Documentation of the Benson Diesel Engine Simulation Program

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1.0 INTRODUCTION

This report documents the Benson Diesel Engine Simulation Program and explains how it can be used to predict the performance of diesel engines. This program was obtained from the Garrett Turbine Engine Company but has been extensively modified since that time. The program is a thermodynamic simulation of the diesel engine cycle which uses a single zone combustion model. It can be used to predict the effect of changes in engine design and operating parameters such as valve timing, speed and boost pressure. The most significant change made to this program is the addition of a more detailed heat transfer model to predict metal part temperatures.

This report contains a description of the sub-models used in the Benson program, a description of the input parameters and sample program runs.

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2.0 OVERVIEW OF PROGRAM

As shown in Figure 2.1, the Benson program uses a large number of subroutines to accomplish specialized tasks during the calculation procedure. However, most of the cycle calculations are performed in two subroutines: CYLNDR, which calculates the gas exchange processes and POWER which takes care of compression, combustion and expansion. The development of the energy balance and a discussion of how it is evaluated is given below.

2.1 Energy Balance - Benson Model

The chemical equation for the combustion process in the diesel engine can be simplified to the following expression.

$$C_n H_m + \frac{[n + m/2]}{\phi} [O_2 + 3.77 \, N_2]$$
$$\rightarrow n \, CO_2 + \frac{m}{2} H_2O + \left[\frac{[n + m/2]}{\phi} - n - \frac{m}{4}\right]O_2 + 3.77 \frac{[n + m/2]}{\phi} N_2$$
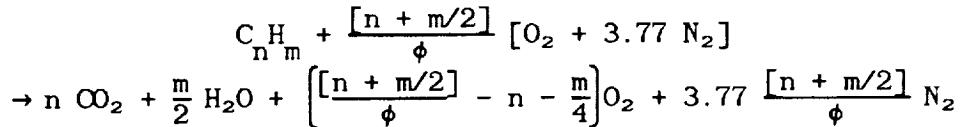
where n and m are stoichiometric coefficients and ϕ is the equivalence ratio.

The first law of thermodynamics must be satisfied at all times as this reaction occurs in the engine. For the period when the intake and exhaust ports are closed, the first law can be written for an interval of time from t to t+dt,

$$E_2 - E_1 = \delta Q - \delta W$$

where E_2 and E_1 are given by

$$E_2 = a_{N_2} e_{N_2}(T_2) + a_{O_2} e_{O_2}(T_2) + a_{CO_2} e_{CO_2}(T_2) + a_{H_2O} e_{H_2O}(T_2) + a_{C_n H_m} e_{C_n H_m}(T_2)$$

$$E_1 = b_{N_2} e_{N_2}(T_1) + b_{O_2} e_{O_2}(T_1) + b_{CO_2} e_{CO_2}(T_1) + b_{H_2O} e_{H_2O}(T_1) + b_{C_n H_m} e_{C_n H_m}(T_1)$$

The coefficients, a_i and b_i, are the number of moles of species i present in the cylinder and

$$e_i(T) = e_i(0) + [e_i(T) - e_i(0)]$$

```
        ┌─────────────────────┐
        │ SUBROUTINE  BENSON  │
        └─────────────────────┘
                   │
                   ▼
  ┌─────────────────────┐          ┌─────────────────────┐
  │ Open input/output   │ ───────► │ SUBROUTINE  FOPEN   │
  │ files               │ ◄─────── │                     │
  │ CALL FOPEN          │          └─────────────────────┘
  └─────────────────────┘
                   │
                   ▼
  ┌─────────────────────┐          ┌─────────────────────┐
  │ Read input variables│ ───────► │ SUBROUTINE  INPUT   │
  │ CALL INPUT          │ ◄─────── └─────────────────────┘
  │ CALL INPUT2         │          ┌─────────────────────┐
  │                     │ ───────► │ SUBROUTINE  INPUT2  │
  │                     │ ◄─────── └─────────────────────┘
  └─────────────────────┘
                   │
                   ▼
  ┌─────────────────────┐   ┌──────────────┐   ┌────────┐
  │ Initialize variables│ ─►│ SUBROUTINE   │─► │ UNITT  │
  │ CALL INITLZ         │ ◄─│ INITLZ       │◄─ │ UNITP  │
  └─────────────────────┘   └──────────────┘   │ UNITW  │
                   │                            └────────┘
                   ▼
  ┌─────────────────────┐          ┌─────────────────────┐
  │ Write file headings │ ───────► │ SUBROUTINE  HEADER  │
  │ to output files     │ ◄─────── └─────────────────────┘
  │ CALL HEADER         │
  └─────────────────────┘
                   │
                   ▼
  ┌─────────────────────┐   ┌──────────────┐   ┌────────┐
  │ Perform cycle       │ ─►│ SUBROUTINE   │─► │ SPLFIT │
  │ calculations        │ ◄─│ CYLNDR       │◄─ │ STROK  │
  │ CALL CYLNDR         │   └──────────────┘   │ MASSFL │
  └─────────────────────┘        │   ▲         │ SREA   │
                   │              ▼   │         │ BAL    │
                   ▼        ┌──────────────┐    │ CYLVOL │
  ┌─────────────────────┐   │ SUBROUTINE   │    └────────┘
  │       RETURN        │   │ POWER        │
  └─────────────────────┘   └──────────────┘
                                 │   ▲
                                 ▼   │
                           ┌──────────────┐
                           │ SUBROUTINE   │
                           │ HTRANS       │
                           └──────────────┘
                                 │   ▲
                                 ▼   │
                           ┌──────────────┐
                           │ SUBROUTINE   │
                           │ ELIM         │
                           └──────────────┘
```

Figure 2.1 Flow Chart for Benson Program

where $e_i(0)$ is the partial molar internal energy of species i at absolute zero and $[e_i(T) - e_i(0)]$ is the sensible internal energy difference between absolute zero and T.

