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

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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 turbo-machinery.
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 \( \text{CH}_x \), a single equation for the combustion-gas heat capacity is obtained. Finally, the enthalpy and constant-pressure entropy changes are obtained as

\[ \Delta h = \int_{T_1}^{T_2} c_p \, dT \]  

\[ \Delta \phi = \int_{T_1}^{T_2} \frac{c_p}{T} \, dT \]  

The equations for \( \Delta h \) and \( \Delta \phi \) 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 \( \Delta h \) and equation (B12) for \( \Delta \phi \) will be denoted as

\[ \Delta h = H(T_1, T_2, f) \]  

\[ \Delta \phi = \Phi(T_1, T_2, f) \]  

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

\[ T_1' = T_0 \]  
\[ p_1' = p_0 r_1 \]  
\[ w_1 = 1 + m \]  

The ambient static temperature \( T_0 \), ambient static pressure \( p_0 \), inlet pressure recovery \( r_1 \), 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

\[ p_{C, \text{ex}}' = p_{C, \text{in}} r_C \]  

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 \( T_{C, \text{ex}, \text{id}}' \) is found by iteration from

\[ \Phi(T_{C, \text{in}}', T_{C, \text{ex}, \text{id}}', 0) = \frac{R}{J} \ln r_C \]  

Compressor specific work is then found from the efficiency definition

\[ \Delta h_C' = \frac{H(T_{C, \text{in}}', T_{C, \text{ex}, \text{id}}', 0)}{\eta_{C, o}} \]  

and compressor exit temperature from
With polytropic efficiency, the compressor exit temperature is found from

\[ \Phi(T'_C, \text{in}, T'_C, \text{ex}, 0) = \frac{1}{\eta_C, p} R \ln r_C. \]  

(12)

and compressor specific work from

\[ \Delta h'_C = H(T'_C, \text{in}, T'_C, \text{ex}, 0) \]  

(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:

\[ P_{C, j} = w_1 \sum \Delta h'_{C, j} \]  

(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 \( r_{INT} \)

\[ p'_{INT, \text{ex}} = p'_{INT, \text{in}} r_{INT} \]  

(15)

The heat rejected in each intercooler can be found as

\[ \Delta h'_{INT} = H(T'_{INT, \text{ex}}, T'_{INT, \text{in}}, 0) \]  

(16)

**Re 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

\[ w_2 = w_1 - w_l - \sum w_{T, c} \]  

(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 $r_{R,\text{cold}}$:

$$p'_3 = p'_2 r_{R,\text{cold}}$$

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,

$$T'_{3,\text{est}} = T'_2 + \frac{\eta}{2} (T'_4 - T'_2)$$

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 $T'_{B,\text{in}}$, pressure $p'_{B,\text{in}}$, and mass flow rate $w_{B,\text{in}}$ having a composition corresponding to a fuel-air ratio of $f_{B,\text{in}}$. For the primary burner, $T'_{B,\text{in}} = T'_3$, $p'_{B,\text{in}} = p'_3$, $w_{B,\text{in}} = w_2$, and $f_{B,\text{in}} = 0$. Gas leaves the burner with temperature $T'_{B,\text{ex}}$, which is a program input, and pressure $p'_{B,\text{ex}}$, which is determined from the input value of pressure recovery $r_B$

$$p'_{B,\text{ex}} = p'_{B,\text{in}} r_B$$

and with flow

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

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

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

where $w_{f,B,\text{in}}$ is the amount of fuel added in previous burners and $w_{\text{air},B}$ 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
\[ w_f, B H_f(T_r, T_f') + \eta_B w_f, B \Delta h_{cb} + w_B, b H(T_r, T_B, f_B, b) = w_B, ex H(T_r, T_B', f_B, ex) \]  

(23)

The heat of combustion \( \Delta h_{cb} \) must be that at the reference temperature \( T_r \) and is a program input along with the burner efficiency \( \eta_B \). 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)

\[ \text{RHS} = w_B, ex \left( \frac{1}{1 + f_B, ex + m} \right) \left[ (1 + m)H(T_r, T_B, ex, 0) + f_B, ex I(T_r, T_B, ex) \right] \]  

(24)

Substituting for \( f_B, ex \) from equation (22), equating the constant air flow in terms of inlet and exit conditions such that

\[ w_{air, B} = \frac{w_B, ex}{1 + f_B, ex + m} = \frac{w_B, in}{1 + f_B, in + m} \]  

(25)

and expressing \( w_f, B \) as

\[ w_f, B = f_B w_{air, B} \]  

yield for equation (24)

\[ \text{RHS} = w_B, in \left( \frac{1}{1 + f_B, in + m} \right) \left[ (1 + m)H(T_r, T_B', ex, 0) + f_B, in I(T_r, T_B, ex) \right] \]  

\[ + w_f, B I(T_r, T_B', ex) \]  

(26)

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

\[ \text{RHS} = w_B, in H(T_r, T_B', f_B, in) + w_f, B I(T_r, T_B', ex) \]  

(27)

Now, substituting equation (27) back into equation (23), combining terms, and rearranging yield
\[ w_{f, B} = \frac{w_{B, in} H(T'_{B, in}, T'_{B, ex}, f_{B, in})}{H_f(T_r, T'_r) + \eta_B \Delta h_{cb} - I(T_r, T'_r, B, ex)} \] (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

\[ P_{T, j} = P_{C, j} K_P \] (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

\[ \Delta h'_T = \frac{P_T}{w_{T, in}} \] (30)

and turbine exit temperature from

\[ H(T'_T, ex', T'_T, in', f_T, in) = \Delta h'_T \] (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

\[ \Delta h'_{T, id} = \frac{\Delta h'_T}{\eta_{T, o}} \] (32)

and turbine ideal exit temperature from

\[ H(T'_T, ex, id', T'_T, in', f_T, in) = \Delta h'_{T, id} \] (33)

Turbine exit pressure is then

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

With polytropic efficiency, turbine exit pressure is

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

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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

$$p'_5 = p_0 \left( \frac{p'_7}{p_0} \right) \frac{1}{R_{R,\text{hot}} r_D}$$

(36)

where the recuperator-exit total-to-static pressure ratio $p'_7/p_0$, the recuperator hot-side pressure recovery $R_{R,\text{hot}}$, and the diffuser pressure recovery $r_D$ are program inputs. The individual turbine inlet and exit pressures $p'_{T,i,n}$ and $p'_{T,e,x}$ are then obtained from the input pressure ratio distribution. With polytropic efficiency specified, turbine exit temperature $T'_{T,e,x}$, 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 $T'_{T,e,x}$ 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 $p'_{T,e,x,m}$ after mixing is equal to the turbine exit total pressure $p'_{T,e,x}$. The mixed total flow rate is equal to

$$w_{T,e,x,m} = w_{T,i,n} + w_{T,c}$$

(37)

and the air flow is

$$w_{\text{air},T,e,x,m} = w_{\text{air},T,i,n} + w_{T,c} \left( \frac{1}{1 + m} \right)$$

(38)

The fuel-air ratio is then

$$f_{T,e,x,m} = f_{T,i,n} \left( \frac{w_{\text{air},T,i,n}}{w_{\text{air},T,e,x,m}} \right)$$

(39)

The total temperature $T'_{T,e,x,m}$ after mixing is found from a heat balance for the mixing process:

$$w_{T,e,x,m} H(T'_{T,e,x,m}) = w_{T,i,n} H(T'_{T,i,n})$$

(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 $r_D$

$$p'_6 = p'_5 r_D$$

(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 $r_{R, hot}$

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

(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:

$$H(T'_2, T'_3, 0) = \eta_R H(T'_2, T'_6, 0)$$

(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:

$$w_6 H(T'_7, T'_6, f_6) = w_2 H(T'_2, T'_3, 0)$$

(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

$$w_8 = w_7 + w_f$$

(45)

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

$$w_8 H(T'_2, T'_8, f_8) = w_7 H(T'_2, T'_7, f_7)$$

(46)

**Overall Performance**

The net shaft output power is
\[ P_{\text{sh,net}} = \sum_{j=1}^{n_{\text{sh}}} (P_{T,j} - P_{C,j}) - w_{f,\text{tot}} \Delta h_{f,C}^{r} \]  

where the fuel-compression specific work \( \Delta h_{f,C}^{r} \) is obtained from equation (C9). The net plant output power is

\[ P_{\text{net}} = \eta_{cv} P_{\text{sh,net}} \]  

where the conversion efficiency \( \eta_{cv} \) reflects a generator, gearbox, or other device.

