1*(1.-WCAWA-WLAOWA)
      WAIR2=W2/W1
C
C     RECUPERATOR - INITIAL ESTIMATE MADE FOR TT3
C
      PT3=R32*PT2
      W3=W2
      TT3=TT2+ER*(TT4-TT2)/2.
      PT5=PSC/R76/R65/RSTEX
C
```

```
C     START BURNER-TURBINE LOOP
C
  161 WFTOT=0.0
      POWTSH= 0.0
      DO 170 IS=1,NSHAFT
      POWSH(IS)= W1*DELHSH(IS)*POWFAC(IS)
      IF(IS-1) 171,171,172
  171 TT=TT3
      PT=PT3
      WT=W3
      WAIRT=WAIP2
      FA=0.0
      GO TO 173
  172 JJ=NTURB(IS-1)
      TT= TTTOM(JJ,IS-1)
      PT=PTTOM(JJ,IS-1)
      WT=WTOM(JJ,IS-1)
      WAIRT=WARTOM(JJ,IS-1)
      FA=FOATOM(JJ,IS-1)
  173 L=NTURB(IS)
      IF(IS.EQ.NSHAFT) PRSH=PT/PT5*RBURNT
      DO 180 IT=1,L
      IF(IT.EQ.1) GO TO 174
      TT=TTTOM(IT-1,IS)
      PT=PTTOM(IT-1,IS)
      WT=WTOM(IT-1,IS)
      WAIRT=WARTOM(IT-1,IS)
      FA= FOATOM(IT-1,IS)
  174 IF(IBURN(IT,IS).EQ.0) GO TO 175
C
C     BURNER
C
      PTTI(IT,IS)= PT*RBURN(IT,IS)
      TTTI(IT,IS)= TTI(IT,IS)
      FBOA(IT,IS)=(1.+FA+W)*H(TT,TTTI(IT,IS),FA)/(ETAB(IT,IS)*HVF-HF(TR,
     1TTTI(IT,IS))+HFF)
      GO TO 176
  175 PTTI(IT,IS)=PT
      TTTI(IT,IS)=TT
      FBOA(IT,IS)= 0.0
  176 FOATI(IT,IS)= FA+FBOA(IT,IS)
      IF(FOATI(IT,IS).GT.FSTOIC) GO TO 500
      WF(IT,IS)=FBOA(IT,IS)*WAIRT
      WTI(IT,IS)=WT+WF(IT,IS)
      WFTOT=WFTOT+WF(IT,IS)
C
C     TURBINE
C
      IF(IS.EQ.NSHAFT) GO TO 178
      POWT(IT,IS)= POWSH(IS)*TSPLIT(IT,IS)
      DELHT(IT,IS)=POWT(IT,IS)/WTI(IT,IS)
      TTTO(IT,IS)=T2H(TTTI(IT,IS),FOATI(IT,IS),-DELHT(IT,IS))
      IF(KPOLY.EQ.1) GO TO 177
      DHID=DELHT(IT,IS)/ETAT(IT,IS)
      TTTOID(IT,IS)= T2H(TTTI(IT,IS),FOATI(IT,IS),-DHID)
      PTTO(IT,IS)=PTTI(IT,IS)*EXP(J/R(FOATI(IT,IS))*S(TTTI(IT,IS),
     1TTTOID(IT,IS),FOATI(IT,IS)))
      GO TO 182
  177 PTTO(IT,IS)=PTTI(IT,IS)*EXP(J/R(FOATI(IT,IS))/ETAT(IT,IS)*
```

```
     1S(TTTI(IT,IS),TTTO(IT,IS),FOATI(IT,IS)))
      GO TO 182
  178 PRT(IT,IS)= PRSH**TSPLIT(IT,IS)
      PST=R(FOATI(IT,IS))/J*ALOG(1./PRT(IT,IS))
      PTTO(IT,IS)= PTTI(IT,IS)/PRT(IT,IS)
      IF(KPOLY.EQ.1) GO TO 179
      TTTOID(IT,IS)=T2S(TTTI(IT,IS),FOATI(IT,IS),PST)
      DELHT(IT,IS)=ETAT(IT,IS)*H(TTTOID(IT,IS),TTTI(IT,IS),FOATI(IT,IS))
      TTTO(IT,IS)=T2H(TTTI(IT,IS),FOATI(IT,IS),-DELHT(IT,IS))
      GO TO 181
  179 PST=PST*ETAT(IT,IS)
      TTTO(IT,IS)=T2S(TTTI(IT,IS),FOATI(IT,IS),PST)
      DELHT(IT,IS)=H(TTTO(IT,IS),TTTI(IT,IS),FOATI(IT,IS))
  181 POWT(IT,IS)= WTI(IT,IS)*DELHT(IT,IS)
      POWTSH=POWTSH+POWT(IT,IS)
C
C     COOLANT MIXING
C
  182 PTTOM(IT,IS)= PTTO(IT,IS)
      IF(PTTO(IT,IS).LT.PT5*.9999) GO TO 200
      WTOM(IT,IS)= WTI(IT,IS)+W1*WCAOWA(IT,IS)
      WARTOM(IT,IS)= WAIRT+WCAOWA(IT,IS)
      FOATOM(IT,IS)= FOATI(IT,IS)*WAIRT/WARTOM(IT,IS)
      IF(WCAOWA(IT,IS).EQ.0.0) GO TO 183
      DHM=WTI(IT,IS)/WTOM(IT,IS)*H(TCOOL,TTTO(IT,IS),FOATI(IT,IS))
      TTTOM(IT,IS)=T2H(TCOOL,FOATOM(IT,IS),DHM)
      GO TO 180
  183 TTTOM(IT,IS)= TTTO(IT,IS)
  180 CONTINUE
  170 CONTINUE
      IF(POWTSH.LT.W1*DELHSH(NSHAFT)) GO TO 400
      TT5=TTTOM(JJJ,NSHAFT)
      PT5= PTTOM(JJJ,NSHAFT)
      W5=WTOM(JJJ,NSHAFT)
      FOA5=FOATOM(JJJ,NSHAFT)
      WAIR5=WARTOM(JJJ,NSHAFT)
C
C     RECOVERY DIFFUSER
C
      TT6=TT5
      PT6=PT5*R65
      FOA6=FOA5
      W6=W5
      WAIR6=WAIR5
C
C     RECUPERATOR
C
      IF(ER.EQ.0.0) GO TO 24
      IF(TT6.LT.TT2) GO TO 300
      DHR=ER*H(TT2,TT6,0.0)
      TT3PRE=TT3
      TT3=T2H(TT2,0.0,DHR)
      IF(ABS(TT3-TT3PRE).GT.TTOL) GO TO 161
      TT7=T2H(TT6,FOA6,-W2/W6*DHR)
      GO TO 25
   24 TT7=TT6
   25 W7=W6
      FOA7=FOA6
      WAIR7=WAIR6
```

```
      PT7=PT6*R76
C
C     LEAKAGE MIXING
C
      PT8=PT7
      W8=W7+W1*WLAOWA
      WAIR8=WAIR7+WLAOWA
      FOA8=FOA7*WAIR7/WAIR8
      IF(WLAOWA.EQ.0.0) GO TO 27
      DHL=H(TT2,TT7,FOA7)
      TT8=T2H(TT2,FOA8,W7/W8*DHL)
      GO TO 31
   27 TT8=TT7
C
C     PERFORMANCE PARAMETERS
C
   31 SHPOBT=0.0
      IF(NSHAFT.EQ.1) GO TO 33
      NS=NSHAFT-1
      DO 32 I=1,NS
   32 SHPOBT=SHPOBT+POWSH(I)*(1.-1./POWFAC(I))
   33 SHPOBT=SHPOBT+POWTSH-W1*DELHSH(NSHAFT)
      IF(ITF.LT.10) GO TO 34
      FUELPO=WFTOT*DELHF
      SHPOBT=SHPOBT-FUELPO
      FLPOKW=FUELPO*1.0542
      GO TO 35
   34 FLPOKW=0.0
   35 OVPOKW=SHPOBT*1.0542*ETAETA
      OVHP=SHPOBT*1.4145*ETAETA
      SFC=WFTOT*3600./OVHP
      QF=WFTOT*HVF
      ETACY=SHPOBT/QF*ETAETA
      IF(IU.EQ.2)  GO TO 59
      OVPOKW= OVPOKW/.45359237
      OVHP= OVHP/.45359237
      SFC= WFTOT*3600./OVPOKW
      FLPOKW= FLPOKW/.45359237
C
C     WRITE OUTPUT
C
   59 IF(KOUT.EQ.1)  GO TO 190
      WRITE (6,2010) RC,OVPOKW,OVHP,SFC,ETACY,FLPOKW
 2010 FORMAT(1X,F7.2,2F11.2,3F11.4)
      GO TO 600
  190 CONTINUE
      IF(RC.EQ.FCMIN) WRITE (6,3000)
 3000 FORMAT (1H1)
      WRITE(6,3010) OVPOKW,X7,RC,X10,OVHP,X7,X6,X5,X6,X5,X5,X9,SFC,X7,X8
 3010 FORMAT (114HOPRESSURE RATIO     COOL     INLET     INLET     INLET    E
     1XIT     EXIT        MIX        MIX        WORK           NET POWER=,F7.2,
     24H KW/,A2,4H AIR/F11.2,9X,68HOR       FLOW      PRESS     TEMP      PRES
     3S     TEMP      TEMP      FLOW      ,A3,4H PER,18X,1H=,F7.2,4H HP/,A2,4
     4H AIR/19X,4HBURN,11X,A6,4X,4HDEG ,A1,3X,A6,4X,4HDEG ,A1,4X,4HDEG ,
     5A1,12X,A2,5H FLOW,9X,10HFUEL CONS=,F7.4,1X,A2,4H/HP/,A2),
      K=1
      DO 310 I=1,NSHAFT
      IS=NSHAFT+1-I
      L=NCOMP(IS)
```