For convenience, the sum of the sensible terms can be defined as E^*

$$E^*(T) = a_{N_2}[e_{N_2}(T) - e_{N_2}(0)] + a_{O_2}[e_{O_2}(T) - e_{O_2}(0)]$$
$$+ a_{CO_2}[e_{CO_2}(T) - e_{CO_2}(0)] + a_{H_2O}[e_{H_2O}(T) - e_{H_2O}(0)]$$

Thus $E_2 - E_1$ can be written as

$$E_2 - E_1 = (E_2^* - E_1^*) + (a_{N_2} - b_{N_2})e_{N_2}(0) + (a_{O_2} - b_{O_2})e_{O_2}(0)$$
$$+ (a_{CO_2} - b_{CO_2})e_{CO_2}(0) + (a_{H_2O} - b_{H_2O})e_{H_2O}(0)$$
$$+ (a_{C_nH_m} - b_{C_nH_m})e_{C_nH_m}(0)$$

If dM_f moles of fuel are burned as the reaction progresses from t to t+dt, atom balances can be used to fix relations between the a_i and b_i coefficients.

$$a_{N_2} = b_{N_2}$$
$$a_{O_2} = b_{O_2} - [n + \frac{m}{4}] dM_f$$
$$a_{CO_2} = b_{CO_2} + n \, dM_f$$
$$a_{H_2O} = b_{H_2O} + \frac{m}{2} dM_f$$
$$a_{C_nH_m} = b_{C_nH_m} - dM_f$$

The constant volume heat of combustion with the water in the products present as vapor can be defined as

$$Q_v \equiv E_{prod}(T_s) - E_{reac}(T_s)$$

where $E_{prod} = n \, e_{CO_2}(T_s) + \frac{m}{2} e_{H_2O}(T_s)$

$E_{reac} = [n + m/2] e_{O_2}(T_s) + e_{C_nH_m}(T_s)$

T_s = reference temperature where Q_v is defined.

By combining the definition of the constant volume heat of combustion and the definition of the constant volume heat of combustion at absolute zero

$$\Delta E_o \equiv E_{prod}(0) - E_{reac}(0)$$

we can obtain

$$Q_v = \Delta E_o + n[e_{CO_2}(T_s) - e_{CO_2}(0)] + \frac{m}{2}[e_{H_2O}(T_s) - e_{H_2O}(0)]$$
$$- (n + \frac{m}{4})[e_{O_2}(T_s) - e_{O_2}(0)] - [e_{C_nH_m}(T_s) - e_{C_nH_m}(0)]$$

Substituting this into the equation for (E_2-E_1) gives

$$E_2 - E_1 = E_2^* - E_1^* - Q_v \, dM_f - (a_{CO_2} - b_{CO_2})[e_{CO_2}(T_s) - e_{CO_2}(0)]$$
$$- (a_{H_2O} - b_{H_2O})[e_{H_2O}(T_s) - e_{H_2O}(0)]$$
$$+ (a_{O_2} - b_{O_2})[e_{H_2O}(T_s) - e_{H_2O}(0)]$$
$$+ a_{C_nH_m}[e_{C_nH_m}(T_2) - e_{C_nH_m}(T_s)]$$
$$- b_{C_nH_m}[e_{C_nH_m}(T_1) - e_{C_nH_m}(T_s)]$$

Since the fuel is such a small fraction of the total mass in the cylinder, the fuel internal energy terms can be neglected and the terms evaluated at T_s can be written as

$$E_2 - E_1 = [E_2^* - E_2^*(T_s)] - [E_1^* - E_1^*(T_s)] - Q_v \, dM_f$$

where $E_1^*(T_s)$ designates the sum of the sensible internal energy terms using the composition at state 1 and evaluating the partial molar internal energies at T_s.

Finally, the first law of thermodynamics can be written as

$$[E_2^* - E_2^*(T_s)] - [E_1^* - E_1^*(T_s)] - Q_v \, dM_f = \delta Q - \delta W$$

for the period where the intake and exhaust ports are closed and when the ports are open the first law becomes

$$[E_2^* - E_2^*(T_s)] - [E_1^* - E_1^*(T_s)] - Q_v \, dM_f = \delta Q - \delta W + m_{in}h_{in} - m_{out}h_{out}$$

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Each of the terms in this equation will be discussed in turn.

2.2 Change in Internal Energy

The internal energy is calculated using fourth order polynomial curve fits of the JANAF tables [1]. These curve fits provide the sensible enthalpy change between absolute zero and some temperature T. The values of internal energy are obtained from $e = h - RT$.

2.3 Combustion

The rate at which fuel is burned, and its energy released, is determined by the choice of combustion model. Currently, four combustion models may be selected for use in the Benson Program along with one user supplied model. The choice of model is determined by the values of the input parameters, NPCWF and DEL3. The values of these parameters corresponding to each model are given below.

NPCWF = 0 and DEL3 > 0.	Wiebe combustion model
NPCWF = 0 and DEL3 = 0.	AVL combustion model
NPCWF = -1	Whitehouse-Way combustion model
NPCWF = 1	Watson combustion model
NPCWF = 2	User supplied model

Each of the combustion models will be discussed in turn.

2.3.1 Wiebe Model

The Wiebe model is a simple functional model consisting of a two parameter exponential function which has the flexibility to assume the shape of known burning rate curves in supercharged diesel engines. The following

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expression is used to calculate the fraction of fuel burned.

$$\% \text{ Fuel Burned} = 100. \times [1 - \exp(-\delta_1 \tau^{\delta_2})]$$

where δ_1 and δ_2 are parameters which determine the shape of the function

     τ is a dimensionless time parameter $= \dfrac{CA - ACB}{HRD}$

     CA is the current crank angle

     ACB is the crank angle at which combustion begins

     HRD is the combustion duration, equal to (ACF - ACB)

2.3.2 The AVL Model

The AVL model is the same as the Wiebe model except that AVL has recommended a way to specify the combustion duration. AVL suggests that the combustion duration parameter be chosen so that it is a linear function of the equivalence ratio.

$$HRD = 15 + 115 \ (\phi)$$

where ϕ is the fuel-air equivalence ratio.

2.3.3 The Whitehouse-Way Model

Of the models supplied with the Benson Program, the Whitehouse-Way [2,3] model is the only one that attempts to model the physics of the combustion event. The fuel injection rate is supplied as an input and the model relates the burning rate to this injection rate. The injection rate is specified by two parameters: the initial injection rate and the timing at which the maximum injection rate occurs. The injection rate is defined by the following function.

$$\text{Injection Rate} = AAN(1) + \left[\frac{AA2 - AAN(1)}{AAN(2)}\right] \tau \qquad\qquad 0 < \tau < AAN(2)$$

$$= \frac{AA2}{AAN(2) - 1} \ (\tau - 1) \qquad\qquad AAN(2) < \tau < 1$$

where AAN(1) and AAN(1) are user specified injection rate parameters

$$AA2 = 2 - \left[AAN(2) \cdot AAN(1)\right]$$

τ = defined same as above under Wiebe

Fuel is assumed to be prepared for combustion according to a relation of the form

$$P = K \ M_i^{1-x} \ M_u^{x} \ P_{O_2}^{m}$$

where x and m are empirical parameters which should be constant for a given

problem.