The specific fuel consumption is

\[ SFC = \frac{3600 \ w_{f,\text{tot}}}{P_{\text{net}}} \]  

and the cycle efficiency is

\[ \eta_{cy} = \frac{P_{\text{net}}}{w_{f,\text{tot}} \Delta h_{cb}} \]  

**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 \((X(1) \text{ to } X(N))\) 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 \( N \times M \) 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:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Preset value</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSO</td>
<td>ambient temperature, K (°R)</td>
<td>518.7</td>
</tr>
<tr>
<td>PS0</td>
<td>ambient pressure, N/cm² (psia)</td>
<td>14.696</td>
</tr>
<tr>
<td>W</td>
<td>ambient air absolute humidity</td>
<td>0.0</td>
</tr>
<tr>
<td>R10</td>
<td>inlet total pressure recovery</td>
<td>1.0</td>
</tr>
<tr>
<td>NSHAFT</td>
<td>number of shafts</td>
<td>1</td>
</tr>
<tr>
<td>(NCOMP(J),</td>
<td>number of compressors on each shaft</td>
<td>1 (for J=1 only)</td>
</tr>
<tr>
<td>J=1,NSHAFT)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>((ETAC(I,J),</td>
<td>compressor efficiency (See IETAC and</td>
<td>---</td>
</tr>
<tr>
<td>I=1,NCOMP(J))</td>
<td>KPOLY. Only ETAC(1,1) need be input if IETAC=0.)</td>
<td></td>
</tr>
<tr>
<td>J=1,NSHAFT)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IETAC</td>
<td>compressor efficiency value indicator:</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>0 - all ETAC(I,J)=ETAC(1,1)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 - each ETAC(I,J) must be input</td>
<td></td>
</tr>
<tr>
<td>KPOLY</td>
<td>compressor and turbine efficiency type indicator:</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>0 - overall (isentropic) efficiency</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 - polytropic efficiency</td>
<td></td>
</tr>
<tr>
<td>RCMIN</td>
<td>minimum value of overall compression ratio</td>
<td>---</td>
</tr>
<tr>
<td>RCDEL</td>
<td>increment in overall compression ratio</td>
<td>---</td>
</tr>
<tr>
<td>RCMAX</td>
<td>maximum value of overall compression ratio (Calculations made at increments of RCDEL for each compression ratio starting at RCMIN and ending at RCMAX.)</td>
<td>---</td>
</tr>
<tr>
<td>Variable</td>
<td>Description</td>
<td>Preset value</td>
</tr>
<tr>
<td>----------</td>
<td>-------------</td>
<td>--------------</td>
</tr>
<tr>
<td>(RCSHSP(J), J=1, NSHAFT)</td>
<td>shaft compression ratio factor, fractional power of overall compression ratio (Sum of RCSHSP(J) must equal 1.0.)</td>
<td>1.0 (for J=1 only)</td>
</tr>
<tr>
<td>((RCCOSP(I,J), I=1, NCOMP(J)), J=1, NSHAFT)</td>
<td>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.)</td>
<td>1.0 (for I=1, J=1 only)</td>
</tr>
<tr>
<td>((ICOOL(I,J), I=1, NCOMP(J)), J=1, NSHAFT)</td>
<td>intercooling indicator: 0 - no intercooling 1 - intercooling</td>
<td>0 (for all I, J)</td>
</tr>
<tr>
<td>((RINT(I,J), I=1, NCOMP(J)), J=1, NSHAFT)</td>
<td>intercooler total pressure recovery (Input only for those I, J having ICOOL(I,J)=1. See RINT. Only RINT(1,1) need be input if IRINT=0.)</td>
<td>---</td>
</tr>
<tr>
<td>IRINT</td>
<td>intercooler total pressure recovery value indicator: 0 - all RINT(I,J)=RINT(1,1) 1 - each RINT(I,J) must be input</td>
<td></td>
</tr>
<tr>
<td>((TINT(I,J), I=1, NCOMP(J)), J=1, NSHAFT)</td>
<td>intercooler exit temperature, K (°R) (Input only for those I, J having ICOOL(I,J)=1. See ITINT. Only TINT(1,1) need be input if ITINT=0.)</td>
<td>---</td>
</tr>
<tr>
<td>ITINT</td>
<td>intercooler exit temperature value indicator: 0 - all TINT(I,J)=TINT(1,1) 1 - each TINT(I,J) must be input</td>
<td>0</td>
</tr>
<tr>
<td>WLAOWA</td>
<td>recuperator leakage flow, fraction of inlet flow</td>
<td>0.0</td>
</tr>
<tr>
<td>(NTURB(J), J=1, NSHAFT)</td>
<td>number of turbines on each shaft</td>
<td>1 (for J=1 only)</td>
</tr>
<tr>
<td>((IBURN(I,J), I=1, NTURB(J)), J=1, NSHAFT)</td>
<td>reheating indicator: 0 - no reheating 1 - reheating</td>
<td>1 (for I=1, J=1 only) 0 (for all other I, J)</td>
</tr>
<tr>
<td>Variable</td>
<td>Description</td>
<td>Preset value</td>
</tr>
<tr>
<td>------------------</td>
<td>------------------------------------------------------------------------------</td>
<td>--------------</td>
</tr>
<tr>
<td>((ETAB(I, J),</td>
<td>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.)</td>
<td>---</td>
</tr>
<tr>
<td>I=1, NTURB(J))</td>
<td></td>
<td></td>
</tr>
<tr>
<td>J=1, NSHAFT)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IETAB</td>
<td>burner efficiency value indicator:</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>0 - all ETAB(I, J)=ETAB(1,1)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 - each ETAB(I, J) must be input</td>
<td></td>
</tr>
<tr>
<td>((RBURN(I, J),</td>
<td>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.)</td>
<td>---</td>
</tr>
<tr>
<td>I=1, NTURB(J))</td>
<td></td>
<td></td>
</tr>
<tr>
<td>J=1, NSHAFT)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IRBURN</td>
<td>burner total pressure recovery value indicator:</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>0 - all RBURN(I, J)=RBURN(1,1)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 - each RBURN(I, J) must be input</td>
<td></td>
</tr>
<tr>
<td>((TTI(I, J),</td>
<td>burner exit (turbine inlet) temperature, K (°R) (Input only for those I, J having IBURN(I, J)=1. See ITTI. Only TTI(1,1) need be input if ITTI=0.)</td>
<td>---</td>
</tr>
<tr>
<td>I=1, NTURB(J))</td>
<td></td>
<td></td>
</tr>
<tr>
<td>J=1, NSHAFT)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ITTI</td>
<td>burner exit temperature value indicator:</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>0 - all TTI(I, J)=TTI(1,1)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 - each TTI(I, J) must be input</td>
<td></td>
</tr>
<tr>
<td>HVF</td>
<td>lower heating value of fuel at temperature TR, J/kg (Btu/lb)</td>
<td>18 640</td>
</tr>
<tr>
<td>TR</td>
<td>reference temperature for fuel heating value, K (°R)</td>
<td>760</td>
</tr>
<tr>
<td>HOC</td>
<td>mass ratio of hydrogen to carbon in fuel</td>
<td>0.16786</td>
</tr>
<tr>
<td>ITF</td>
<td>indicator for fuel temperature entering burner:</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>0 - fuel enters burner at temperature TR</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 - fuel enters burner at temperature TF</td>
<td></td>
</tr>
<tr>
<td></td>
<td>≥10 - fuel enters burner at temperature calculated from fuel compression work (Second digit indicates number of inter-cools back to TFIN during fuel compression. In this case fuel compression power is subtracted from gross shaft power output.)</td>
<td></td>
</tr>
<tr>
<td>le</td>
<td>Description</td>
<td>Preset value</td>
</tr>
<tr>
<td>----</td>
<td>-----------------------------------------------------------------------------</td>
<td>--------------</td>
</tr>
<tr>
<td>te</td>
<td>temperature of fuel entering burner K (°R) (Input only when ITF=1.)</td>
<td>---</td>
</tr>
<tr>
<td>BF</td>
<td>constant $A_f$ in fuel heat capacity equation (eq. (C1)), $J/(kg)(K)(Btu/(lb)(°R))$ (Input only when ITF &gt; 0.)</td>
<td>---</td>
</tr>
<tr>
<td>CF</td>
<td>constant $B_f$ in fuel heat capacity equation (eq. (C1)), $J/(kg)(K^2)(Btu/(lb)(°R^2))$ (Input only when ITF &gt; 0.)</td>
<td>---</td>
</tr>
<tr>
<td>TFIN</td>
<td>temperature of fuel entering fuel compressor, K (°R) (Input only when ITF ≥ 10.)</td>
<td>---</td>
</tr>
<tr>
<td>PRFIN</td>
<td>ratio of pressure of fuel entering fuel compressor to ambient pressure (Input only when ITF ≥ 10.)</td>
<td>1.0</td>
</tr>
<tr>
<td>ETACF</td>
<td>fuel compressor polytropic efficiency (Input only when ITF ≥ 10.)</td>
<td>---</td>
</tr>
<tr>
<td>MWF</td>
<td>fuel molecular weight (Input only when ITF ≥ 10.)</td>
<td>---</td>
</tr>
<tr>
<td>((ETAT(I,J), I=1, NTURB(J)), J=1, NSHAFT)</td>
<td>turbine efficiency (See IETAT and KPOLY. Only ETAT(1, 1) need be input if IETAT = 0.)</td>
<td>---</td>
</tr>
<tr>
<td>IETAT</td>
<td>turbine efficiency value indicator: 0 - all ETAT(I,J)=ETAT(1, 1) 1 - each ETAT(I,J) must be input</td>
<td>0</td>
</tr>
<tr>
<td>(POWFAC(J), J=1, NSHAFT-1)</td>
<td>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.)</td>
<td>1.0 (for all J)</td>
</tr>
<tr>
<td>((TSPLIT(I,J), I=1, NTURB(J)), J=1, NSHAFT)</td>
<td>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</td>
<td>1.0 (for I=1, J=1 only)</td>
</tr>
<tr>
<td>Variable</td>
<td>Description</td>
<td>Preset value</td>
</tr>
<tr>
<td>-------------------</td>
<td>-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>--------------</td>
</tr>
<tr>
<td>((WCAOWA(I, J),</td>
<td>specifies pressure ratio for each turbine as a fractional power of shaft pressure ratio. Sum of TSPLIT(I, J) must equal 1.0 for each J.</td>
<td></td>
</tr>
<tr>
<td>I=1, NTURB(J))</td>
<td>turbine coolant flow, fraction of inlet flow</td>
<td>0.0 (for all I, J)</td>
</tr>
<tr>
<td>J=1, NSHAFT)</td>
<td>ITCOOL</td>
<td>0</td>
</tr>
<tr>
<td>TCOOL</td>
<td>turbine coolant temperature indicator:</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td>0 - turbine coolant temperature equals last compressor exit temperature</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 - turbine coolant temperature equals input TCOOL</td>
<td></td>
</tr>
<tr>
<td>R65</td>
<td>turbine exit diffuser total pressure recovery</td>
<td>1.0</td>
</tr>
<tr>
<td>ER</td>
<td>recuperator effectiveness</td>
<td>0.0</td>
</tr>
<tr>
<td>R32</td>
<td>recuperator cold-side total pressure recovery</td>
<td>1.0</td>
</tr>
<tr>
<td>R76</td>
<td>recuperator hot-side total pressure recovery</td>
<td>1.0</td>
</tr>
<tr>
<td>RSTEX</td>
<td>cycle exit static-to-total pressure ratio</td>
<td>1.0</td>
</tr>
<tr>
<td>ETAETA</td>
<td>shaft power conversion efficiency</td>
<td>1.0</td>
</tr>
<tr>
<td>TTOL</td>
<td>temperature tolerance for iterative calculations, K °R</td>
<td>0.1</td>
</tr>
<tr>
<td>KOUT</td>
<td>output indicator:</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>0 - output for each cycle point consists of overall performance only</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 - output for each cycle point consists of overall performance plus all internal temperatures, pressures, and flow rates</td>
<td></td>
</tr>
<tr>
<td>IU</td>
<td>units indicator:</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>1 - SI units</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 - U.S. customary units</td>
<td></td>
</tr>
</tbody>
</table>