```
      IF(L.EQ.0) GO TO 310
      DO 308 M=1,L
      IC=L+1-M
      IF(IU.EQ.2)  GO TO 191
      TTCI(IC,IS)= TTCI(IC,IS)/1.8
      TTCO(IC,IS)= TTCO(IC,IS)/1.8
      DELHC(IC,IS)= DELHC(IC,IS)*1055.87/453.59237
  191 YN= OFF
      IF(ICOOL(IC,IS).NE.0) YN=ON
      WRITE (6,3020) IS,IC,YN,W1,PTCI(IC,IS),TTCI(IC,IS),PTCO(IC,IS),
     1TTCO(IC,IS),DELHC(IC,IS)
 3020 FORMAT(6H SHAFT,I2,7H - COMP,I2,A5,F9.4,4F9.1,21X,F7.2)
      IF(K.EQ.1) WRITE (6,3021) ETACY
 3021 FORMAT(1H+,103X,10HCYCLE EFF=,F7.4)
      IF(K.EQ.2)  WRITE(6,3022) FLPOKW,X7
 3022 FORMAT(1H+,103X,10HFUEL POWR=,F7.4,4H KW/,A2,4H AIR)
      K=K+1
  308 CONTINUE
  310 CONTINUE
      IF(IU.EQ.2)  GO TO 311
      TT2= TT2/1.8
      TT3= TT3/1.8
  311 WRITE(6,3030) W2,PT2,TT2,PT3,TT3
 3030 FORMAT(12H RECUPERATOR,10X,F9.4,4F9.1)
      IF(K.EQ.2)  WRITE(6,3022) FLPOKW,X7
      DO 320 IS=1,NSHAFT
      L=NTURB(IS)
      DO 320 IT=1,L
      IF(IU.EQ.2)  GO TO 312
      TTTI(IT,IS)= TTTI(IT,IS)/1.8
      TTTO(IT,IS)= TTTO(IT,IS)/1.8
      TTTOM(IT,IS)= TTTOM(IT,IS)/1.8
      DELHT(IT,IS)= DELHT(IT,IS)*1055.87/453.59237
  312 YN= OFF
      IF(IBURN(IT,IS).NE.0) YN=ON
  320 WRITE (6,3040) IS,IT,YN,WTI(IT,IS),PTTI(IT,IS),TTTI(IT,IS),PTTO(IT
     1,IS),TTTO(IT,IS),TTTOM(IT,IS),WTOM(IT,IS),DELHT(IT,IS)
 3040 FORMAT(6H SHAFT,I2,7H - TURB,I2,A5,F9.4,5F9.1,F9.4,F10.2)
      IF(IU.EQ.2)  GO TO 313
      TT6 = TT6/1.8
      TT7= TT7/1.8
      TT8= TT8/1.8
  313 WRITE(6,3050)  W6,PT6,TT6,PT7,TT7,TT8,W8
 3050 FORMAT(12H RECUPERATOR,10X,F9.4,5F9.1,F9.4//)
      GO TO 600
  100 IF(IU.EQ.1)  TT2= TT2/1.8
      IF(IU.EQ.1)  TTI(1,1)= TTI(1,1)/1.8
      WRITE(6,5000)  RC,TT2,TTI(1,1)
 5000 FORMAT(1X,F7.2,4X,
     1             22HCOMPRESSOR EXIT TEMP (,F6.1,35H) GREATER THAN TURBIN
     1E INLET TEMP (,F6.1,1H))
      IF(IU.EQ.1)  TTI(1,1)= TTI(1,1)*1.8
      GO TO 1
  200 WRITE (6,6000) RC,PT5,IT,IS,PTTO(IT,IS)
 6000 FORMAT(1X,F7.2,4X,30HTURBINE-SYSTEM EXIT PRESSURE (,F6.2,42H) GREA
     1TER THAN TURBINE EXIT PRESSURE PTTO(,I1,1H,,I1,2H)=,F6.2)
      GO TO 600
  300 IF(IU.EQ.1)  TT6= TT6/1.8
      IF(IU.EQ.1)  TT2= TT2/1.8
```

```
      WRITE (6,7000) RC,TT6,TT2
 7000 FORMAT(1X,F7.2,4X,
     1             32HRECUPERATOR HOT GAS INLET TEMP (,F6.1,35H) COLDER TH
     1AN COLD GAS INLET TEMP (,F6.1,1H))
      GO TO 1
  400 WRITE (6,8000) RC,NSHAFT
 8000 FORMAT(1X,F7.2,4X,49HTURBINE POWER LESS THAN COMPRESSOR POWER ON S
     1HAFT,I2)
      GO TO 600
  500 WRITE (6,9000) RC,IT,IS
 9000 FORMAT(1X,F7.2,4X,24HOXYGEN USED UP IN BURNER,I2,9H ON SHAFT,I2)
  600 CONTINUE
      RC=RC+RCDEL
      IF(RC-TEST) 6,1,1
      END
```

Subroutine FUEL

Subroutine FUEL performs the computations involving the fuel thermodynamic properties and the fuel compression.

Program variables. - Certain of the variables transfer between main program MULTI and subroutine FUEL by means of labeled common block /CFUEL/. These variables, which were defined in the MULTI variable list, are AF, BF, CF, DELHF, ETACF, HFF, ITF, MWF, PRFIN, RC, TF, TFIN, and TR. The remaining variables in subroutine FUEL are defined as follows:

CP	arithmetic statement function for heat capacity of fuel, eq. (C1)
DFSCF	derivative of FSCF with respect to TF
FSCF	difference between right- and left-hand sides of eq. (C8)
H	arithmetic statement function for fuel enthalpy difference, eq. (C2)
NCF	number of fuel compressors with intervening intercoolers
PRC	pressure ratio across one fuel compressor
PSCF	value of function Φ_f in eq. (C8)
S	arithmetic statement function defined by eq. (C3)
T	temperature
TF1	previous value of TF

Program listing. - The FORTRAN listing for subroutine FUEL is as follows:

```
  SUBROUTINE FUEL
  REAL MWF
  COMMON/CFUEL/AF,BF,CF,TFIN,TF,ETACF,ITF,RC,HFF,TR,DELHF,MWF,PRFIN
  CP(T)=AF+BF*T**2+CF*T**3
  H(T1,T2)=AF*(T2-T1)+BF/2.*(T2**2-T1**2)+CF/3.*(T2**3-T1**3)
  S(T1,T2)=AF*ALOG(T2/T1)+BF*(T2-T1)+CF/2.*(T2**2-T1**2)
  IF(ITF.LT.10) GO TO 2
  NCF =MOD(ITF,10)+1
  PRC=(RC/PRFIN)**(1./FLOAT(NCF))
  IF(RC/PRFIN.LT.1.0) PRC=1.0
  PSCF=1545./MWF/778./ETACF*ALOG(PRC)
  TF=TFIN*EXP(PSCF/CP(TFIN))
1 FSCF=PSCF-S(TFIN,TF)
  DFSCF=-CP(TF)/TF
  TF1=TF
  TF=TF-FSCF/DFSCF
  IF(ABS(TF-TF1).GT..1) GO TO 1
  DELHF=FLOAT(NCF)*H(TFIN,TF)
2 HFF=H(TR,TF)
  RETURN
  END
```

Combustion-Gas Thermodynamic-Property Subprograms

All calculations directly involving the combustion-gas thermodynamic properties are performed by subroutine THERMO. In order to use the values computed in THERMO directly in arithmetic statements of the calling program, there are six function subprograms used in conjunction with THERMO. Each function subprogram calls on THERMO to do one particular computation, and the results of this computation is then set equal to the function. The six types of computation done by THERMO and the associated functions, with arguments, are as follows:

Function	Computation
CP(T, F)	heat capacity c_p from eq. (B5)
H(T1, T2, F)	enthalpy difference Δh from eq. (B7)
T2H(T1, F, X)	final temperature T_2 by iteration from eq. (B7)
S(T1, T2, F)	entropy function $\Delta\varphi$ from eq. (B12)
T2S(T1, F, X)	final temperature T_2 by iteration from eq. (B12)
HF(T1, T2)	function $I(T_1, T_2)$ from eq. (B10)

The function arguments, which are known values for each computation, are defined as follows:

F	fuel-air ratio
T	temperature
T1	initial temperature
T2	final temperature
X	function value of Δh or $\Delta\varphi$

The call on subroutine THERMO is CALL THERMO(TIN, TOUT, FOA, FUNC, IND) where the arguments are defined as follows:

FOA	fuel-air ratio
FUNC	function value
IND	computation-type indicator: 1 - c_p 2 - Δh 3 - T_2 from Δh 4 - $\Delta\varphi$ 5 - T_2 from $\Delta\varphi$ 6 - $I(T_1, T_2)$
TIN	initial temperature
TOUT	final temperature

This set of subprograms can be used with any program requiring combustion-gas thermodynamic properties.

Program variables. - The only variables used in the function subprograms are the function and its arguments, all of which have been defined. Certain of the variables used in subroutine THERMO are transmitted from main program MULTI through unlabeled common. These are HOC, TTOL, and W, which were defined in the MULTI variable list. The remaining variables in THERMO, with the exception of the functions and arguments defined previously, are defined as follows:

A	constant A_{air} in eq. (B5)
ACO2	constant A_{CO_2} in eq. (B5)
AH2O	constant A_{H_2O} in eq. (B5)
AO2	constant A_{O_2} in eq. (B5)

A1	constant K_1 in eq. (B5)
A2	constant K_2 in eq. (B5)
A3	constant K_3 in eq. (B5)
B	constant B_{air} in eq. (B5)
BCO2	constant B_{CO_2} in eq. (B5)
BH2O	constant B_{H_2O} in eq. (B5)
BO2	constant B_{O_2} in eq. (B5)
C	constant C_{air} in eq. (B5)
CCO2	constant C_{CO_2} in eq. (B5)
CH2O	constant C_{H_2O} in eq. (B5)
CO2	constant C_{O_2} in eq. (B5)
D	constant D_{air} in eq. (B5)
DCO2	constant D_{CO_2} in eq. (B5)
DFCN	derivative of function FCN with respect to TOUT
DH2O	constant D_{H_2O} in eq. (B5)
DO2	constant D_{O_2} in eq. (B5)
E	constant E_{air} in eq. (B5)
ECO2	constant E_{CO_2} in eq. (B5)
EH2O	constant E_{H_2O} in eq. (B5)
EO2	constant E_{O_2} in eq. (B5)
FCN	difference function for iterative solution for TOUT
TPRE	previous value of TOUT

Program listing. - The FORTRAN listings for function subprograms CP, H, T2H, S, T2S, and HF and for subroutine THERMO are as follows:

```
FUNCTION CP(T,F)
CALL THERMO (T,1.,F,X,1)
CP=X
RETURN
END
```

```
FUNCTION H(T1,T2,F)
CALL THERMO (T1,T2,F,X,2)
H=X
RETURN
END
```

```
FUNCTION T2H(T1,F,X)
CALL THERMO (T1,T2,F,X,3)
T2H=T2
RETURN
END
```

```
FUNCTION S(T1,T2,F)
CALL THERMO (T1,T2,F,X,4)
S=X
RETURN
END
```

```
FUNCTION T2S(T1,F,X)
CALL THERMO (T1,T2,F,X,5)
T2S=T2
RETURN
END
```

```
FUNCTION HF(T1,T2)
CALL THERMO (T1,T2,1.,X,6)
HF=X
RETURN
END
```

```
      SUBROUTINE THERMO (TIN,TOUT, FOA, FUNC, IND)
C
C     THERMODYNAMIC PROPERTY SUBROUTINE
C
C     IND          GIVEN                        CALCULATED
C     ---   -----------------------            ---------------
C      1    TIN,FOA                            CP(TIN,FOA)
C      2    TIN,TOUT,FOA                       H(TOUT,TIN,FOA)
```

```
C        3      TIN,FOA,H(TOUT,TIN,FOA)     TOUT
C        4      TIN,TOUT,FOA                S(TOUT,TIN,FOA)
C        5      TIN,FOA,S(TOUT,TIN,FOA)     TOUT
C        6      TIN,TOUT                    HF(TOUT,TIN)
       COMMON HOC, TTOL, W
C
C      THERMODYNAMIC PROPERTY FUNCTIONS
C
       CP(T,F)= (1.0/(1.0+F+W))
      1                           *(A+B*T+C*T**2+D*T**3+ E*T**4+(F/(1.0+HOC))
      1*(A1*(AO2+BO2*T+CO2*T**2+DO2*T**3+EO2*T**4)+ A2*(ACO2+BCO2*T+CCO2*
      2T**2+DCO2*T**3+ECO2*T**4)
      1)+(A3*F/(1.0+HOC)+W)
      1                                     *(AH2O+BH2O*T+CH2O*T**2+DH2O*T**3+
      3EH2O*T**4))
       H(T2,T1,F)= (1.0/(1.0+F+W))
      1                                *(A*(T2-T1)+B*(T2**2-T1**2)/2.0 +C*(T2
      1**3-T1**3)/3.0 +D*(T2**4-T1**4)/4.0 +E*(T2**5-T1**5)/5.0 +(F/(1.0+
      2HOC))*(A1*(AO2*(T2-T1)+BO2*(T2**2-T1**2)/2.0+CO2*(T2**3-T1**3)/3.0
      3+DO2*(T2**4-T1**4)/4.0+EO2*(T2**5-T1**5)/5.0)+A2*(ACO2*(T2-T1)+
      4BCO2*(T2**2-T1**2)/2.0+CCO2*(T2**3-T1**3)/3.0+DCO2*(T2**4-T1**4)/
      54.0+ECO2*(T2**5-T1**5)/5.0)
      1)+(A3*F/(1.0+HOC)+W)
      5                                      *(AH2O*(T2-T1)+BH2O*(T2**2-T1**2)/2.
      6+CH2O*(T2**3-T1**3)/3.0+DH2O*(T2**4-T1**4)/4.0+EH2O*(T2**5-T1**5)/
      75.0))
       S(T2,T1,F)= (1.0/(1.0+F+W))
      1                                *(A*ALOG(T2/T1)+B*(T2-T1)+C*(T2**2-T1**2
      1)/2.0+D*(T2**3-T1**3)/3.0+E*(T2**4-T1**4)/4.0 +(F/(1.0+HOC))*(A1*
      2(AO2*ALOG(T2/T1)+BO2*(T2-T1)+CO2*(T2**2-T1**2)/2.0+DO2*(T2**3-T1**
      33)/3.0+EO2*(T2**4- T1**4)/4.0)+A2*(ACO2*ALOG(T2/T1)+BCO2*(T2-T1)
      4+CCO2*(T2**2-T1**2)/2.0+DCO2*(T2**3-T1**3)/3.0+ECO2*(T2**4-T1**4
      5    )/4.0)
      1)+(A3*F/(1.0+HOC)+W)
      5                  *(AH2O*ALOG(T2/T1)+BH2O*(T2-T1)+CH2O*(T2**2-T1**2) /
      62.0+DH2O*(T2**3-T1**3)/3.0+EH2O*(T2**4-T1**4)/4.0))
       HF(T2,T1) = (1.0/(1.0+HOC))*
      1         (A1*(AO2*(T2-T1)+BO2*(T2**2-T1**2)/2.0+CO2*(T2**3-T1**3)/3.0
      2+DO2*(T2**4-T1**4)/4.0+EO2*(T2**5-T1**5)/5.0)+A2*(ACO2*(T2-T1)+
      3BCO2*(T2**2-T1**2)/2.0+CCO2*(T2**3-T1**3)/3.0+DCO2*(T2**4-T1**4)/
      44.0+ECO2*(T2**5-T1**5)/5.0)+A3*(AH2O*(T2-T1)+BH2O*(T2**2-T1**2)/2.
      5+CH2O*(T2**3-T1**3)/3.0+DH2O*(T2**4-T1**4)/4.0+EH2O*(T2**5-T1**5)/



       THERM        -  EFN   SOURCE STATEMENT  -  IFN(S)

65.0))
 A = .24062
 B = -.017724E-3
 C = .038056E-6
 D = -.012662E-9
 E = .0013012E-12
 AO2 = .20334
 BO2 =.02968E-3
 CO2 =.0089971E-6
 DO2 = -.0058842E-9
```