K is a parameter which needs to be determined for each individual

problem.

P is the fuel preparation rate.

M_i is the mass of fuel injected.

M_u is the mass of fuel unburnt.

The burning rate is calculated from an exponential expression of the form:

$$R = \frac{K}{N} \frac{P_{O_2}}{\sqrt{T}} \int (P - R) \ dx \cdot \exp(\frac{-act}{T})$$

where R is the burning rate

"act" is an effective activation energy which must be specified

P_{O_2} is the partial pressure of oxygen

N is the engine speed, Rev/min

The integral is evaluated in the Benson program as a summation

$$\Sigma(P-R)\Delta CA$$

and R is calculated using the value of the summation calculated up to the

beginning of the time step.

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Although the authors of this model have attempted to incorporate combustion theory into this model, it should be recognized that it is based on an understanding of diesel combustion that assumes droplet effects are important. Current understanding of diesel combustion assumes that the fuel vaporizes very soon after it is injected and that the combustion has more in common with a turbulent gaseous diffusion flame than droplet combustion.

2.3.4 The Watson Model

The Watson model [4] is a functional model, like the Wiebe model, which uses simple algebraic functions chosen for their ability to produce burning curves similar to those observed in diesel engines. The Watson model was developed to reproduce the "premixed spike" at the start of typical diesel heat release curve. Instead of a single exponential curve like the Wiebe model, the Watson model uses two curves which are superimposed. The first curve has a very high rate of combustion and simulates the premixed combustion. This curve dies out very quickly after the start of combustion and the second curve, which is an exponential exactly like the Wiebe model, becomes dominant. A weighting factor is used to determine how much emphasis is given to each of the curves. The Watson model is as follows.

$$\% \text{ Fuel Burned} = 100 \cdot \left[\beta \left[1 - [1 - \tau^{C_{p_1}}]^{C_{p_2}} \right] + (1 - \beta) \left[1 - \exp[-C_{d_1} \tau^{C_{d_2}}] \right] \right]$$

where β = weighting factor = $1. - \delta_1 \phi^{\delta_2} \text{actr}^{-\delta_3}$

$$C_{p_1} = 2. + 1.25 \times 10^{-8} (\text{actr} \cdot \text{Nr} \cdot 60.)^{2.4}$$

$$C_{p_2} = 5000.$$

$$C_{d_1} = 14.2 \phi^{-0.644}$$

$$C_{d_2} = 0.79 \cdot C_{d_1}^{0.25}$$

actr = ignition delay period, which may be estimated from

$$actr = 3.45 \exp(2100./T_m) \, P_m^{-1.02}$$

where T_m and P_m are the mean temperature and pressure

during the ignition delay period.

ϕ = equivalence ratio

Nr = engine speed, rev/sec

δ_1, δ_2, δ_3 = parameters chosen to vary shape of the model.

(Watson suggests $\delta_1 = 0.926$, $\delta_2 = 0.37$ and $\delta_3 = -0.26$)

The Watson model, because it can simulate premixed combustion, is appropriate for conditions where premixed combustion is important such as light loads and cold starting with naturally aspirated engines. This model is also appropriate when running on low cetane fuels. Under highly supercharged conditions the amount of premixed combustion will be small ($\beta \cong 0$) so the Watson model reduces to the Wiebe model.

2.3.5 User supplied model

The user may provide a mass burning rate function of any arbitrary shape through the subroutine BURNRT. The subroutine should be written so that at a given value of crank position, designated by ANGLA, the amount of fuel burned in a one degree time step is returned as DWFUEL.

2.4 Heat Transfer

Two correlations are available for use in calculating the heat transfer in the Benson Program: The Annand [5] correlation and the Woschni [6] correlation. The Annand correlation takes the following form.

$$q/A = \frac{a\ k}{D}\ (Re)^b\ (T - T_w) + c\ (T^4 - T_w^4)$$

where q = heat transfer

A = Area of surface exposed to heat transfer

k = Thermal conductivity

Re = Reynolds number = $\dfrac{\rho\ \bar{U}_p\ D}{\mu}$

T = Gas Temperature

T_w = Wall Temperature

$\bar{U}_p$ = Mean Piston speed

ρ = gas density

μ = gas viscosity

D = Bore of engine

a,b,c = User supplied constants, called ANNA, ANNB and ANNC in the Benson

Program.

The constant, a, depends on the intensity of gas motion in the cylinder and Annand recommends a value between 0.35 and 0.8, with higher values corresponding to more intense motion. The constant, b, should be 0.7 and the constant c should be:

during compression, c = 0.

during combustion and expansion,

$c = 3.266 \times 10^{-11} \dfrac{kW}{m^2 - K^4}$ for diesel engine

$c = 4.286 \times 10^{-12} \dfrac{kW}{m^2 - K^4}$ for spark ignition engine

Woschni's correlation is of the following form.

$$q/A = a\ \frac{k}{D}\ (Re)^b\ (T - T_w)$$

where Re = Reynolds Number = $\dfrac{\rho\,w\,D}{\mu}$

w = in-cylinder gas velocity

$$= 6.18\ \overline{U}_p \quad \text{during scavenging period, m/s.}$$

$$= 2.28\ \overline{U}_p \quad \text{during compression, m/s}$$

$$= 2.28\ \overline{U}_p + 3.24 \times 10^{-3}\ \frac{V_s\ T_1}{P_1\ V_1}\ (p - p_o) \quad \text{during combustion}$$

and expansion, m/s

V_s = displacement volume.

P_1, V_1, T_1 = pressure, volume and temperature at some point when the cylinder is closed for use in estimating the trapped mass.

p = instantaneous cylinder pressure

P_o = cylinder pressure for an unfired cycle at the same crank position and under the same conditions as p.

a,b = User supplied constants, called ANNA and ANNB in the Benson program. Woschni recommends a value of 0.035 for constant a and 0.8 for constant b.