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...
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 $K_{OUT} = 0$ (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 $K_{OUT} = 1$, 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 \( \text{C}_{11} \) being greater than the primary burner \( \text{B}_{11} \) 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 \( \text{PTT0}(i,j)\)=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 \( (J=\text{NSHAFT}) \) 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:

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

22
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ETACF</td>
<td>fuel compressor efficiency</td>
</tr>
<tr>
<td>ETACY</td>
<td>cycle efficiency</td>
</tr>
<tr>
<td>ETAETA</td>
<td>shaft power conversion efficiency</td>
</tr>
<tr>
<td>ETAT(I, J)</td>
<td>turbine efficiency</td>
</tr>
<tr>
<td>EXP1</td>
<td>data statement word EXPAN for output use</td>
</tr>
<tr>
<td>EXP2</td>
<td>data statement word SION for output use</td>
</tr>
<tr>
<td>FA</td>
<td>fuel-air ratio</td>
</tr>
<tr>
<td>FBOA(I, J)</td>
<td>fuel-air ratio addition in burner</td>
</tr>
<tr>
<td>FLPOKW</td>
<td>fuel compression power</td>
</tr>
<tr>
<td>FOATI(I, J)</td>
<td>fuel-air ratio at turbine inlet</td>
</tr>
<tr>
<td>FOATOM(I, J)</td>
<td>fuel-air ratio after turbine coolant mixing</td>
</tr>
<tr>
<td>FOA5</td>
<td>fuel-air ratio at station 5</td>
</tr>
<tr>
<td>FOA6</td>
<td>fuel-air ratio at station 6</td>
</tr>
<tr>
<td>FOA7</td>
<td>fuel-air ratio at station 7</td>
</tr>
<tr>
<td>FOA8</td>
<td>fuel-air ratio at station 8</td>
</tr>
<tr>
<td>FSTOIC</td>
<td>stoichiometric fuel-air ratio</td>
</tr>
<tr>
<td>FUELPO</td>
<td>fuel compression power</td>
</tr>
<tr>
<td>H</td>
<td>function defined by eq. (B7), see Combustion-Gas Thermodynamic Property Subprograms</td>
</tr>
<tr>
<td>HF</td>
<td>function defined by eq. (B10), see Combustion-Gas Thermodynamic Property Subprograms</td>
</tr>
<tr>
<td>HFF</td>
<td>fuel enthalpy relative to reference temperature</td>
</tr>
<tr>
<td>HOC</td>
<td>mass ratio of hydrogen to carbon in fuel</td>
</tr>
<tr>
<td>HVF</td>
<td>lower heating value of fuel</td>
</tr>
<tr>
<td>I</td>
<td>dummy index</td>
</tr>
<tr>
<td>IBURN(I, J)</td>
<td>reheating indicator, see Input section</td>
</tr>
<tr>
<td>IC</td>
<td>compressor number index</td>
</tr>
<tr>
<td>ICOOL(I, J)</td>
<td>intercooling indicator, see Input section</td>
</tr>
<tr>
<td>IETAB</td>
<td>burner efficiency value indicator, see Input section</td>
</tr>
<tr>
<td>IETAC</td>
<td>compressor efficiency value indicator, see Input section</td>
</tr>
</tbody>
</table>
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
TSO   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:

```fortran
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,HF,F,TR,DELHF,MWF,PRFIN
COMMON HOC,TTOL,W
REAL J,PW,MWF,MINUS
DIMENSION WCAOWAf5,5) , ICQ515,5) , IBlURN(5,5) , RCCESP(5,5) , TSLIT(5,5)
1) , RURN(5,5) , TCO(5,5) , PTCI(5,5) , TCI(5,5) , PTCI(5,5) ,
2R INT(5,5) , DELHINT(5,5) , RCCOMP(5,5) , TCOID(5,5) , DELHC(5,5) , ETAC(5,5) ,
3TTI(5,5) , TTTOM(5,5) , TTOM(5,5) , WTOM(5,5) , WARTOM(5,5) , FOATOM(5,5) ,
4PTTI(5,5) , TTTI(5,5) , FBNA(5,5) , ETAH(5,5) , FOAT(5,5) , WFH(5,5) , WTH(5,5) ,
5PWW(5,5) , DEUH(5,5) , ETAT(5,5) , TTOID(5,5) , PLLH(5,5) , FII(5,5) ,
6TTP(5,5) , POWFAC(5) , NCOMP(5) , NTURB(5) , RSHSP(5) , RSHFT(5) , DELSH(5)
7), POWSH(5)

C NAM E LI S7/INPUT/TSO,PSG,R.10,
1ETAC,WCAOWA,ER,R32,HVF,TR,ETAR,INT,
1R BURN,TITI,ETAT,ETAETA,W,ICQOL,IBURN,ITCOOL,IE TAC,IE TAT,IE TAB,
2POWFAC,SHAFT,NCOMP,TURB,RCHSP,RCCESP,TSPLIT,TTI,ITINT,HOC,RC65,
3RI, RILL,TCL,TINT,RCMN,RODEL,PCMAX,TCOOL,TF,AF,CF,ETAC,F,MWF,TFIN,
4TURBIP,IP INT,IFKUT,KPOLY,WCAOWA,PRFIN,PSTEY,II
MWF=1.0+F+W/0.34522+(F/1.0+HOC)*(2.4832*HOC)*W/19.016
R(F)=1545/MWF
DATA PLUS,MINUS/LH+1,1H-/H
DATA PCH1,POWZ,EXP1,EXP2/5H POW,ZHEH ,ZHEXPAN,ZHSHION/
DATA TIPEFP,TY PE F1/5H POLY,5H ISE4/
```

29
DATA US, EFF, YES, 5H, NO/
DATA TPI, TPI2, TPIK, TPK2, TPK, TPK, 4HRANKK, 3HTE, 4FELV, 3HIN, 1HR, 1HK/
DATA PPSI, PNC, 2/6PSIA, 6H, N/CMP/
DATA WLR, WKG, 2HEL, 2HKG, PHP, PKW, 2HIP, 2HK/

C

INITIALIZATION

C

TSO = 51 E. 7
PSO = 14. 696
W = 0. 0
ETAETA = 1. 0
10 = 1. 0
DO 72 L = 1, 5
DO 71 M = 1, 5
WCAOWA(L, M) = 0. 0
ICOL(L, M) = 0
71 IRUPN(L, M) = 0
72 POWFAC(L) = 1. 0

NSHAFT = 1
NCOMP(I) = 1
NTUPA(I) = 1
RCOSHSP(I) = 1. 0
RCCOSP(I, I) = 1. 0
TSPLIT(1, 1) = 1. 0
IZUPN(I, 1) = 1
II = 0
ITINT = C
ITINT = C
ITCLOL = C
II = C
ITETAC = C
II = C
ITETAT = C
II = C
ITEX = C
II = C
IRUPN = C
II = C
KOUT = 0
II = C
WLAOWA = 0. 0
II = C
ITF = 0
II = C
ER = C. 0
II = C
RO = 1. 0
II = C
HNC = 16786
III = 18640
TR = 760
III = 100
PRFIN = 1. 0
III = 100
R65 = 1. 0
III = 100
R76 = 1. 0
III = 100
RSTEX = 1. 0
II = 2
II = 778. 0
TTOL = 1
1 IF (II .EQ. 2) GO TO 73