```
      EO2 =.00076764E-12
      ACO2 =.11097
      BCO2 =.21110E-3
      CCO2 =-.088140E-6
      DCO2 =.018003E-9
      ECO2 =-.0014317E-12
      AH2O =.44266
      BH2O =-.033155E-3
      CH2O =.087761E-6
      DH2O =-.024552E-9
      EH2O =.0021734E-12
      A1 =-2.6644*(1.0+2.9787*HOC)
      A2 = 3.6644
      A3 = 8.9365*HOC
      GO TO (10,20,30,40,50,60), IND
   10 FUNC=CP(TIN,FOA)
      RETURN
   20 FUNC=H(TOUT,TIN,FOA)
      RETURN
   30 TOUT=TIN+FUNC/CP(TIN,FOA)
   31 FCN=FUNC-H(TOUT,TIN,FOA)
      DFCN=-CP(TOUT,FOA)
      TPRE=TOUT
      TOUT=TOUT-FCN/DFCN
      IF(ABS(TOUT-TPRE).GT.TTOL) GO TO 31
      RETURN
   40 FUNC=S(TOUT,TIN,FOA)
      RETURN
   50 TOUT=TIN*EXP(FUNC/CP(TIN,FOA))
   51 FCN=FUNC-S(TOUT,TIN,FOA)
      DFCN=-CP(TOUT,FOA)/TOUT
      TPRE=TOUT
      TOUT=TOUT-FCN/DFCN
      IF(ABS(TOUT-TPRE).GT.TTOL) GO TO 51
      RETURN
   60 FUNC=HF(TOUT,TIN)
      RETURN
      END
```

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 3, 1974,
501-24.

APPENDIX A

SYMBOLS

A	constant in heat capacity equation, eq. (B4), J/(kg)(K) (Btu/(lb)(${}^{\circ}R$))
B	constant in heat capacity equation, eq. (B4), J/(kg)(K^2) (Btu/(lb)(${}^{\circ}R^2$))
C	constant in heat capacity equation, eq. (B4), J/(kg)(K^3) (Btu/(lb)(${}^{\circ}R^3$))
c_p	heat capacity, J/(kg)(K) (Btu/(lb)(${}^{\circ}R$))
D	constant in heat capacity equation, eq. (B4), J/(kg)(K^4) (Btu/(lb)(${}^{\circ}R^4$))
E	constant in heat capacity equation, eq. (B4), J/(kg)(K^5) (Btu/(lb)(${}^{\circ}R^5$))
f	fuel-air ratio
H	enthalpy function Δh as defined by eq. (B7), J/kg (Btu/lb)
H_f	enthalpy function Δh_f as defined by eq. (C4), J/kg (Btu/lb)
Δh	enthalpy difference or specific work, J/kg (Btu/lb)
Δh_{cb}	heat of combustion of fuel, J/kg (Btu/lb)
I	enthalpy correction function as defined by eq. (B10), J/kg (Btu/lb)
J	dimensional constant, 1 (778 ft-lb/Btu)
K_p	ratio of turbine power to compressor power
K_1, K_2, K_3	constants in heat capacity equation, eq. (B5)
M	molecular weight
m	ambient air absolute humidity
$n_{C,f}$	number of fuel compressors with intervening intercoolers
n_{sh}	number of shafts
P	power, kW (Btu/sec)
p	absolute pressure, N/cm^2 (psia)
R	gas constant, J/(kg)(K) (ft)(lbf)/(lbm)(${}^{\circ}R$))
r	ratio of component exit to inlet total pressure
SFC	specific fuel consumption, kg/(hr)(kW) (lb/(hr)(hp))
T	absolute temperature, K (${}^{\circ}R$)
w	mass flow rate per pound of inlet air, kg/sec (lb/sec)

x	atom ratio of hydrogen to carbon in fuel
y	mass ratio of hydrogen to carbon in fuel
η	efficiency or effectiveness
Φ	entropy function $\Delta\varphi$ as defined by eq. (B12), J/(kg)(K) (Btu/(lb)($^{\circ}$R))
Φ_f	entropy function $\Delta\varphi_f$ as defined by eq. (C8), J/(kg)(K) (Btu/(lb)($^{\circ}$R))
$\Delta\varphi$	constant-pressure entropy change, J/(kg)(K) (Btu/(lb)($^{\circ}$R))

Subscripts:

air	air
B	burner
C	compressor
CO_2	carbon dioxide
c	turbine coolant
cold	cold side
cv	conversion
cy	cycle
D	diffuser
est	estimated
ex	exit
f	fuel
H_2O	water vapor
hot	hot side
I	inlet component
INT	intercooler
id	ideal
in	inlet
j	shaft j
l	recuperator leakage
m	mixed
net	net
O_2	oxygen

o	overall
p	polytropic
R	recuperator
r	reference
sh	shaft
T	turbine
tot	total
0	ambient condition, see fig. 5
1	initial; station between inlet and compressor, see fig. 5
2	final; station between compressor and recuperator, see fig. 5
3	station between recuperator and primary burner, see fig. 5
4	station between primary burner and turbine, see fig. 5
5	station between turbine and diffuser, see fig. 5
6	station between diffuser and recuperator, see fig. 5
7	station at recuperator hot-side through-flow exit, see fig. 5
8	station at recuperator hot-side exit after leakage mixing, see fig. 5

Superscipt:

'	absolute total state

APPENDIX B

DERIVATION OF COMBUSTION-GAS PROPERTY EQUATIONS

Reaction Stoichiometry

The fuel used has the composition CH_x, and the general combustion equation with associated formula weights is

$$\underbrace{CH_x}_{12.010 + 1.008\,x} + \underbrace{\left(1 + \frac{x}{4}\right)O_2}_{32.000\left(1 + \frac{x}{4}\right)} \rightarrow \underbrace{CO_2}_{44.010} + \underbrace{\left(\frac{x}{2}\,H_2O\right)}_{18.016\left(\frac{x}{2}\right)} \tag{B1}$$

The variable used in the computer program to express fuel composition is the mass ratio y of hydrogen to carbon. In terms of this mass ratio, the atom ratio x is

$$x = \frac{12.010}{1.008}\,y = 11.914683\,y \tag{B2}$$

and the formula weights associated with the components of equation (B1) are $CH_x = 12.010(1 + y)$, $O_2 = 32.000 + 95.317460\,y$, $CO_2 = 44.010$, and $H_2O = 107.327460\,y$.

If one mass unit of air, with an associated m mass units of water vapor, is reacted with f mass units of fuel, the reactant and product masses w per mass unit of air are as shown in table IV. The composition of the combustion gas used in the cycle analysis is defined by the product masses shown in table IV.

Heat Capacity

The heat capacity of the combustion gas is

$$c_p = \frac{\sum (wc_p)_{\text{components}}}{1 + f + m} \tag{B3}$$

The heat capacity of each component is expressed in the form

$$c_p = A + BT + CT^2 + DT^3 + ET^4 \tag{B4}$$

The coefficients A, B, C, D, and E were obtained by a least-squares regression analysis of the tabulated data of reference 1. These coefficients and the molecular weight of each component are given in table V.

Equation (B3) for combustion gas heat capacity is evaluated by substituting for w according to table IV and for c_p according to equation (B4). Performing the summation yields

$$c_p = \left(\frac{1}{1 + f + m}\right)\Bigg\{A_{air} + B_{air}T + C_{air}T^2 + D_{air}T^3 + E_{air}T^4$$

$$+ \left(\frac{f}{1 + y}\right)\Bigg[K_1\left(A_{O_2} + B_{O_2}T + C_{O_2}T^2 + D_{O_2}T^3 + E_{O_2}T^4\right)$$

$$+ K_2\left(A_{CO_2} + B_{CO_2}T + C_{CO_2}T^2 + D_{CO_2}T^3 + E_{CO_2}T^4\right)\Bigg]$$

$$+ \left(\frac{K_3 f}{1 + y} + m\right)\left(A_{H_2O} + B_{H_2O}T + C_{H_2O}T^2 + D_{H_2O}T^3 + E_{H_2O}T^4\right)\Bigg\} \qquad \text{(B5)}$$

where

$$A_{air} = 1.00821\ \text{J/(kg)(K)}\ (0.24062\ \text{Btu/(lb)}(^{\circ}\text{R}))$$

$$B_{air} = -1.33675\times10^{-1}\ \text{J/(kg)(K}^2)\ (-0.017724\times10^{-3}\ \text{Btu/(lb)}(^{\circ}\text{R}^2))$$

$$C_{air} = 5.16637\times10^{-4}\ \text{J/(kg)(K}^3)\ (0.038056\times10^{-6}\ \text{Btu/(lb)}(^{\circ}\text{R}^3))$$

$$D_{air} = -3.09412\times10^{-7}\ \text{J/(kg)(K}^4)\ (-0.012662\times10^{-9}\ \text{Btu/(lb)}(^{\circ}\text{R}^4))$$

$$E_{air} = 5.72336\times10^{-11}\ \text{J/(kg)(K}^5)\ (0.0013012\times10^{-12}\ \text{Btu/(lb)}(^{\circ}\text{R}^5))$$

$$K_1 = -2.6644\ (1 + 2.9787\ y)$$

$$K_2 = 3.6644$$

$$K_3 = 8.9365\ y$$

The O_2, CO_2, and H_2O coefficients are as listed in table V. The coefficients subscripted air were obtained by combining the component coefficients according to the air composition shown in table IV.

Enthalpy Change

The change in gas enthalpy resulting from a change in gas temperature from T_1 to T_2 is

$$\Delta h = \int_{T_1}^{T_2} c_p \, dT \tag{B6}$$