The principal difference between these two correlations is that Annand's correlation separates the convective and radiative terms while Woschni's correlation combines the convection and radiation in a single term. The user supplied parameters ANNA, ANNB and ANNC are used to select which correlation will be used in the program and to adjust the significance of heat transfer in the energy balance. When ANNC is equal to 0.0, the Woschni correlation will be used, and when ANNC is equal to a non-zero number, the Annand correlation will be used. ANNB is normally set to the respective author's suggested value. ANNA is also normally set to the author's values unless data is available which indicate the total amount of heat loss for the cycle in which

case ANNA can be adjusted to obtain this amount.

2.5 Work

The work term is calculated from time step to time step by taking the average pressure for the time step multiplied by the volume change for the time step.

$$\delta W = \frac{P_1 + P_2}{2} \cdot (V_2 - V_1)$$

2.6 Mass Flow Terms

The mass flow terms are calculated using subroutine MASSFL which calculates the mass entering or leaving the cylinder through the intake or exhaust ports. The techniques involved in this calculation are explained later in the discussion of that subroutine. After calculating the mass flow rates, the enthalpy is calculated using the polynomial curve-fits to the JANAF tables.

3.0 STEADY STATE HEAT TRANSFER ANALYSIS

3.1 Introduction

The original version of the Benson Program received from Garrett contains a simple heat transfer analysis which calculates convective heat transfer coefficients using either the Annand or the Woschni correlations as described in section 2.4. The analysis described in this section has been added to the Benson program to allow prediction of the effect of varying engine design parameters and operating conditions on metal part temperatures. The analysis provides an estimate of the gas and coolant side wall temperatures for the piston crown, the cylinder wall, the head and the exhaust valve along with the top compression ring temperature.

The model is one-dimensional and assumes the temperatures of the various components do not change during the cycle. The model has been developed for a single cylinder engine and can not distinguish between end cylinders or internal cylinders of a multi-cylinder engine. Submodels for the heat generated by piston/ring friction and for crevice volume heat transfer are included.

The analysis requires that a number of critical engine dimensions be specified along with heat transfer path lengths. Although these heat transfer path lengths can be estimated, a high level of accuracy requires that experimental measurements be used to calculate these path lengths and thus "tune" the heat transfer analysis. Without experimental data, the absolute values of the temperatures provided by this analysis can be no more accurate than the path lengths supplied as input. However, even though the numerical values of temperature may be in doubt, the analysis should still predict

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trends accurately.

3.2 Definition of Temperatures

Figure 3.1 shows a cross-section of the engine cylinder and identifies the various temperatures used in the analysis. Heat transfer occurs from the hot cylinder gases through the metal parts to the engine coolant. Three coolant temperatures are identified: the head coolant, the cylinder wall coolant and the piston coolant. The exhaust valve receives heat from the cylinder gases and loses it to the head by conduction through the valve seat, to the valve guide by conduction up the valve stem and to the exhaust port gases by convection.

The temperatures labeled in Figure 3.1 are defined below.

```
   TC1 = Piston cooling oil temperature
   TC2 = Cylinder wall coolant temperature
   TC3 = Head coolant temperature
  TWCC = Coolant side cylinder wall temperature
  TWGC = Gas side cylinder wall temperature
  TWCH = Coolant side head temperature
  TWGH = Gas side head temperature
  TWCP = Coolant side piston temperature
  TWGP = Gas side piston temperature
  TWPR = Piston rim temperature
  TWCR = Top compression ring temperature
  TWEV = Exhaust valve temperature
 TWEVG = Exhaust valve guide temperature
 TEXHP = Exhaust port gas temperature
```

3.3 Network Diagram

It is common in heat transfer problems to take advantage of the analogy between heat transfer through thermal resistance and direct current flow through electrical resistance. Steady state heat transfer relations such as

$$Q = h \, A \, (T_2 - T_1) \quad \text{and} \quad Q = k \, A \, \frac{(T_1 - T_2)}{L}$$
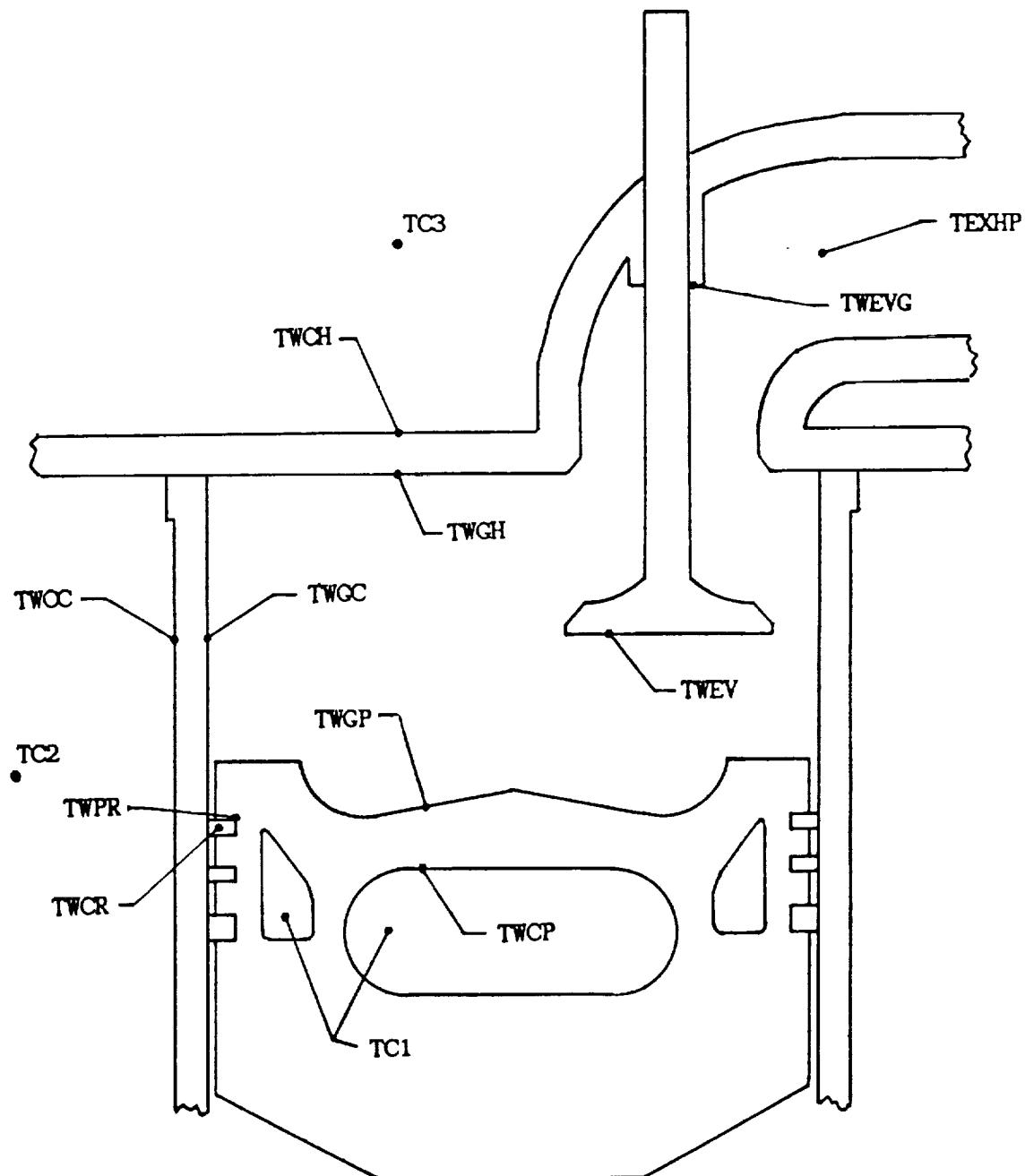
Figure 3.1 Cross-section of Cylinder