TSO = TSC/1. 8
DO 76 I = 1, NSHAFT
II = NCOMP(I)
76 DO 76 L = 1, II
74 TINT(L, I) = TINT(L, I)/1. 8
I = 1
73 DO 77 L = 1, I
75 TTI(L, I) = TTI(L, I)/1. 8
93
CONTINUE

HVF=HVF*1055.87/.45355237
TR=TR/1.8
TF=TF/1.8
AF=AF*1055.87/.45355237/1.8
RF=RF*1055.87/.45355237/1.8
CF=CF*1055.87/.45355237/1.8
IF(1T6<.G1.10) TF=IN/1.8
IF(1T6<CL<.E0.1) TC=NL=TC/1.8

READ (5,INPUT)
X3=TPR 1
X4=TPR 2
X5=TPR
X6=PPSI
X7=WLR
X8=PHP
X9=WLP
X10=WRL
IF(1U.EQ.2) GO TO 7
X3=TPK 1
X4=TPK 2
X5=TPK
X6=PNC 2
X7=WP
X8=PKW
X9=WGM
X10=WLS

7 TEST=RCMAX+.1*RCDEL
FSTDIC=.2314*1.8/10.8644+7.9365*HDC
IF(1TF.EQ.0) TF=TR
JJJ=NTRPR(NSHAFT)
WCAWA=C.0
PRU=1.0
DO 13 M=1,NSHAFT
L=NCOMP(M)
IF(L.EQ.0) GO TO 12
DO 11 I=1,L
IF(3OCCL(I,M,EQ.0) GO TO 11
IF(1IT6T.EQ.0) TINT(I,M)=INT(1,1)
IF(1IINT.EQ.0) RINT(I,M)=INT(1,1)
11 IF(1TAC.EQ.0) ETAC(I,M)=ETAC(1,1)

12 N=NTRPR(M)
DO 13 I=1,N
WCAWA=WCAWA+WCAWA(I,M)
IF(3IRUN(I,M).EQ.0) GO TO 13
IF(IETAB.EQ.0) ETAB(I,M)=ETAB(1,1)
IF(I3IRUN.EQ.0) 3RURN(I,M)=3RUN(I,1)
IF(M.EQ.NSHAFT) PRU=PRU*3URN(I,M)
IF(IETAT.EQ.0) ETAT(I,M)=ETAT(1,1)
13 IF(IETAT.EQ.0) ETAT(I,M)=ETAT(1,1)

WRITE INPUT VALUES

WRITE (6,1000) NSHAFT,T5O,X3,X4,PS0,X6,R10,R65,
1ST,TPR,32,P76,WCAWA,HVF,TR,X3,X4,HDC
1000 FORMAT(1H1,1L,54H-SHAFT POWER SYSTEM OPERATING AT AMBIENT CONDITION
1NS OF,F8.2,54 DEG,A4,A3,4H AND,F8.3,46 /
231H INLET TOTAL PRESSU
3RECOVERY=F5.3,544, Turbine exhaust diffuser total pressure
3RECOVERY=F5.3,29H, EXIT STAT/CT PRESS FAT,,F5.3,

31
TOTAL PRESSURE RECOVERY = F5.3, 35H, HOT SIDE TOTAL PRESSURE RECOVERY
5/20H FUEL HEATING VALUE = F9.0, 3H AT, F6.0, 5H DEG, A4, A3, 12H, H
6/C PAT = F7.5

IF (ITF .GE. 10) GO TO 42
WRITE (6,1010) TF, X3, X4
1010 FORMAT (1H+, 65X, 23H, FUEL ENTERS BURNER AT, F6.0, 5H DEG, A4, A3 /)
IF (IF1 .EQ. 0) GO TO 43
42 SIGNBF = PLLS
SIGNCF = MINUS
IF (BF .LT. 0.0) SIGNBF = MINUS
IF (CF .LT. 0.0) SIGNCF = PLUS
ABSBF = ABS(BF)
ABSCF = ABS(CF)
WRITE (6,1020) AB, SIGNBF, AB, SIGNCF, ABSCF
1020 FORMAT (1H FUEL GAS : P=, F9.4, 12H, FUEL TOTAL PRESSURE =, F6.0, 5H DEG, A4, A3 )
IF (ITF .LT. 10) GO TO 43
WRITE (6,1021) MWF, TFIN, PRFIN, ETACF
1021 FORMAT (1H FUEL MOL WT=, F9.3, 17H, FUEL INLET TEMP=, F5.0, 25H, FUEL INLET COMP.
20RESSION =, F5.1, 24H, FUEL COMPRESSION EFF. =, F5.3 )
43 DO 50 I = 1, NSHAFT
IS = NSHAFT + 1 - I
L = COMP(IS)
M = TURB(IS)
WRITE (6,1030) IS, L, RCSHP(IS), M
1030 FORMAT (1H SHAFT , 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 , THAT DELIVER, F7.4, 25H * COMPRESSOR SHAFT POWER)
IF (LT .EQ. 0) GO TO 46
DO 45 LL = 1, L
IC = L + 1 - LL
WRITE (6,1050)
1050 FORMAT (1H)
IF (IC .EQ. 0) WRITE (6,1060) IC, TINT(IC, IS), X3, X4, RINT(IC, IS)
1060 FORMAT (6X, 24H FLOW ENTERING COMPRESSOR, I2, 13H IS COOLED TO, F6.0, 5H
10 Coff, A4, A3, 30H WITH TOTAL PRESSURE RECOVERY =, F5.3 )
45 WRITE (6,1070) IC, RCOEF(IS), ETAC(IS)
1070 FORMAT (6X, 10H COMPRESSOR, I2, 9H PROVIDES, F7.4, 38H OF SHAFT COMPRESSION
10 N WITH EFFICIENCY =, F5.3 )
46 DO 50 IT = 1, M
WRITE (6,1050)
1050 FORMAT (1H)
IF (BURN(IS) .EQ. 0) WRITE (6,1080) IT, TINT (IT, IS), X3, X4, ETAB (IT, IS), IRRURN (IT, IS)
1080 FORMAT (6X, 21H FLOW ENTERING TURBINE, I2, 13H IS HEATED TO, F7.1, 5H DEG
10 Coff, A4, A3, 29H WITH COMBUSTION EFFICIENCY =, F5.3, 29H AND TOTAL PRESSU
2RE RECOVERY =, F5.3 )
IF (IS .EQ. NSHAFT) 47, 48, 48
47 X1 = POW1
X2 = POW2
GO TO 40
48 X1 = EXP1
X2 = EXP2
49 WRITE (6,1090) IT, TSLP(IS), X1, X2, ETAT(IS)
1090 FORMAT (6X, 7HTURBINE, I2, 9H PROVIDES, F7.4, 10H OF SHAFT, 2A5, 16H WITH
10 EFFICIENCY =, F5.3 )
IF(WCAOWA(IT,IS).EQ.0.0) GO TO 50
WRITE (6,1100) IT,WCAOWA(IT,IS)
1100 FORMAT(6X,THURBINE,12,15H IS COOLED WITH,F7.4,24H OF COMPRESSOR E
1XIT FCW)
IF(ITECOLD.NE.0) WRITE (6,1110) TECO,L,X3,X4
1110 FORMAT(6X,6HCOOH TO,F7.1,5H OF COMPRESSOR)
50 CONTINUE
TYPEF=TYPEFP
IF(KPOLY.NE.0) TYPEF=TYPEFI
WRITE (6,1120) ETAET,TYPEF
1120 FORMAT(20HOOHT PUT POWER £OUALS» F7. * , 1 5H OF SHAFT POWER, 20X , 31HTURB
IOMACHINERY EFFICIENCIES ARE ,A5,6HTFOPIC)
IF(KOUT.NE.0) WRITE(6, 2000) X7,X7,X8
2000 FORMAT( 1XIT PRESS. , 6X,3HMET, 8X,3HNEM, 8X,4HFUE, 7X,5HCYCLE, 6X,4HFUE
1, 18X, 18HPower VALUES REFER /7H RATIO,6X,5HPower,6X,5HPower, 5X , 8HC
20NSUMP , 6X,3HEFF, 6X,5HPOWER, 18X,7HTD ONE ,A2,8H PER SEC/14X,2HKW,9
3X,2HHP, 7X,A2,4H/HR/A2,17X,2HKW,19X,17HOF INLET AIR FLOW)
IF(II.EQ.2) GO TO 16
TSO=TSC*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=NTU RAI(I)
DO 37 L=1,II
37 TTL(L,I)=TTTL(L,I)*1.8
36 CONTINUE
HV F=HV F/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(ITEF.GE.10) TFIN= TF IN*1.8
IF(ITCOLD.EQ.1) TECO=TECO*1.8
C C INLET CONDITIONS
C 16 TTO= TSC
PTO=PSO
WO=1.*W
C C INLET
C 5 TTL= TTO
PT1=PT(C*R10
WI=WO
RC=RC_MIN
6 CONTINUE
DH MC=0.0
CALL FUEL
C C START INTERCOOLER-COMPRESSOR LOOP
C 150 IS=NSHAFT+1- I
RCSHFT(IS)= RC**RC SHP(IS)
DEL=SH(IS)=0.0
IFI(I-1) 2,2,3
2 TT = TT1
PT = PT1
GO TO 4
3 TT = TTCO(I, IS + 1)
PT = PTCO(I, 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 INTER COOLER
131 IF(ICOOL(IC, IS).EQ.0) GO TO 132
   TTCO(IC, IS) = TINT(IC, IS)
   PTCO(IC, IS) = PT*INT(IC, IS)
   DELHIC(IC, IS) = H(TTCO(IC, IS), TT, 0.0)
   GO TO 133
132 TTCO(IC, IS) = TT
   PTCO(IC, IS) = PT
   DELHIC(IC, IS) = 0.0
   C COMPRESSOR
133 RCOMP(IC, IS) = RSHIFTC(IS) * RCOMP(IS)
   PTCO(IC, IS) = PTCO(IC, IS) * RCOMP(IS)
   PSC = R(C, 0) / JOINT(RCOMP(IC, IS))
   IF(KPPLY.EQ.1) GO TO 134
   TTCO(ID(IS), IS) = T2S(TTCO(IC, IS), 0.0, PSC)
   DELHIC(IC, IS) = H(TTCO(IC, IS), TTCO(IS), 0.0, DELHIC(IS))
   TTCO(IS) = T2H(TTCO(IC, IS), 0.0, DELHHC(IS))
   GO TO 140
134 PSC = PSC / ETAC(IC, IS)
   TTCO(IS) = T2S(TTCO(IS), 0.0, PSC)
   DELHIC(IS) = H(TTCO(IS), TTCO(IS), 0.0)
140 DELHSH(IS) = DELHSH(IS) + DELHIC(IS)
   GO TO 150
141 TTCO(1, IS) = TT
   PTCO(1, IS) = PT
   DLHC = DLHC + DELHSH(IS)
   TT2 = TTCO(1, 1)
   IF(ITC0OL.EQ.0) TC0OL = TT2
   IF(TT2.GT.TT(I, 1)) GO TO 100
   PT2 = PTCO(1, 1)
   C BYPASS AIR
   W2 = W1*(1. - WCAWA - WLAWA)
   WAIR2 = W2/W1
   C RECUPERATOR - INITIAL ESTIMATE MADE FOR TT3
   PT3 = R32*PT2
   W3 = W2
   TT3 = TT2 + ER*(TT4 - TT2)/2.
   PT5 = PSC/P76/R65/RSTEX
START BURNER-TURBINE LOOP