Substituting equation (B5) into equation (B6) and integrating yield

$$
\begin{aligned}
\Delta h = {} & \left(\frac{1}{1+f+m}\right)\Biggl\langle A_{air}(T_2 - T_1) + \frac{B_{air}}{2}\left(T_2^2 - T_1^2\right) + \frac{C_{air}}{3}\left(T_2^3 - T_1^3\right) \\
& + \frac{D_{air}}{4}\left(T_2^4 - T_1^4\right) + \frac{E_{air}}{5}\left(T_2^5 - T_1^5\right) + \left(\frac{f}{1+y}\right)\Biggl\{K_1\Biggl[A_{O_2}(T_2 - T_1) + \frac{B_{O_2}}{2}\left(T_2^2 - T_1^2\right) \\
& + \frac{C_{O_2}}{3}\left(T_2^3 - T_1^3\right) + \frac{D_{O_2}}{4}\left(T_2^4 - T_1^4\right) + \frac{E_{O_2}}{5}\left(T_2^5 - T_1^5\right)\Biggr] \\
& + K_2\Biggl[A_{CO_2}(T_2 - T_1) + \frac{B_{CO_2}}{2}\left(T_2^2 - T_1^2\right) + \frac{C_{CO_2}}{3}\left(T_2^3 - T_1^3\right) + \frac{D_{CO_2}}{4}\left(T_2^4 - T_1^4\right) \\
& + \frac{E_{CO_2}}{5}\left(T_2^5 - T_1^5\right)\Biggr]\Biggr\} + \left(\frac{K_3 f}{1+y} + m\right)\Biggl[A_{H_2O}(T_2 - T_1) + \frac{B_{H_2O}}{2}\left(T_2^2 - T_1^2\right) \\
& + \frac{C_{H_2O}}{3}\left(T_2^3 - T_1^3\right) + \frac{D_{H_2O}}{4}\left(T_2^4 - T_1^4\right) + \frac{E_{H_2O}}{5}\left(T_2^5 - T_1^5\right)\Biggr]\Biggr\rangle
\end{aligned}
\tag{B7}
$$

For brevity in the cycle analysis procedure, equation (B7) will be expressed as

$$\Delta h = H(T_1, T_2, f) \tag{B8}$$

In order to facilitate burner calculations, it is desired to extract the fuel-air ratio f from the function H. To do this, equation (B8) is written

$$\Delta h = \frac{1}{1 + f + m} (1 + m)H(T_1, T_2, 0) + fI(T_1, T_2) \tag{B9}$$

Comparison of equation (B9) with equation (B7) shows that the function $I(T_1, T_2)$ is

$$\begin{aligned}
I(T_1, T_2) = \left(\frac{1}{1 + y}\right)\Bigg\{K_1\Bigg[&A_{O_2}(T_2 - T_1) + \frac{B_{O_2}}{2}\left(T_2^2 - T_1^2\right) + \frac{C_{O_2}}{3}\left(T_2^3 - T_1^3\right) \\
&+ \frac{D_{O_2}}{4}\left(T_2^4 - T_1^4\right) + \frac{E_{O_2}}{5}\left(T_2^5 - T_1^5\right)\Bigg] + K_2\Bigg[A_{CO_2}(T_2 - T_1) + \frac{B_{CO_2}}{2}\left(T_2^2 - T_1^2\right) \\
&+ \frac{C_{CO_2}}{3}\left(T_2^3 - T_1^3\right) + \frac{D_{CO_2}}{4}\left(T_2^4 - T_1^4\right) + \frac{E_{CO_2}}{5}\left(T_2^5 - T_1^5\right)\Bigg] \\
&+ K_3\Bigg[A_{H_2O}(T_2 - T_1) + \frac{B_{H_2O}}{2}\left(T_2^2 - T_1^2\right) + \frac{C_{H_2O}}{3}\left(T_2^3 - T_1^3\right) \\
&+ \frac{D_{H_2O}}{4}\left(T_2^4 - T_1^4\right) + \frac{E_{H_2O}}{5}\left(T_2^5 - T_1^5\right)\Bigg]\Bigg\}
\end{aligned} \tag{B10}$$

Constant-Pressure Entropy Change

The change in gas entropy resulting from a change in gas temperature from T_1 to T_2 at constant pressure is

$$\Delta\varphi = \int_{T_1}^{T_2} \frac{c_p}{T}\, dT \tag{B11}$$

This function is used in the evaluation of ideal (isentropic) and polytropic processes in turbomachines. Substituting equation (B5) into equation (B11) and integrating yield

$$\begin{aligned}\Delta\varphi = \left(\frac{1}{1+f+m}\right)\Bigg\langle & A_{air}\ln\frac{T_2}{T_1} + B_{air}(T_2 - T_1) + \frac{C_{air}}{2}\left(T_2^2 - T_1^2\right) + \frac{D_{air}}{3}\left(T_2^3 - T_1^3\right) \\ & + \frac{E_{air}}{4}\left(T_2^4 - T_1^4\right) + \left(\frac{f}{1+y}\right)\Bigg\{K_1\Bigg[A_{O_2}\ln\frac{T_2}{T_1} + B_{O_2}(T_2 - T_1) + \frac{C_{O_2}}{2}\left(T_2^2 - T_1^2\right) \\ & + \frac{D_{O_2}}{3}\left(T_2^3 - T_1^3\right) + \frac{E_{O_2}}{4}\left(T_2^4 - T_1^4\right)\Bigg] + K_2\Bigg[A_{CO_2}\ln\frac{T_2}{T_1} + B_{CO_2}(T_2 - T_1) \\ & + \frac{C_{CO_2}}{2}\left(T_2^2 - T_1^2\right) + \frac{D_{CO_2}}{3}\left(T_2^3 - T_1^3\right) + \frac{E_{CO_2}}{4}\left(T_2^4 - T_1^4\right)\Bigg]\Bigg\} \\ & + \left(\frac{K_3 f}{1+y} + m\right)\Bigg[A_{H_2O}\ln\frac{T_2}{T_1} + B_{H_2O}(T_2 - T_1) + \frac{C_{H_2O}}{2}\left(T_2^2 - T_1^2\right) \\ & + \frac{D_{H_2O}}{3}\left(T_2^3 - T_1^3\right) + \frac{E_{H_2O}}{4}\left(T_2^4 - T_1^4\right)\Bigg]\Bigg\rangle \end{aligned} \tag{B12}$$

For brevity in the cycle analysis procedure, equation (B12) will be expressed as

$$\Delta\varphi = \Phi(T_1, T_2, f) \tag{B13}$$

Molecular Weight

The molecular weight of the gas is equal to the weight of the gas divided by the total number of moles (sum of the moles of the components). Therefore, molecular weight can be expressed as

$$M = \frac{1 + f + m}{\sum\left(\frac{w}{M}\right)_{components}} \tag{B14}$$

With w obtained from table IV and M from table V, equation (B14) expands to

$$M = \frac{1 + f + m}{0.034522 + 0.24802\, y\left(\frac{f}{1 + y}\right) + \frac{m}{18.016}} \tag{B15}$$

APPENDIX C

FUEL PROPERTIES AND COMPRESSION

Thermodynamic Properties

The heat capacity of the CH_x fuel is expressed as

$$c_{p,f} = A_f + B_f T + C_f T^2 \tag{C1}$$

The coefficients A_f, B_f, and C_f depend on the particular fuel being used and must be provided as program input.

The change in fuel enthalpy with temperature change, in accordance with equation (B6), is

$$\Delta h_f = A_f(T_2 - T_1) + \frac{B_f}{2}\left(T_2^2 - T_1^2\right) + \frac{C_f}{3}\left(T_2^3 - T_1^3\right) \tag{C2}$$

In accordance with equation (B11), the change in fuel entropy resulting from a temperature change at constant pressure is

$$\Delta \varphi_f = A_f \ln \frac{T_2}{T_1} + B_f(T_2 - T_1) + \frac{C_f}{2}\left(T_2^2 - T_1^2\right) \tag{C3}$$

In a similar manner as was done for the combustion gas in appendix B, equations (C2) and (C3) will be expressed

$$\Delta h_f = H_f(T_1, T_2) \tag{C4}$$

and

$$\Delta \varphi_f = \Phi_f(T_1, T_2) \tag{C5}$$

Fuel Compression

In some cases it may be necessary to compress the fuel in order to get it into the burner. For such a case, it may be desirable to charge the cycle output for the fuel-compression power. The program provides for the computation of fuel compression work with or without intercooling. Although it is recognized that a gaseous fuel may deviate significantly from ideal-gas behavior, an ideal-gas analysis is used because the fuel-compression power is small as compared with the cycle output power.

The fuel inlet temperature $T'_{f,in}$, fuel inlet pressure $p'_{f,in}$, fuel compressor polytropic efficiency $\eta_{C,f,p}$, and number of compressors $n_{C,f}$ with intervening intercoolers are specified by the program input. It is assumed that the fuel must be compressed to a pressure defined by the cycle pressure ratio r_{cy}

$$p'_{f,C,ex} = p_0 r_{cy} \tag{C6}$$

Each fuel compressor is assumed to have the same pressure ratio

$$r_{C,f} = \left(\frac{p'_{f,C,ex}}{p'_{f,in}}\right)^{1/n_{C,f}} \tag{C7}$$

and each intercooler is assumed to cool the fuel back to the fuel inlet temperature $T'_{f,in}$. The fuel-compressor exit temperature $T'_{f,C,ex}$ is then obtained from

$$\Phi_f\left(T'_{f,in}, T'_{f,C,ex}\right) = \frac{1}{\eta_{C,f,p}} \frac{R_f}{J} \ln r_{C,f} \tag{C8}$$

and the fuel-compression specific work is

$$\Delta h'_{f,C} = n_{C,f} H_f\left(T'_{f,in}, T'_{f,C,ex}\right) \tag{C9}$$

REFERENCE

1. McBride, Bonnie J.; Heimel, Sheldon; Ehlers, Janet G.; and Gordon, Sanford: Thermodynamic Properties to 6000^{0} K for 210 Substances Involving the First 18 Elements. NASA SP-3001, 1963.

TABLE I. - INPUT FORM WITH DATA FOR ILLUSTRATIVE EXAMPLE