can be written as

$$Q = \frac{T_2 - T_1}{R_1} \quad \text{and} \quad Q = \frac{T_1 - T_2}{R_2}$$

where

$$R_1 = \frac{1}{h\,A} \quad \text{and} \quad R_2 = \frac{L}{k\,A}$$

the temperatures T_1 and T_2 represent potentials similar to voltages and the thermal resistances R_1 and R_2 are analogous to electrical resistances. One advantage of this approach is that it allows the heat transfer problem to be represented pictorially as a resistance network diagram.

Figure 3.2 shows the network diagram of the heat transfer problem identified above. The node points in this diagram correspond to the temperatures identified in Figure 3.2. The resistances are defined below.

R_1 = Conductive resistance between exhaust valve and the valve guide

R_2 = Convective resistance between exhaust valve and exhaust port gases.

R_3 = Conductive resistance between exhaust valve and the cylinder head through the valve seat.

R_4 = Conductive resistance through the cylinder head.

R_5 = Convective resistance between head and head coolant

R_6 = Conductive resistance from the gas side of piston crown to oil-cooled under-side of piston.

R_7 = Convective resistance on oil-cooled underside of piston

R_8 = Conductive resistance between piston and cylinder wall through the lower rings and the oil film.

R_9 = Conductive resistance between piston crown and piston rim.

R_{10} = Conductive resistance between top compression ring and the cylinder wall.

R_{11} = Conductive resistance through cylinder wall.

R_{12} = Conductive resistance between piston rim and top compression ring.

R_{13} = Convective resistance between cylinder wall and coolant.

R_{14} = Combined convective and radiative resistance between cylinder
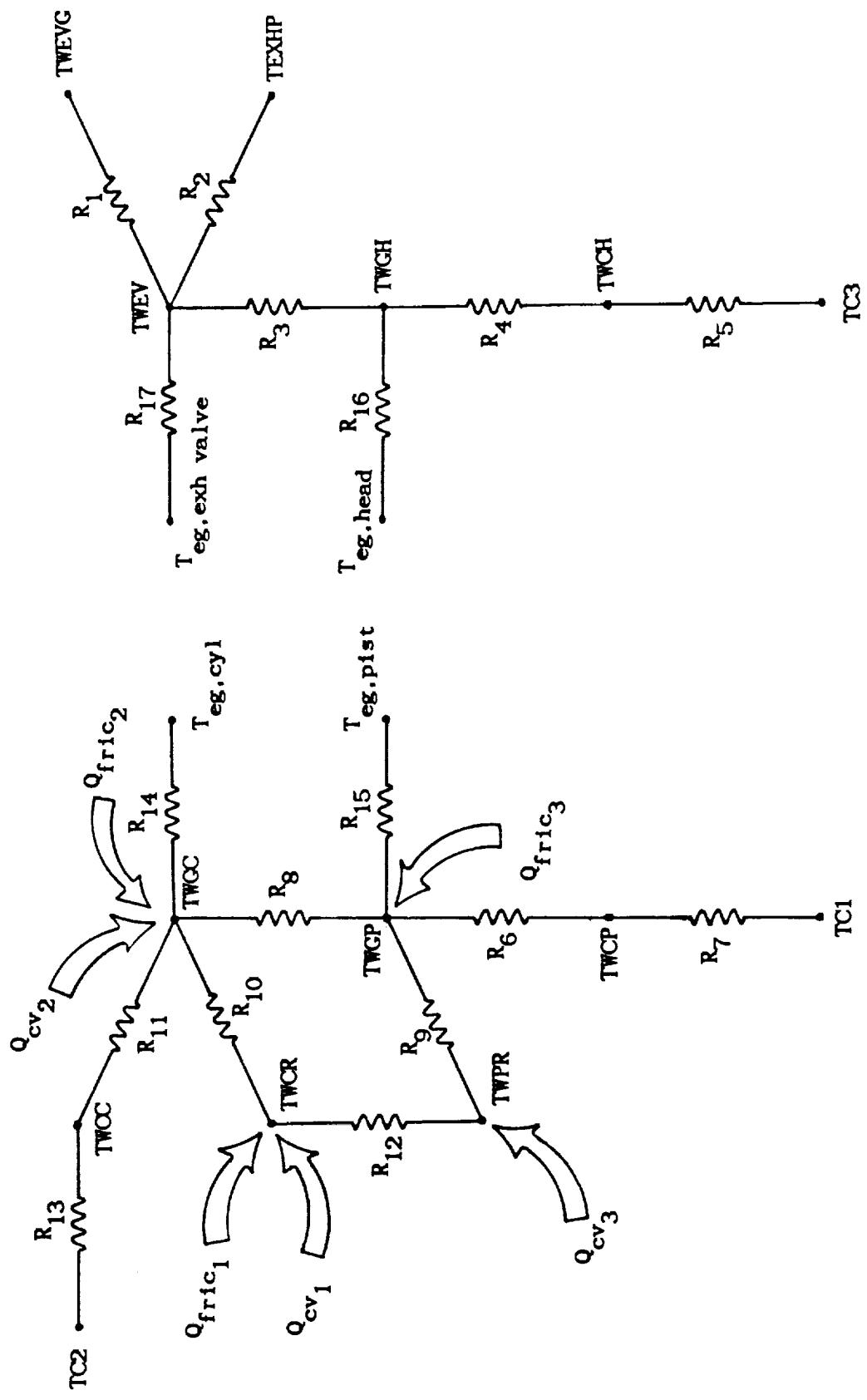
Figure 3.2 Network Diagram

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wall and cylinder gases.