161 WFNTOT=C.0
POWSH= 0.0
DO 170 IS=1,NSHAFT
POWSH(IS)= W1*DELHSH(IS)*POWFAC(IS)
IF(IS .EQ. 1) 171, 171, 172
171 TT=TT3
PT=PT3
WT=W3
WAIT=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)
WAIT=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=WTTOM(IT-1,IS)
WAIT=WARTOM(IT-1,IS)
FA=FOATOM(IT-1,IS)
174 IF( IBURN(IT,IS) .LT.0.0) GO TO 175
C BURNER
C PTTI(IT,IS)= PT*RRURN(IT,IS)
TTTI(IT,IS)= TTI(IT,IS)
FOA(IT,IS)=(1.+FA+W)*H(TT,TTTI(IT,IS),FA)/(ETAB(IT,IS)*HVF-HF(TR,
TTTTI(IT,IS))+HFF)
GO TO 176
175 PTTI(IT,IS)=PT
TTTI(IT,IS)=TT
FOA(IT,IS)= 0.0
176 FOATI(IT,IS)= FA+FOA(IT,IS)
IF(FOATI(IT,IS) .GT. FSTOIC) GO TO 500
WF(IT,IS)=FB3A(IT,IS)*WAIT
WTI(IT,IS)=WT+WF(IT,IS)
WFTOT=WFTOT+WF(IT,IS)
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)
TTTOIT(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)
TTTOITD(IT,IS)= T2H(TTTI(IT,IS),FOATI(IT,IS),-DHID)
PTTOITD(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 PTTOIT(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 PTTI(IT,IS)= PRSH**TSPLIT(IT,IS)
PST=P(FOATI(IT,IS)/J*Aalog1./PRT(IT,IS))
PTTO(IT,IS)= PTTI(IT,IS)/PRT(IT,IS)
IF(KPPLY.EQ.1) GO TO 179
TTTOO(IT,IS)=T2S(TTTI(IT,IS),FOATI(IT,IS),PST)
DELHT(IT,IS)=LTAT(IT,IS)*H(TTTI(I7,IS),TTTI(IT,IS),FOATI(IT,IS))
TTTO(IT,IS)=T2H(TTTI(IT,IS),FOATI(IT,IS),-DELHT(IT,IS))
GO TO 181
179 PTTI=PT*ETAT(IT,IS)
TTTO(IT,IS)=T2S(TTTI(IT,IS),FOATI(IT,IS),PST)
DELHT(IT,IS)=H(TTTI(IT,IS),TTTI(IT,IS),FOATI(IT,IS))
181 PWTSH=PWTSH*POWER(IT,IS)
COOLANT MIXING
182 PTTIM(IT,IS)= PTTO(IT,IS)
IF(PTTC(IT,IS).LT.PT5*.9999) GO TO 200
WTTM(IT,IS)= WTI(IT,IS)+W1*WCAOWA(IT,IS)
WARTM(IT,IS)= WART*WCAOWA(IT,IS)
FOATOM(IT,IS)= FOATI(IT,IS)*WART/WARTM(IT,IS)
IF(WCAOWA(IT,IS).EQ.0.0) GO TO 183
DHM=WTI(IT,IS)/WTTM(IT,IS)*H(TCOOL,TTTO(IT,IS),FOATI(IT,IS))
TTTIM(IT,IS)=T2H(TCOOL,FOATOM(IT,IS),DHM)
GO TO 180
183 TTTTIM(IT,IS)= TTTI(IT,IS)
180 CONTINUE
17C CONTINUE
IF(POW<7SH.LT.W1*C)ELHSH(NSHAFT)) GO TO 300
TT5=TTTIM(JJJ,NSHAFT)
PT5= PTTIM(JJJ,NSHAFT)
W5=WTTM(JJJ,NSHAFT)
FOA5=FOATOM(JJJ,NSHAFT)
WAF5=WARTM(JJJ,NSHAFT)
RECOVERY DIFFUSER
TT6=TT5
PT6=PT5*R65
FOA6=FOA5
W6=W5
WAF6=WAF5
RECUPERATOR
IF(ER.EQ.0.0) GO TO 24
IF(TT6.LT.TT2) GO TO 300
DHP=ER*H(TT2,TT6,0.0)
TT3PRE=TT3
TT3=T2H(TT2,0.0,DHP)
IF(ABS(TT3-TP3PE).GT.TTOL) GO TO 161
TT7=T2H(TT6,FOA6,-W2/W6*DHR)
GO TO 25
24 TT7=TT6
25 W7=W6
FOA7=FOA6
WAF7=WAF6
LEAKAGE MIXING

\[ PT_8 = PT_7 + W_7 + W_8 \]

\[ W_{AIR8} = W_{AIR7} + W_{LWA8} \]

\[ FOA8 = FOA7 + W_{LWA8} \]

IF (W_{LWA8} > 0) GO TO 27

\[ DHL = H(TT_2, TT_7, FOA7) \]

\[ TT_8 = T2H(TT_2, FOA8, W_7/W_8 * DHL) \]

GO TO 21

27 TT_8 = TT_7

PERFORMANCE PARAMETERS

31 SHPORT = C.0

IF (NSHAFT > 0.1) GO TO 33

NS = NSHAFT - 1

DO 32 I = 1, NS

32 SHPORT = SHPORT + POWSH(I) * (1.0 - 1.0 / POWFAC(I))

33 SHPORT = SHPORT + POWTSH - W_1 * DELHSH(NSHAFT)

IF (ITF.LT.10) GO TO 34

FLP0KW = FWTOT * 1.0542

GO TO 35

34 FLP0KW = C.0

35 OVPOKW = SHPORT * 1.0542 * ETAETA

OVHVP = SHPORT * 1.4145 * ETAETA

SFC = WFTOT * 3600.0 / OVHVP

QF = WFTOT * HVF

ETACY = SHPORT / QF * ETAETA

IF (IUR.EQ.2) GO TO 59

OVPOKW = OVPOKW / 45359237

OVHVP = OVHVP / 45359237

SFC = WFTOT * 3600.0 / OVPOKW

FLP0KW = FLP0KW / 45359237

WRITE OUTPUT

59 IF (KOUT.LT.0.1) GO TO 190

WRITE (6, 2010) RC, OVPOKW, OVHVP, SFC, ETACY, FLP0KW

2010 FORMAT (1X, F7.2, 2F11.2, 3F11.4)

GO TO 600

190 CONTINUE

IF (PC.EQ.FCIM) WRITE (6, 3000)

3000 FORMAT (1H1)

WRITE (6, 3100) OVPOKW, X7, RC, X10, OVHVP, X7, X6, X5, X6, X5, X5, X9, SFC, X7, X8

3100 FORMAT (114 hypressure, ratio cool inlet inlet inlet e

EXIT EXIT MIX MIX WORK NET POWER = F7.2, 24H KW/A2, 4H AIR/F11.2, 9X, 68HOK FLOW PRESS TEMP PRES

3S TEMP TEMP FLOW A3, 4H PER, 18X, 1H, F7.2, 4H HP/A2, 4

4H AIR/19X, 4HURM, 11X, A6, 4X, 4HDEG, A1, 3X, A6, 4X, 4HDEG, A1, 4X, 4HDEG, 5A1, 12X, A2, 5H FLOW, 9X, 1OHUEL CJNS = F7.4, 1X, A2, 4H/HP/A21.