```
$INPUT  TSO=288.,PSO=10.13,W=.01,R10=.99,NSHAFT=2,NCOMP=1,4, ETAC=.88,RCMIN=5.,
RCDEL=5.,RCMAX=100.,RCSHSP=.4,.6,RCCOSP(1,2)=.20,.25,.25,.30,ICOOL=1,
ICOOL(1,2)=3*1,RINT=.98,TINT=306.,NTURB=2,2,IBURN=2*1,IBURN(1,2)=2*1,ETAB=.98,
RBURN=.97,TTI=1389.,HVF=43.39E06,TR=298.,HOC=.3077,ITF=10,AF=6.696E02,
BF=5.0326,CF=1.3525E-03,TFIN=288.,PRFIN=35.,ETACF=.88,MWF=18.85,ETAT=.90,
TSPLIT=2*.5, TSPLIT(1, 2)=.4,.6,WCAOWA=2*.025,WCAOWA(1,2)=2*.025,R65=.99,ER=.9,
R32=.98,R76=.96,RSTEX=.98,ETAETA=.95,TTOL=.05,IU=1  $
```

TABLE III. - DETAILED OUTPUT FOR ONE COMPRESSION RATIO

```
PRESSURE RATIO     COOL   INLET     INLET    INLET    EXIT     EXIT      MIX       MIX      WORK          NET POWER= 646.97 KW/KG AIR
    50.0C           OR    FLOW      PRESS    TEMP     PRESS    TEMP      TEMP      FLOW    JLS PER                  = 868.08 HP/KG AIR
                   BURN             N/CM2    DEG K    N/CM2    DEG K     DEG K             GM FLOW       FUEL CONS= 0.1710 KG/HR/KW
SHAFT 2 - COMP 4    NO   1.0100      10.0    288.0     20.3    361.5                        74.78        CYCLE EFF= 0.4860
SHAFT 2 - COMP 3   YES   1.0100      19.9    306.0     35.7    369.7                        64.91        FUEL POWR= 0.1919 KW/KG AIR
SHAFT 2 - COMP 2   YES   1.0100      35.0    306.0     63.0    369.7                        64.91
SHAFT 2 - COMP 1   YES   1.0100      61.7    306.0     98.7    356.0                        50.93
SHAFT 1 - COMP 1   YES   1.0100      96.7    306.0    462.5    504.4                       204.23
RECUPERATOR              0.9090     462.5    504.4    453.3    903.9
SHAFT 1 - TURB 1   YES   0.9225     439.7   1389.0    320.3   1300.2   1281.1   0.9478    111.80
SHAFT 1 - TURB 2   YES   0.9511     310.7   1389.0    228.8   1303.6   1285.1   0.9763    108.44
SHAFT 2 - TURB 1   YES   0.9797     221.9   1389.0     67.2   1081.4   1068.3   1.0049    387.34
SHAFT 2 - TURB 2   YES   1.0155      65.2   1389.0     10.9    956.2    946.4   1.0407    552.36
RECUPERATOR              1.0407      10.8    946.4     10.3    625.1    625.1   1.0407
```

TABLE II. - OUTPUT FOR ILLUSTRATIVE EXAMPLE

```
2-SHAFT POWER SYSTEM OPERATING AT AMBIENT CONDITIONS OF  298.00 DEG KELVIN  AND  10.130 N/CM2
INLET TOTAL PRESSURE RECOVERY=0.990,    TURBINE EXHAUST DIFFUSER TOTAL PRESSURE RECOVERY=0.990,  EXIT STAT/TOT PRESS RATIO=0.980
RECUPERATOR EFFECTIVENESS=0.900, COLD SIDE TOTAL PRESSURE RECOVERY=0.980, HOT SIDE TOTAL PRESSURE RECOVERY=0.960, BYPASS FLOW=0.
FUEL HEATING VALUE=43390000. AT  298. DEG KELVIN , H/C RATIO=0.30770
FUEL GAS CP= 669.5000 + 5.0326E+00 * T + 1.3525E-03 * T**2
FUEL MOL WGT= 18.850 FUEL INLET TEMP= 298., FUEL INLET COMPRESSION= 35.0, FUEL COMPRESSION EFF.=0.880

SHAFT 2 HAS 4 COMPRESSORS THAT SUPPLY 0.5000 OF TOTAL COMPRESSION AND 2 TURBINES

     COMPRESSOR 4 PROVIDES 0.3000 OF SHAFT COMPRESSION WITH EFFICIENCY=0.880

     FLOW ENTERING COMPRESSOR 3 IS COOLED TO  306. DEG KELVIN  WITH TOTAL PRESSURE RECOVERY=0.980
     COMPRESSOR 3 PROVIDES 0.2500 OF SHAFT COMPRESSION WITH EFFICIENCY=0.880

     FLOW ENTERING COMPRESSOR 2 IS COOLED TO  306. DEG KELVIN  WITH TOTAL PRESSURE RECOVERY=0.980
     COMPRESSOR 2 PROVIDES 0.2500 OF SHAFT COMPRESSION WITH EFFICIENCY=0.880

     FLOW ENTERING COMPRESSOR 1 IS COOLED TO  306. DEG KELVIN  WITH TOTAL PRESSURE RECOVERY=0.980
     COMPRESSOR 1 PROVIDES 0.2000 OF SHAFT COMPRESSION WITH EFFICIENCY=0.880

     FLOW ENTERING TURBINE 1 IS HEATED TO 1389.0 DEG KELVIN  WITH COMBUSTION EFFICIENCY =0.980 AND TOTAL PRESSURE RECOVERY=0.970
     TURBINE 1 PROVIDES 0.4000 OF SHAFT EXPANSION WITH EFFICIENCY=0.900
     TURBINE 1 IS COOLED WITH 0.0250 OF COMPRESSOR EXIT FLOW

     FLOW ENTERING TURBINE 2 IS HEATED TO 1389.0 DEG KELVIN  WITH COMBUSTION EFFICIENCY =0.980 AND TOTAL PRESSURE RECOVERY=0.970
     TURBINE 2 PROVIDES 0.6000 OF SHAFT EXPANSION WITH EFFICIENCY=0.900
     TURBINE 2 IS COOLED WITH 0.0250 OF COMPRESSOR EXIT FLOW

SHAFT 1 HAS 1 COMPRESSORS THAT SUPPLY 0.4000 OF TOTAL COMPRESSION AND 2 TURBINES THAT DELIVER 1.0000 * COMPRESSOR SHAFT POWER

     FLOW ENTERING COMPRESSOR 1 IS COOLED TO  306. DEG KELVIN  WITH TOTAL PRESSURE RECOVERY=0.980
     COMPRESSOR 1 PROVIDES 1.0000 OF SHAFT COMPRESSION WITH EFFICIENCY=0.880

     FLOW ENTERING TURBINE 1 IS HEATED TO 1389.0 DEG KELVIN  WITH COMBUSTION EFFICIENCY =0.980 AND TOTAL PRESSURE RECOVERY=0.970
     TURBINE 1 PROVIDES 0.5000 OF SHAFT   POWER   WITH EFFICIENCY=0.900
     TURBINE 1 IS COOLED WITH 0.0250 OF COMPRESSOR EXIT FLOW

     FLOW ENTERING TURBINE 2 IS HEATED TO 1389.0 DEG KELVIN  WITH COMBUSTION EFFICIENCY =0.980 AND TOTAL PRESSURE RECOVERY=0.970
     TURBINE 2 PROVIDES 0.5000 OF SHAFT   POWER   WITH EFFICIENCY=0.900
     TURBINE 2 IS COOLED WITH 0.0250 OF COMPRESSOR EXIT FLOW