R_{15} = Combined convective and radiative resistance between piston crown and cylinder gases.

R_{16} = Combined convective and radiative resistance between head and cylinder gases.

R_{17} = Combined convective and radiative resistance between exhaust valve and cylinder gases.

These resistances can be expressed in terms of more fundamental quantities as follows,

$$R_1 = \frac{XXEVG}{AEXVS \cdot CEXV} \qquad R_2 = \frac{1}{HEXHP \cdot AEXV}$$

$$R_3 = \frac{XXEVH}{AEXST \cdot CEXV} \qquad R_4 = \frac{XXHED}{AHEAD \cdot CHEAD}$$

$$R_5 = \frac{1}{HCHD \cdot AHEAD} \qquad R_6 = \frac{XXPIS}{APIST1 \cdot CPIST}$$

$$R_7 = \frac{1}{HOILP \cdot APIST2} \qquad R_8 = \frac{XXPSL}{ASLEEV \cdot CPIST}$$

$$R_9 = \frac{XXPCR}{APISTR \cdot CPIST} \qquad R_{10} = \frac{XXRSL}{ARING1 \cdot CRING}$$

$$R_{11} = \frac{XXSLV}{ASLEEV \cdot CSLEEV} \qquad R_{12} = \frac{XXPRG}{ARING2 \cdot CRING}$$

$$R_{13} = \frac{1}{HCSL \cdot ASLEEV}$$

where the heat transfer path lengths, areas, thermal conductivities, and convection coefficients are given below

XXEVG = Path length from exhaust valve to valve guide
XXEVH = Path length from exhaust valve to valve seat
XXHED = Path length through head
XXPIS = Path length through piston
XXPSL = Path length from piston to cylinder wall through lower rings and oil film
XXPCR = Path length from piston crown to piston rim
XXRSL = Path length from top compression ring to cylinder wall
XXSLV = Path length through cylinder wall
XXPRG = Path length from piston rim to top compression ring

AEXVS = Area of exhaust valve stem
AEXV = Area of exhaust valve exposed to combustion chamber
AEXST = Exhaust valve seat contact area

AHEAD = Cylinder head area not covered by exhaust valves
APIST1= Cross-sectional area of cylinder
APIST2= Surface area exposed to oil on underside of piston
ASLEEV= Characteristic area for heat transfer through cylinder wall
APISTR= Characteristic area between piston crown and piston rim
ARING1= Contact area between top compression ring and cylinder wall
ARING2= Contact area between top compression ring and piston rim

CEXV = Thermal conductivity of exhaust valve
CHEAD = Thermal conductivity of head
CPIST = Thermal conductivity of piston
CRING = Thermal conductivity of ring
CSLEEV= Thermal conductivity of cylinder wall

HEXHP = Convection coefficient from back side of exhaust valve to
        gases in exhaust port
HCHD = Convection coefficient for coolant on backside of head
HOILP = Convection coefficient for cooling oil on backside of piston
HCSL = Convection coefficient for coolant on backside of cylinder wall

R_{14} through R_{17} are combined convective and radiative resistances between

the time varying cylinder gas and the cylinder wall, and must be handled in a

special way. The heat transfer to one of the combustion chamber surfaces,

such as the head, piston, cylinder wall or exhaust valve, is given for an

entire cycle by

$$Q_{cycle} = \oint h_i \, A_i \, (T_i - T_{gas}) \, dt$$

and the average continuous heat transfer rate is obtained by multiplying by

the engine speed

$$\dot{Q} = N_r \oint h_i \, A_i \, (T_i - T_{gas}) \, dt$$

The convection coefficient, h_i, in this expression will be obtained from

either the Annand or Woschni correlations already present in the Benson

program. The Annand correlation includes a radiation term, $c \, (T_i^4 - T_{gas}^4)$, and

this term must be included by defining a psuedo-convective coefficient as

follows,

$$\dot{Q} = (h_c + h_r) \, A_i \, (T_i - T_{gas})$$

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where h_c = conventional convective coefficient,

h_r = radiative coefficient = $c \ [T_i^3 + T_i^2 \ T_{gas} + T_i \ T_{gas}^2 + T_{gas}^3]$

When using the Annand Correlation, the coefficient h_i is equal to the sum of h_c and h_r.

The integral in the expression for $\dot{Q}$ can be separated and T_i can be removed from its integral since it is a constant.

$$\dot{Q} = N_r \ T_i \oint h_i \ A_i \ dt \ - \ N_r \oint h_i \ A_i \ T_{gas} \ dt$$

or

$$\dot{Q} = N_r \oint h_i \ A_i \ dt \left[T_i - \frac{\oint h_i \ A_i \ T_{gas} \ dt}{\oint h_i \ A_i \ dt} \right]$$

By defining an effective gas temperature, T_{eg},

$$T_{eg} = \frac{\oint h_i \ A_i \ T_{gas} \ dt}{\oint h_i \ A_i \ dt}$$

the heat transfer rate from the gas to surface i becomes

$$\dot{Q} = N_r \oint h_i \ A_i \ dt \left[T_i - T_{eg} \right]$$

or

$$\dot{Q} = \frac{T_i - T_{eg}}{R}$$

where $R = \dfrac{1}{N_r \oint h_i \ A_i \ dt}$

It should be noted that the effective gas temperature will be a different value for each surface.

$T_{eg,exh \ valve}$ = Effective gas temperature for exhaust valve

$T_{eg,head}$ = Effective gas temperature for head

$T_{eg,pist}$ = Effective gas temperature for piston

$T_{eg,cyl}$ = Effective gas temperature for cylinder wall

3.4 Definition of Heat Generation Terms

In addition to the resistances and nodes shown on the network diagram in Figure 3.2, there are a number of heat source terms which are identified as either Q_{fric} or Q_{cv}. The Q_{fric} terms relate to the heat generated by friction between the cylinder wall and the piston and rings. The Q_{cv} terms relate to the heat transferred from the cylinder gases as they cool in the crevice volume between the piston and cylinder wall above the top ring.