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=I+1-M
IF(IU.EQ.2) GO TO 191
TTCI(IC,IS)= TTCl(IC,IS)/1.8
TTIC(IC,IS)= TTT0(IC,IS)/1.8
DELHC(IC,IS)= DELHC(IC,IS)*1055.87/453.59237
191
YN= OFF
IF(ICOND(IC,IS).NE.0) YN=ON
WRITE (6,3020) IS,IC,YN,WO,PTCI(IC,IS),TTCl(IC,IS),PTCO(IC,IS),
TTTO(IC,IS),DELHC(IC,IS)
3020 FORMAT(6H SHAFT,12,7H = COMP,12,A5,F9.4,4F9.1,21Y,F7.2)
IF(K.EQ.1) WRITE (6,3021) CYACY
3021 FORMAT(1H+,103X,10HCYCLE EFF=,F7.4)
IF(K.EQ.2) WRITE (6,3022) FLPOKW,X7
3022 FORMAT(1H+,103X,10HFUEL POW=,F7.4,4H KW/,A2,AH 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(6H SHAFT,12,7H - TURB,12,A5,F9.4,5F9.1)
IF(K.EQ.1) WRITE (6,3040) CYACY
3040 FORMAT(6H SHAFT,12,7H - TURB,12,A5,F9.4,5F9.1,21Y,F7.2)
DO 320 IS=1,NSHAFT
L=NTURP(IS)
DO 320 IT=1,L
IF(IT.EQ.2) GO TO 312
TTIT(IT,IS)= TTT0(IT,IS)/1.8
TTTO(IT,IS)= TTTO(IT,IS)/1.8
TTTOM(IT,IS)= TTT0M(IT,IS)/1.8
DELHT(IT,IS)= DELHT(IT,IS)*1055.87/453.59237
312
YN= OFF
IF(IRUNP(IT,IS).NE.0) YN=ON
320 WRITE (6,3050) IS,IT,YN,WI(IT,IS),PTI(IT,IS),TTT0(IT,1,IS),PTTO(IT,1,IS),
TTT0M(IT,IS),WTOM(IT,IS),DELHT(IT,IS)
3050 FORMAT(6H SHAFT,12,7H = TURB,12,A5,F9.4,4F9.1,21Y,F7.2)
IF(IU.EQ.2) GO TO 313
TT6= TT6/1.8
TT7= TT7/1.8
TT8= TT8/1.8
313 WRITE(6,3060) W6,PT6,TT6,PT7,TT7,TT8,WW
3060 FORMAT(6H SHAFT,12,7H - TURB,12,A5,F9.4,4F9.1,21Y,F7.2)
GO TO 600
100 IF(IU.EQ.1) TT2= TT2/1.8
IF(IU.EQ.1) TTT1(1,1)= TTT1(1,1)/1.8
WRITE (6,5000) RC,TT2,TTTI(1,1)
5000 FORMAT(1X,F7.2,4X,1E INLET TEMP (.F6.1,35H) GREATER THAN TURBIN
1E INLET TEMP (.F6.1,1H))
IF(IU.EQ.1) TTT1(1,1)= TTT1(1,1)*1.8
GO TO 1
200 WRITE (6,6000) RC,PT5,IT,IS,PTTO(IT,IS)
6000 FORMAT(1X,F7.2,4X,1E SYSTEM EXIT PRESSURE (.F6.2,42H) GREYA
1ER THAN TURBINE EXIT PRESSURE PTTO(.I1,1H,.I1,2H)=.F6.2)
GO TO 600
200 IF(IU.EQ.1) TT6= TT6/1.8
IF(IU.EQ.1) TT2= TT2/1.8
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 $\Phi_f$ 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:
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:

<table>
<thead>
<tr>
<th>Function</th>
<th>Computation</th>
</tr>
</thead>
<tbody>
<tr>
<td>CP(T,F)</td>
<td>heat capacity $c_p$ from eq. (B5)</td>
</tr>
<tr>
<td>H(T1,T2,F)</td>
<td>enthalpy difference $\Delta h$ from eq. (B7)</td>
</tr>
<tr>
<td>T2H(T1,F,X)</td>
<td>final temperature $T_2$ by iteration from eq. (B7)</td>
</tr>
<tr>
<td>S(T1,T2,F)</td>
<td>entropy function $\Delta \varphi$ from eq. (B12)</td>
</tr>
<tr>
<td>T2S(T1,F,X)</td>
<td>final temperature $T_2$ by iteration from eq. (B12)</td>
</tr>
<tr>
<td>HF(T1,T2)</td>
<td>function $I(T_1,T_2)$ from eq. (B10)</td>
</tr>
</tbody>
</table>