OUTPUT POWER EQUALS 0.9500 OF SHAFT POWER                       TURBOMACHINERY EFFICIENCIES ARE POLYTROPIC



  PRESS.      NET         NET         FUEL       CYCLE       FUEL                          POWER VALUES REFER
  RATIO       POWER       POWER       CONSUMP.    EFF         POWER                         TO ONE KG PER SEC
               KW          HP         KG/HR/KW                 KW                           OF INLET AIR FLOW
    5.00      255.86      343.30      0.2204     0.3770      0.
   10.00      388.26      520.95      0.1898     0.4379      0.
   15.00      459.74      616.87      0.1814     0.4582      0.
   20.00      507.87      691.44      0.1774     0.4684      0.
   25.00      543.73      729.56      0.1751     0.4745      0.
   30.00      572.10      767.62      0.1736     0.4785      0.
   35.00      595.43      798.93      0.1726     0.4814      0.
   40.00      615.16      825.41      0.1719     0.4834      0.0031
   45.00      632.20      848.27      0.1714     0.4849      0.0060
   50.00      646.97      868.08      0.1710     0.4860      0.1919
   55.00      659.85      885.37      0.1707     0.4867      0.6053
   60.00      671.40      900.87      0.1705     0.4873      0.9981
   65.00      681.85      914.89      0.1704     0.4877      1.3811
   70.00      691.37      927.66      0.1703     0.4880      1.7471
   75.00      700.10      939.38      0.1702     0.4882      2.1000
   80.00      708.15      950.19      0.1702     0.4883      2.4430
   85.00      715.62      960.20      0.1701     0.4884      2.7726
   90.00      722.56      969.52      0.1701     0.4884      3.0955
   95.00      729.06      978.23      0.1701     0.4884      3.4054
  100.00      735.14      986.39      0.1702     0.4884      3.7105
```

TABLE IV. - COMBUSTION REACTION STOICHIOMETRY

Component	Reactant mass per unit mass of air	Mass formed (+) or consumed (-) by reaction per unit mass of air	Product mass per unit mass of air
N_2	0.7552	0	0.7552
O_2	.2314	$-\frac{32.000 + 95.317460\ y}{12.010(1 + y)} f$	$0.2314 - \frac{2.664446 + 7.936508\ y}{1 + f} f$
A	.0129	0	0.0129
CO_2	.0005	$+\frac{44.010}{12.010(1 + y)} f$	$0.0005 + \frac{3.664446\ y}{1 + y} f$
H_2O	m	$+\frac{107.327460\ y}{12.010(1 + y)} f$	$m + \frac{8.936508\ y}{1 + y} f$