3.4.1 Friction Submodel

The friction mean effective pressure (FMEP) due to piston/ring cylinder wall friction can be predicted using a correlation developed by Bishop [7].

$$\frac{FMEP}{\rho_o \bar{U}_p^2} = \frac{6.2 \times 10^4 \ r^{0.2}}{Re}$$

where ρ_o = oil density

$\bar{U}_p$ = mean pistion speed

r = compression ratio

Re = Reynolds number = $\dfrac{\rho_o \ \bar{U}_p \ b}{\mu_o}$

b = bore

μ_o = oil viscosity

The torque required to overcome this friction, in a two stroke engine, is

$$T_f = \frac{(FMEP) \ V_d}{2\pi} = \frac{(FMEP) \ b^2 \ S}{8}$$

where V_d is the displacement volume and S is the stroke.

The power required to overcome the friction, and thus the rate at which energy

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must be dissipated by heat transfer is given by

$$P_f = T_f \, \omega = 2 \, \pi \, N_r \, T_f$$

where N_r is the engine speed.

The distribution of the heat transfer must be estimated either from measurements or more detailed analysis than that provided here. This information can be provided to the simulation through two defined parameters.

CFRIC1 which is the fraction of the total piston/ring/cylinder wall friction which is due to the top compression ring and

CFRIC2 which is the fraction of the heat transfer resulting from top ring friction which goes to the ring side.

Using these definitions, the heat source terms for the network diagram in Figure 3.2 become

$$\dot{Q}_{fric_1} = CFRIC1 \cdot CFRIC2 \cdot P_f$$

$$\dot{Q}_{fric_2} = (1 - CFRIC2) \, P_f$$

$$\dot{Q}_{fric_3} = (1 - CFRIC1) \cdot CFRIC2 \cdot P_f$$

3.4.2 Crevice Volume Heat Transfer Submodel

Figure 3.3 shows a cross-section of the crevice volume region of the piston/cylinder wall above the top ring and the dimensions which must be specified to characterize this volume. Gas enters and leaves this volume as the pressure in the cylinder increases and decreases. Heat transfer from these gases to the piston and top ring can significantly raise the top ring temperature above that due to conduction from the piston and frictional heating. It is possible to calculate a characteristic time for conduction as
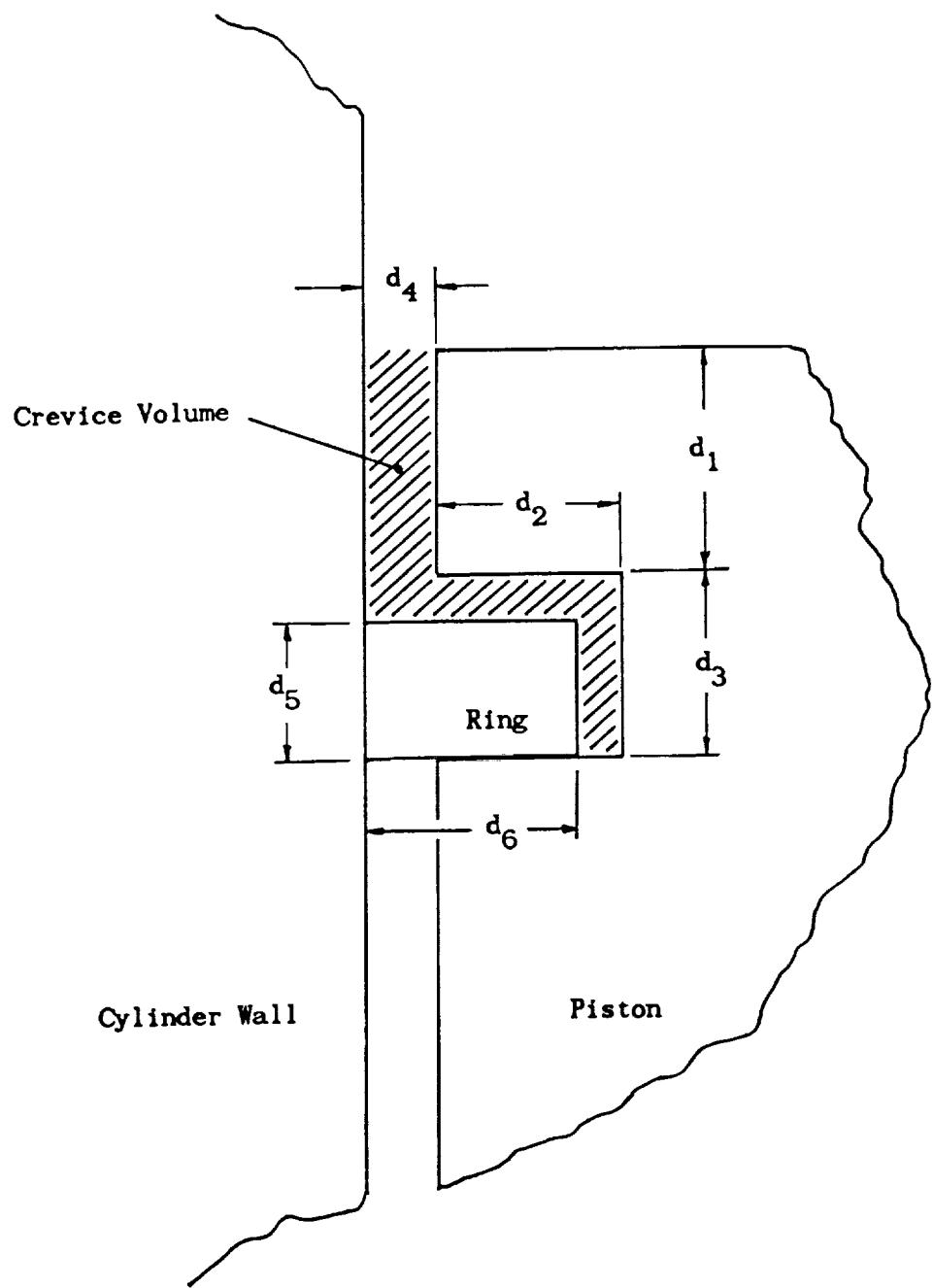
Figure 3.3 Crevice Volume Dimensions

$\tau = \dfrac{L^2}{\alpha}$ where L is a characteristic length and α is the thermal diffusivity of the conducting medium. Assuming a 0.005 inch clearance between the piston and cylinder wall as a characteristic length and the thermal diffusivity of air at 2000 deg F, the characteristic time becomes

$$\tau = \frac{(0.005/12 \text{ ft})^2}{2.83 \times 10^{-3} \text{ ft}^2/\text{sec}} = 6.13 \times 10^{-5} \text{ sec}$$

which is equal to 2.2 degrees of crankshaft rotation at 6000 RPM. This indicates that conduction will rapidly bring any air which enters the crevice volume into thermal equilibrium with the walls.