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 Δφ

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 - Δφ
   5 - \( T_2 \) from Δφ
   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 \( A_{\text{air}} \) in eq. (B5)
ACO2 constant \( A_{\text{CO}_2} \) in eq. (B5)
AH2O constant \( A_{\text{H}_2\text{O}} \) in eq. (B5)
AO2 constant \( A_{\text{O}_2} \) in eq. (B5)
Program listing. - The FORTRAN listings for function subprograms CP, H, T2H, S, T2S, and HF and for subroutine THERMO are as follows:

```fortran
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^2
  RETURN
END

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

\[ CP(T, F) = \left( \frac{1}{1.0 + F + W} \right) \]
\[ * (A + B * T + C * T^2 + D * T^3 + E * T^4 + F / (1.0 + HOC) + 2 * DC * T + CO2 * T^2 + DCO2 * T^3 + EDCO2 * T^4) \]
\[ A * 3 * F / (1.0 + HOC + W) \]
\[ 3 * EH2O * T^3) \]
\[ H(T2, T1, F) = \left( \frac{1}{1.0 + F + W} \right) \]
\[ * (A * (T2 - T1) + B * (T2^2 - T1^2)) / 2.0 + C * (T2 - T1) / 2.0 + D * (T2^2 - T1^2) / 2.0 + E * (T2^3 - T1^3) / 3.0 + F / (1.0 + HOC) + 2 * DC * (T2 - T1) + CO2 * (T2^2 - T1^2) / 2.0 + DCO2 * (T2^3 - T1^3) / 3.0 + EDCO2 * (T2^4 - T1^4) / 4.0 + F / (1.0 + HOC) \]
\[ A * 3 * F / (1.0 + HOC + W) \]
\[ 3 * EH2O * T^3) \]
\[ HF(T2, T1) = \left( \frac{1}{1.0} \right) \]
\[ * (A * (T2 - T1) + B * (T2^2 - T1^2)) / 2.0 + C * (T2 - T1) / 2.0 + D * (T2^2 - T1^2) / 2.0 + E * (T2^3 - T1^3) / 3.0 + F / (1.0 + HOC) \]
\[ A * 3 * F / (1.0 + HOC + W) \]
\[ 3 * EH2O * T^3) \]

THERM - EFN SOURCE STATEMENT - IFNS(5)

A = 2.4062
B = -0.17724E-3
C = 0.38666E-6
D = -0.0126624E-9
E = 0.012012E-12
A02 = 0.20334
B02 = -0.2968E-3
C02 = 0.3899716E-6
D02 = -0.058842E-9
END

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 3, 1974,
APPENDIX A

SYMBOLS

A constant in heat capacity equation, eq. (B4), J/(kg)(K) (Btu/(lb)(°R))

B constant in heat capacity equation, eq. (B4), J/(kg)(K^2) (Btu/(lb)(°R^2))

C constant in heat capacity equation, eq. (B4), J/(kg)(K^3) (Btu/(lb)(°R^3))

c_p heat capacity, J/(kg)(K) (Btu/(lb)(°R))

D constant in heat capacity equation, eq. (B4), J/(kg)(K^4) (Btu/(lb)(°R^4))

E constant in heat capacity equation, eq. (B4), J/(kg)(K^5) (Btu/(lb)(°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)(°R))

r ratio of component exit to inlet total pressure

SFC specific fuel consumption, kg/(hr)(kW) (lb/(hr)(hp))

T absolute temperature, K (°R)

w mass flow rate per pound of inlet air, kg/sec (lb/sec)
atom ratio of hydrogen to carbon in fuel
mass ratio of hydrogen to carbon in fuel
efficiency or effectiveness
entropy function $\Delta \varphi$ as defined by eq. (B12), J/(kg)(K) (Btu/(lb)(°R))
entropy function $\Delta \varphi_f$ as defined by eq. (C8), J/(kg)(K) (Btu/(lb)(°R))
constant-pressure entropy change, J/(kg)(K) (Btu/(lb)(°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$_2$O 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
0  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

Superscript:
'
absolute total state
APPENDIX B

DERIVATION OF COMBUSTION-GAS PROPERTY EQUATIONS

Reaction Stoichiometry

The fuel used has the composition $\text{CH}_x$, and the general combustion equation with associated formula weights is

$$\text{CH}_x + \left(1 + \frac{x}{4}\right)\text{O}_2 \rightarrow \text{CO}_2 + \left(\frac{x}{2}\right)\text{H}_2\text{O}$$  \hspace{1cm} (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

$$x = \frac{12.010}{1.008} y = 11.914683 y$$  \hspace{1cm} (B2)

and the formula weights associated with the components of equation (B1) are $\text{CH}_x = 12.010(1 + y)$, $\text{O}_2 = 32.000 + 95.317460 y$, $\text{CO}_2 = 44.010$, and $\text{H}_2\text{O} = 107.327460 y$.

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

$$c_p = \frac{\sum (w c_p)_{\text{components}}}{1 + f + m}$$  \hspace{1cm} (B3)

The heat capacity of each component is expressed in the form

$$c_p = A + BT + CT^2 + DT^3 + ET^4$$  \hspace{1cm} (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

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

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

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

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

where

$$A_{\text{air}} = 1.00821 \text{ J/(kg)(K)} \left( 0.24062 \text{ Btu/(lb)(°R)} \right)$$

$$B_{\text{air}} = -1.33675 \times 10^{-1} \text{ J/(kg)(K)} \left( -0.017724 \times 10^{-3} \text{ Btu/(lb)(°R)}^2 \right)$$

$$C_{\text{air}} = 5.16637 \times 10^{-4} \text{ J/(kg)(K)} \left( 0.038056 \times 10^{-6} \text{ Btu/(lb)(°R)}^3 \right)$$

$$D_{\text{air}} = -3.09412 \times 10^{-7} \text{ J/(kg)(K)} \left( -0.012662 \times 10^{-9} \text{ Btu/(lb)(°R)}^4 \right)$$

$$E_{\text{air}} = 5.72336 \times 10^{-11} \text{ J/(kg)(K)} \left( 0.0013012 \times 10^{-12} \text{ Btu/(lb)(°R)}^5 \right)$$

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

$$K_2 = 3.6644$$

$$K_3 = 8.9365 y$$

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

\[
\Delta h = \int_{T_1}^{T_2} c_p \, dT
\]

(B6)

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

\[
\Delta h = \left( \frac{1}{1 + f + m} \right) \left[ A_{\text{air}}(T_2 - T_1) + \frac{B_{\text{air}}}{2} \left( T_2^2 - T_1^2 \right) + \frac{C_{\text{air}}}{3} \left( T_2^3 - T_1^3 \right) \right.
\]

\[
+ \frac{D_{\text{air}}}{4} \left( T_2^4 - T_1^4 \right) + \frac{E_{\text{air}}}{5} \left( T_2^5 - T_1^5 \right) + \left( \frac{f}{1 + y} \right) \left\{ K_1 \left[ \frac{A_{O_2}}{2} \left( T_2 - T_1 \right) + \frac{B_{O_2}}{2} \left( T_2^2 - T_1^2 \right) \right] \right.
\]

\[
+ \frac{C_{O_2}}{3} \left( T_2^3 - T_1^3 \right) + \frac{D_{O_2}}{4} \left( T_2^4 - T_1^4 \right) + \frac{E_{O_2}}{5} \left( T_2^5 - T_1^5 \right) \right\]

\[
+ K_2 \left[ A_{\text{CO}_2}(T_2 - T_1) + \frac{B_{\text{CO}_2}}{2} \left( T_2^2 - T_1^2 \right) + \frac{C_{\text{CO}_2}}{3} \left( T_2^3 - T_1^3 \right) + \frac{D_{\text{CO}_2}}{4} \left( T_2^4 - T_1^4 \right) \right.
\]

\[
+ \frac{E_{\text{CO}_2}}{5} \left( T_2^5 - T_1^5 \right) \left\} \right) + \left( \frac{K_3 f}{1 + y} + m \right) \left[ A_{H_2O}(T_2 - T_1) + \frac{B_{H_2O}}{2} \left( T_2^2 - T_1^2 \right) \right.
\]

\[
+ \frac{C_{H_2O}}{3} \left( T_2^3 - T_1^3 \right) + \frac{D_{H_2O}}{4} \left( T_2^4 - T_1^4 \right) + \frac{E_{H_2O}}{5} \left( T_2^5 - T_1^5 \right) \left\} \right)
\]

(B7)

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

\[
\Delta h = H(T_1, T_2, f)
\]

(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
\[ \Delta h = \frac{1}{1 + f + m} (1 + m) H(T_1, T_2, 0) + f I(T_1, T_2) \]  

(B9)

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

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

(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

\[ \Delta \varphi = \int_{T_1}^{T_2} \frac{c_p}{T} \, dT \]  

(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
\[ \Delta \varphi = \left( \frac{1}{1 + f + m} \right) \left( A_{\text{air}} \ln \frac{T_2}{T_1} + B_{\text{air}} (T_2 - T_1) + \frac{C_{\text{air}}}{2} (T_2^2 - T_1^2) + \frac{D_{\text{air}}}{3} (T_2^3 - T_1^3) \right) \]

\[ + \frac{E_{\text{air}}}{4} (T_2^4 - T_1^4) + \left( \frac{f}{1 + y} \right) \left( K_1 \left[ A_{\text{O}_2} \ln \frac{T_2}{T_1} + B_{\text{O}_2} (T_2 - T_1) + \frac{C_{\text{O}_2}}{2} (T_2^2 - T_1^2) \right] \right) \]

\[ + \frac{D_{\text{O}_2}}{3} (T_2^3 - T_1^3) + \frac{E_{\text{O}_2}}{4} (T_2^4 - T_1^4) \right) + K_2 \left[ A_{\text{CO}_2} \ln \frac{T_2}{T_1} + B_{\text{CO}_2} (T_2 - T_1) \right] \]

\[ + \frac{C_{\text{CO}_2}}{2} (T_2^2 - T_1^2) + \frac{D_{\text{CO}_2}}{3} (T_2^3 - T_1^3) + \frac{E_{\text{CO}_2}}{4} (T_2^4 - T_1^4) \right) \]

\[ + \left( \frac{K_3 f}{1 + y} + m \right) \left[ A_{\text{H}_2\text{O}} \ln \frac{T_2}{T_1} + B_{\text{H}_2\text{O}} (T_2 - T_1) + \frac{C_{\text{H}_2\text{O}}}{2} (T_2^2 - T_1^2) \right] \]

\[ + \frac{D_{\text{H}_2\text{O}}}{3} (T_2^3 - T_1^3) + \frac{E_{\text{H}_2\text{O}}}{4} (T_2^4 - T_1^4) \right) \] (B12)

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

\[ \Delta \varphi = \Phi(T_1, T_2, f) \] (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

\[ M = \frac{1 + f + m}{\sum \frac{w}{M}} \] (B14)
With \( w \) obtained from table IV and \( M \) from table V, equation (B14) expands to

\[
M = \frac{1 + f + m}{0.034522 + 0.24802 y \left( \frac{f}{1 + y} \right) + \frac{m}{18.016}} \quad (B15)
\]
APPENDIX C

FUEL PROPERTIES AND COMPRESSION

Thermodynamic Properties

The heat capacity of the \( \text{CH}_x \) fuel is expressed as

\[
\frac{c_{p,f}}{f} = A_f + B_f T + C_f T^2
\]  \hfill (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

\[
\Delta h_f = A_f(T_2 - T_1) + \frac{B_f}{2}(T_2^2 - T_1^2) + \frac{C_f}{3}(T_2^3 - T_1^3)
\]  \hfill (C2)

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

\[
\Delta \phi_f = A_f \ln \frac{T_2}{T_1} + B_f(T_2 - T_1) + \frac{C_f}{2}(T_2^2 - T_1^2)
\]  \hfill (C3)

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

\[
\Delta h_f = H_f(T_1, T_2)
\]  \hfill (C4)

and

\[
\Delta \phi_f = \Phi_f(T_1, T_2)
\]  \hfill (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 \( T_{f,\text{in}} \), fuel inlet pressure \( p_{f,\text{in}} \), 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 \( r_{cy} \)

\[
p_{f, C, \text{ex}} = p_0 r_{cy}
\]

Each fuel compressor is assumed to have the same pressure ratio

\[
r_{C, f} = \left( \frac{p_{f, C, \text{ex}}}{p_{f, \text{in}}} \right)^{1/n_{C, f}}
\]

and each intercooler is assumed to cool the fuel back to the fuel inlet temperature \( T_{f, \text{in}} \). The fuel-compressor exit temperature \( T_{f, C, \text{ex}} \) is then obtained from

\[
\Phi_f(T_{f, \text{in}}, T_{f, C, \text{ex}}) = \frac{1}{\eta_{C, f, p}} \frac{R_f}{J} \ln r_{C, f}
\]

and the fuel-compression specific work is

\[
\Delta h_{f, C} = n_{C, f} H_f(T_{f, \text{in}}, T_{f, C, \text{ex}})
\]
REFERENCE

### 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, RCOS P(1, 2)=.20, .25, .25, .30, I COOL=1,
I COOL(1, 2)=3*1, RI NT=.98, TI NT=306., NTURB=2, 2, I BURN=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, TFI N=288., P RFIN=35., ETACF=.88, MWF=18.85, ETAT=.90,
TSPLI T=2*5, TSPLI T(1, 2)=.4, 6, WCAOWA=2*.025, WCAOWA(1, 2)=2*0.25, R65=.99, ER=.9,
R3 2=.98, R76=.96, R5 TEX=.98, ETAETA=.95, TTOL=.05, I U=1 $ 
```
## Table III - Detailed Output for One Compression Ratio