CH_x	f	-f	0
Total	1 + m + f	0	1 + m + f

TABLE V. - COEFFICIENTS AND MOLECULAR WEIGHTS OF COMPONENTS

Components	Coefficients in equation (B4), SI units (U.S. customary units)					Molecular weight, M
	A	B	C	D	E	
N_2	1064.69 (0.25410)	-246.550×10^{-3} (-0.032690×10^{-3})	647.357×10^{-6} (0.047685×10^{-6})	-365.884×10^{-9} (-0.014973×10^{-9})	65.4721×10^{-12} $(0.0014885\times10^{-12})$	28.016
O_2	852.001 (0.20334)	223.848×10^{-3} (0.029680×10^{-3})	122.142×10^{-6} (0.0089971×10^{-6})	-143.788×10^{-9} $(-0.0058842\times10^{-9})$	33.7649×10^{-12} $(0.00076764\times10^{-12})$	32.000
CO_2	464.968 (0.11097)	1592.13×10^{-3} (0.21110×10^{-3})	-1196.56×10^{-6} (-0.088140×10^{-6})	439.926×10^{-9} (0.018003×10^{-9})	-62.9737×10^{-12} $(-0.0014317\times10^{-12})$	44.010
H_2O	1854.76 (0.44266)	-250.057×10^{-3} (-0.033155×10^{-3})	1191.42×10^{-6} (0.087761×10^{-6})	-599.959×10^{-9} (-0.024552×10^{-9})	95.5976×10^{-12} $(0.0021734\times10^{-12})$	18.016
A	521.156 (0.12438)	0 (0)	0 (0)	0 (0)	0 (0)	39.944

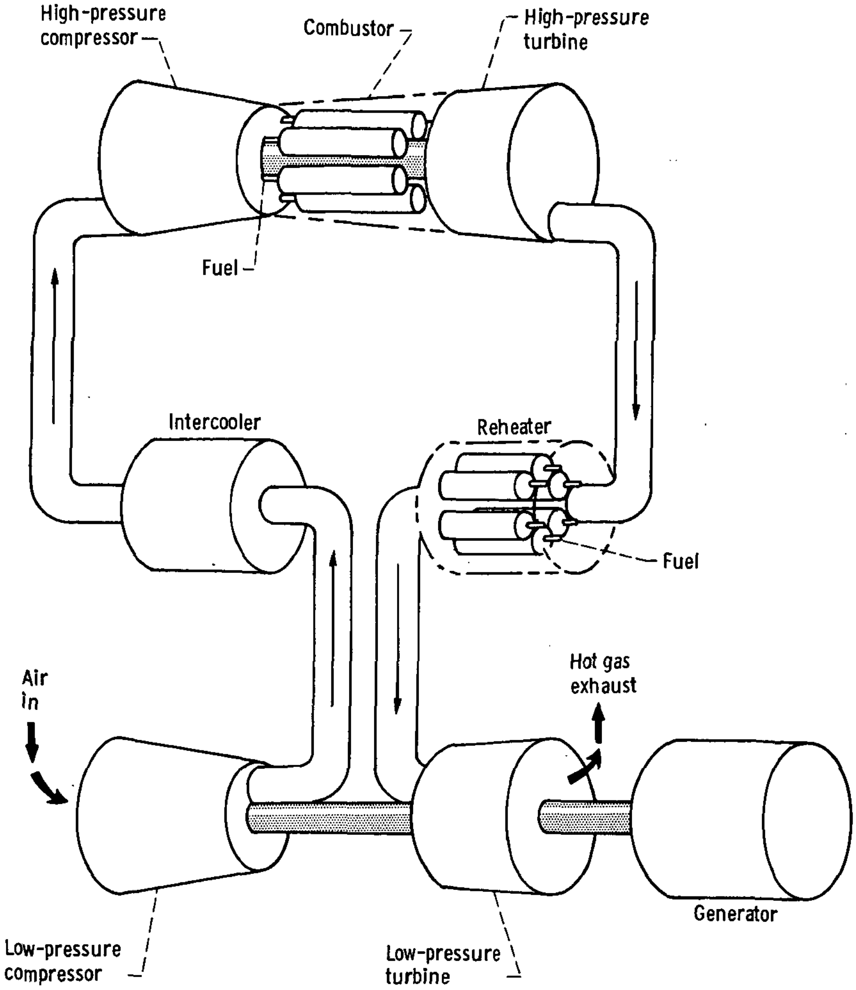


Figure 1. - Open-cycle system with intercooling and reheating.

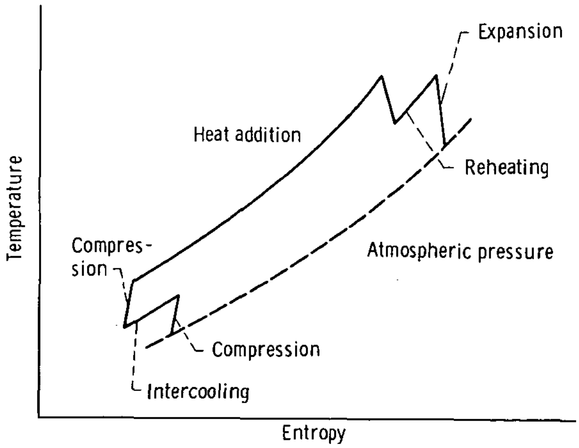


Figure 2. - Thermodynamic diagram for open-cycle system with intercooling and reheating.

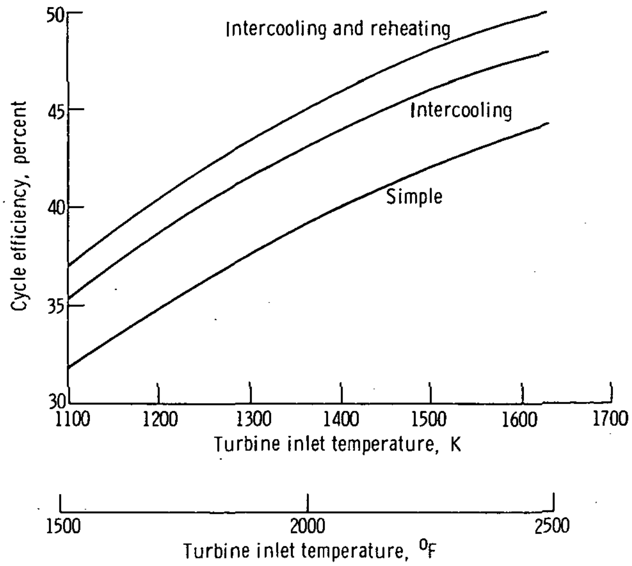


Figure 3. - Effect of intercooling and reheating on cycle efficiency at optimum pressure ratio. Compressor polytropic efficiency, 88 percent; turbine polytropic efficiency, 90 percent.

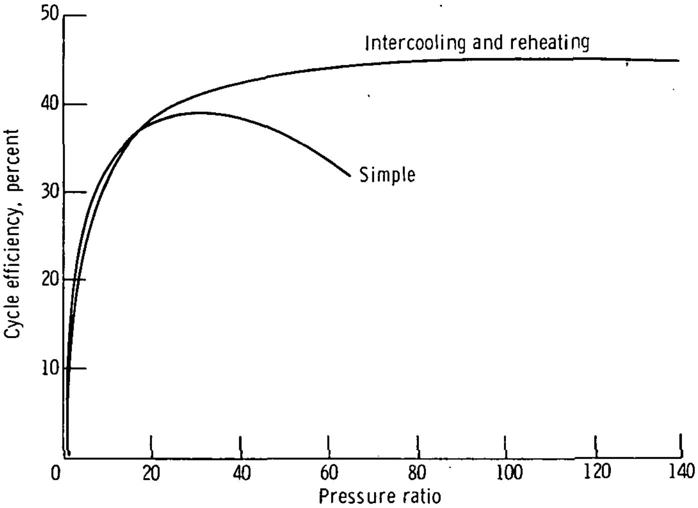
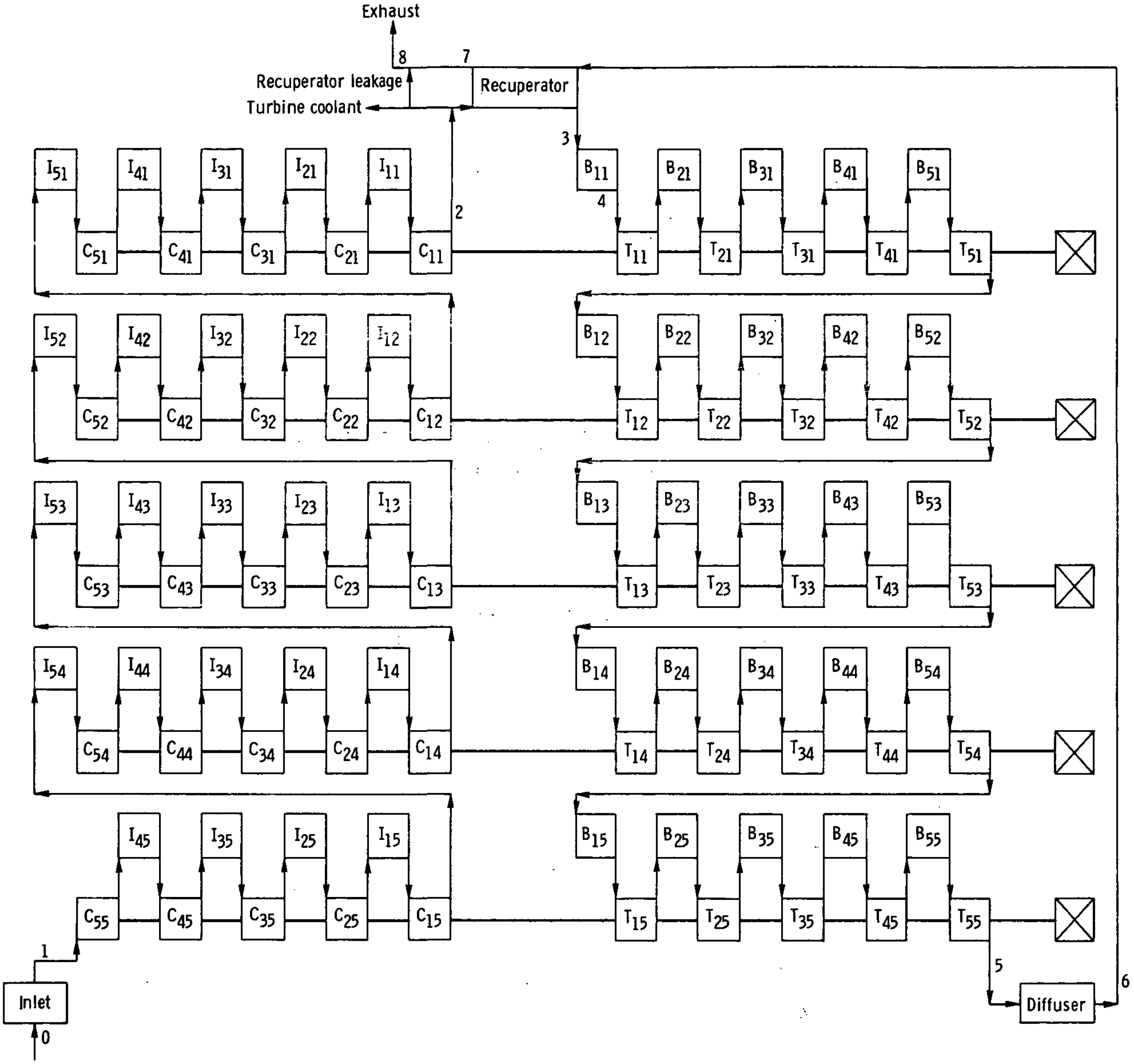
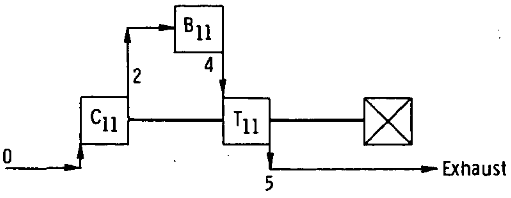


Figure 4. - Effect of intercooling and reheating on pressure ratio selection. Turbine inlet temperature, 1367 K (2000^{0} F).



(a) Maximum number of components.



I	Intercooler
C	Compressor
B	Burner
T	Turbine

(b) Minimum number of components.

Figure 5. - Open-cycle power system schematic.

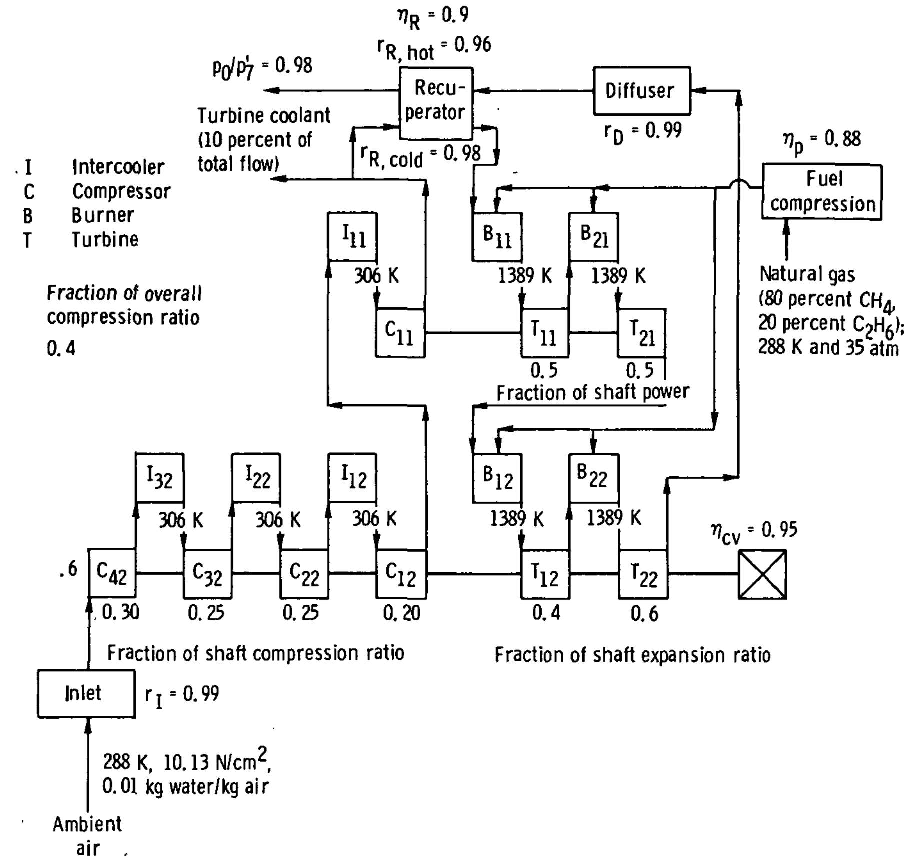


Figure 6. - Illustrative power system for example input and output. The following values are the same for all components of the same type: $\eta_{C,p} = 0.88$, $r_{INT} = 0.98$, $\eta_B = 0.98$, $r_B = 0.97$, $\eta_{T,p} = 0.90$, and $w_{T,c}/w_I = 0.025$.

NASA-Langley, 1974 E-7518

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