<table>
<thead>
<tr>
<th>Pressure Ratio</th>
<th>Cold Air</th>
<th>Inlet Flow</th>
<th>Inlet Press</th>
<th>Inlet Temp</th>
<th>Exit Press</th>
<th>Exit Temp</th>
<th>Mix Temp</th>
<th>Mix Flow</th>
<th>Work</th>
<th>Net Power</th>
<th>Fuel Cons</th>
<th>Cycle Eff</th>
<th>Fuel Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>50.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shaf 2 - Comp 4</td>
<td>NO</td>
<td>1.0100</td>
<td>10.0</td>
<td>288.0</td>
<td>20.0</td>
<td>361.5</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Shaf 2 - Comp 3</td>
<td>YES</td>
<td>1.0100</td>
<td>19.9</td>
<td>306.0</td>
<td>35.7</td>
<td>369.7</td>
<td></td>
<td></td>
<td></td>
<td>74.78</td>
<td>868.08</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shaf 2 - Comp 2</td>
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<td>1.0100</td>
<td>35.0</td>
<td>306.0</td>
<td>63.0</td>
<td>369.7</td>
<td></td>
<td></td>
<td></td>
<td>64.91</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shaf 2 - Comp 1</td>
<td>YES</td>
<td>1.0100</td>
<td>61.7</td>
<td>306.0</td>
<td>98.7</td>
<td>356.0</td>
<td></td>
<td></td>
<td></td>
<td>64.91</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shaf 1 - Comp 1</td>
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<td>1.0100</td>
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<td>306.0</td>
<td>462.5</td>
<td>504.4</td>
<td></td>
<td></td>
<td></td>
<td>204.23</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recuperator</td>
<td>0.9070</td>
<td>462.5</td>
<td>504.4</td>
<td>453.3</td>
<td>903.9</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Shaf 1 - Turb 1</td>
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<td>0.9225</td>
<td>434.7</td>
<td>1389.0</td>
<td>323.3</td>
<td>1300.2</td>
<td>1281.1</td>
<td>0.9478</td>
<td>111.80</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shaf 1 - Turb 2</td>
<td>YES</td>
<td>0.9511</td>
<td>310.7</td>
<td>1389.0</td>
<td>223.8</td>
<td>1303.6</td>
<td>1285.1</td>
<td>0.9763</td>
<td>108.44</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shaf 2 - Turb 1</td>
<td>YES</td>
<td>0.9797</td>
<td>221.9</td>
<td>1389.0</td>
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<td>1068.3</td>
<td>1.0049</td>
<td>387.34</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
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<td>1.0155</td>
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<td>1389.0</td>
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<td>956.2</td>
<td>946.4</td>
<td>1.0407</td>
<td>552.36</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recuperator</td>
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<td>10.8</td>
<td>946.4</td>
<td>10.3</td>
<td>625.1</td>
<td>625.1</td>
<td>1.0407</td>
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</tr>
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</table>
### TABLE II - OUTPUT FOR ILLUSTRATIVE EXAMPLE

2-SHAFT RELIABLE SYSTEM OPERATING AT 400 RTI, HUMIDITY = 40%, TEMPERATURE = 80°C, TOTAL PRESSURE REC = 0.990, EXIT STAT/TOT PRESS RATIO=0.980

<table>
<thead>
<tr>
<th>Shaft</th>
<th>Flow Rate</th>
<th>Total Inlet Flow Rate</th>
<th>Total Compression</th>
<th>Total Expansion</th>
<th>Total Power</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>COMPR 1</td>
<td>10000</td>
<td>10000</td>
<td>10000</td>
<td>10000</td>
<td>10000</td>
<td>0.980</td>
</tr>
<tr>
<td>COMPR 2</td>
<td>10000</td>
<td>10000</td>
<td>10000</td>
<td>10000</td>
<td>10000</td>
<td>0.980</td>
</tr>
</tbody>
</table>

**Shaft 1** has 1 compressor that supplies 0.40 kW of shaft compression and 1 turbine that delivers 1.00 kW of compressor shaft power.

**Shaft 2** has 2 compressors that supply 0.60 kW of total compression and 2 turbines that deliver 1.00 kW of compressor shaft power.

**Cycle Efficiency:**

- Shaft 1: 0.980
- Shaft 2: 0.980

**Pressure Values:**

- Shaft 1: 49500 kPa
- Shaft 2: 52000 kPa

**Cycle Power:**

- Shaft 1: 1.0 kW
- Shaft 2: 1.0 kW

**Ratio:**

- Shaft 1: 1.0
- Shaft 2: 1.0

**Power Values:**

- Shaft 1: 0.4785 kW/kg
- Shaft 2: 0.4785 kW/kg

**Table of Values:**

<table>
<thead>
<tr>
<th>Pressure</th>
<th>Shaft 1</th>
<th>Shaft 2</th>
<th>Total</th>
<th>Cycle</th>
<th>Fuel</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>5000</td>
<td>2.15</td>
<td>2.15</td>
<td>4.30</td>
<td>0.3772</td>
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</tr>
<tr>
<td>10000</td>
<td>4.30</td>
<td>4.30</td>
<td>8.60</td>
<td>0.7544</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>15000</td>
<td>6.45</td>
<td>6.45</td>
<td>12.90</td>
<td>1.1300</td>
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<tr>
<td>20000</td>
<td>8.60</td>
<td>8.60</td>
<td>17.20</td>
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<tr>
<td>25000</td>
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<td>10.75</td>
<td>21.50</td>
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<tr>
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<td>30.10</td>
<td>69.20</td>
<td>5.1151</td>
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<tr>
<td>75000</td>
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<td>80000</td>
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</table>

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### TABLE IV. - COMBUSTION REACTION STOICHIOMETRY

<table>
<thead>
<tr>
<th>Component</th>
<th>Reactant mass per unit mass of air</th>
<th>Mass formed (+) or consumed (-) by reaction per unit mass of air</th>
<th>Product mass per unit mass of air of air</th>
</tr>
</thead>
<tbody>
<tr>
<td>N\textsubscript{2}</td>
<td>0.7552</td>
<td>0</td>
<td>0.7552</td>
</tr>
<tr>
<td>O\textsubscript{2}</td>
<td>0.2314</td>
<td>( \frac{32.000 + 95.317460 y f}{12.010(1 + y)} )</td>
<td>( \frac{0.2314 - 2.664446 + 7.936508 y f}{1 + y} )</td>
</tr>
<tr>
<td>A</td>
<td>0.0129</td>
<td>0</td>
<td>0.0129</td>
</tr>
<tr>
<td>CO\textsubscript{2}</td>
<td>0.0005</td>
<td>( \frac{44.010}{12.010(1 + y)} )</td>
<td>( \frac{0.0005 + 3.664446 y f}{1 + y} )</td>
</tr>
<tr>
<td>H\textsubscript{2}O</td>
<td>m</td>
<td>( \frac{107.327460 y f}{12.010(1 + y)} )</td>
<td>m + ( \frac{8.936508 y f}{1 + y} )</td>
</tr>
<tr>
<td>CH\textsubscript{x}</td>
<td>f</td>
<td>-f</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>( 1 + m + f )</td>
<td>0</td>
<td>( 1 + m + f )</td>
</tr>
</tbody>
</table>

### TABLE V. - COEFFICIENTS AND MOLECULAR WEIGHTS OF COMPONENTS

<table>
<thead>
<tr>
<th>Components</th>
<th>Coefficients in equation (B4), SI units (U.S. customary units)</th>
<th>Molecular weight, M</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>N\textsubscript{2}</td>
<td>1064.69</td>
<td>(-246.550\times10^{-3})</td>
</tr>
<tr>
<td>(0.25410)</td>
<td>(-0.032690\times10^{-3})</td>
<td>(0.047685\times10^{-6})</td>
</tr>
<tr>
<td>O\textsubscript{2}</td>
<td>852.001</td>
<td>223.848\times10^{-3}</td>
</tr>
<tr>
<td>(0.20334)</td>
<td>(0.029680\times10^{-3})</td>
<td>(0.0089971\times10^{-6})</td>
</tr>
<tr>
<td>CO\textsubscript{2}</td>
<td>464.968</td>
<td>1592.13\times10^{-3}</td>
</tr>
<tr>
<td>(0.11097)</td>
<td>(0.21110\times10^{-3})</td>
<td>(-0.088140\times10^{-6})</td>
</tr>
<tr>
<td>H\textsubscript{2}O</td>
<td>1854.76</td>
<td>-250.057\times10^{-3}</td>
</tr>
<tr>
<td>(0.44266)</td>
<td>(-0.033155\times10^{-3})</td>
<td>(0.087761\times10^{-6})</td>
</tr>
<tr>
<td>A</td>
<td>521.156</td>
<td>0</td>
</tr>
<tr>
<td>(0.12438)</td>
<td></td>
<td>(0)</td>
</tr>
</tbody>
</table>
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°F).
(a) Maximum number of components.

(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: $\eta_{\text{p}} = 0.88$, $\eta_{\text{INT}} = 0.98$, $\eta_{\text{B}} = 0.98$, $r_B = 0.97$, $\eta_T, p = 0.90$, and $w_{T, c}/w_1 = 0.025$. 
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—National Aeronautics and Space Act of 1958

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