The following assumptions are used in the model for crevice volume heat transfer.

1. The pressure in the crevice volume is equal to the cylinder pressure.

2. The temperature of the gas in the crevice volume is constant at a value determined by an area-average of the wall temperatures.

$$T_{cv} = \frac{A_P}{A_T} \text{ TWPR} + \frac{A_R}{A_T} \text{ TWCR} + \frac{A_C}{A_T} \text{ TWGC}$$

where T_{cv} = Crevice volume gas temperature

TWPR = Piston rim temperature

TWCR = Top compression ring temperature

TWGC = Gas side cylinder wall temperature

A_P = Piston area exposed to crevice volume

A_R = Ring area exposed to crevice volume

A_C = Cylinder area exposed to crevice volume

$A_T = A_P + A_R + A_C$

3. Since the volume of the crevice is constant, and the temperature and

pressure in the crevice are known from assumptions 1 and 2, the mass of gas in the crevice can be calculated from the ideal gas equation

$$m_{cv} = \frac{P_{cyl} V_{cv}}{R\, T_{cv}}$$

where P_{cyl} = cylinder pressure

V_{cv} = volume of crevice

R = Ideal gas constant for the cylinder contents

From one time step to the next, the mass added to the crevice volume will be

$$\Delta m_{cv} = \frac{V_{cv}}{R\, T_{cv}} [\Delta P_{cyl}]$$

where ΔP_{cyl} is the change in cylinder pressure during the time step

Δm_{cv} is the change in mass of the crevice volume

4. Gas which enters the crevice volume is instantly cooled and this energy is delivered to the walls in proportion to their areas.

$$Q_T = \Delta m\, C_p\, (T_{gas} - T_{cv})$$

and

$$Q_{cv_1} = \frac{A_P}{A_T} Q_T, \qquad Q_{cv_2} = \frac{A_R}{A_T} Q_T, \qquad Q_{cv_3} = \frac{A_C}{A_T} Q_T$$

where Q_T = energy transferred from gas to crevice volume walls.

Δm = Increment of mass added to crevice volume in one time step

T_{gas} = Cylinder gas temperature

Q_{cv_1} = Fraction of heat transfer which goes to piston rim

Q_{cv_2} = Fraction of heat transfer which goes to top compression ring

Q_{cv_3} = Fraction of heat transfer which goes to cylinder wall

Combining these equations gives the following expression for the crevice

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volume heat transfer for one time step.

$$Q = \left[\frac{\gamma}{\gamma-1}\right] V_{cv} \left[\frac{T_{gas}}{T_{cv}} - 1\right] \Delta P_{cyl}$$

The total heat transfer for a cycle is given by summing the heat transfer at each time step

$$Q_T = \sum_{cycle} \left[\frac{\gamma}{\gamma-1}\right] V_{cv} \left[\frac{T_{gas}}{T_{cv}} - 1\right] \Delta P_{cyl}$$

and the average heat transfer rate is obtained by multiplying by the engine speed.

$$\dot{Q}_T = N_r \cdot \sum_{cycle} \left[\frac{\gamma}{\gamma-1}\right] V_{cv} \left[\frac{T_{gas}}{T_{cv}} - 1\right] \Delta P_{cyl}$$

3.5 Node Equations

Based on the concept that at steady state the currents into any node of the network diagram given in Figure 3.2 must add to zero, equations can be written which sum the heat transfer into each node. There is one equation for each of the nine unknown temperatures. These equations are given below.

$$\frac{TC2 - TWOC}{R_{13}} + \frac{TWGC - TWOC}{R_{11}} = 0$$

$$\frac{TC1 - TWCP}{R_7} + \frac{TWGP - TWCP}{R_6} = 0$$

$$\frac{TC3 - TWCH}{R_5} + \frac{TWGH - TWCH}{R_4} = 0$$

$$\frac{TWEVG - TWEV}{R_1} + \frac{TEXHP - TWEV}{R_2} + \frac{TWGH - TWEV}{R_3} + \frac{T_{eg,exh\ valve} - TWEV}{R_{17}} = 0$$

$$\frac{TWCH - TWGH}{R_4} + \frac{TWEV - TWGH}{R_3} + \frac{T_{eg,head} - TWGH}{R_{16}} = 0$$

$$\frac{TWGC - TWGP}{R_8} + \frac{TWPR - TWGP}{R_9} + \frac{TWCP - TWGP}{R_6} + \frac{T_{eg,pist} - TWGP}{R_{15}} + \dot{Q}_{fric_3} = 0$$

$$\frac{TWGP - TWPR}{R_9} + \frac{TWCR - TWPR}{R_{12}} + \dot{Q}_{cv_3} = 0$$

$$\frac{TWCC - TWGC}{R_{11}} + \frac{TWCR - TWGC}{R_{10}} + \frac{TWGP - TWGC}{R_8} + \frac{T_{eg.cyl} - TWGC}{R_{14}} + \dot{Q}_{cv_2} + \dot{Q}_{fric_2} = 0$$

$$\frac{TWGC - TWCR}{R_{10}} + \frac{TWPR - TWCR}{R_{12}} + \dot{Q}_{cv_1} + \dot{Q}_{fric_1} = 0$$

3.6 Solution Technique

The nine node equations listed above are a system of linear algebraic equations and can be solved using a Gaussian elimination procedure. A subroutine for this purpose was obtained from Gerald [8]. The calculation is performed at the end of each cycle iteration providing an updated estimate of the nine metal temperatures. Depending on the value of the user specified parameter, NHEAT, four of these temperatures, the cylinder wall temperature, the piston crown temperature, the head temperature and the exhaust valve temperature, can be used in the next iteration so that the metal temperatures will approach their steady state values (NHEAT = 1). The other option is to fix these four metal temperatures at values specified by the user (NHEAT =0).

4.0 INPUT DATA

Two sets of input data must be provided to the Benson program to define the particular application being considered. The first data set provides general data describing the engine and operating conditions being simulated. The second data set relates specifically to the steady state heat transfer analysis discussed in Chapter 3.0 and contains the thermal properties of the engine components and the appropriate areas and path lengths.

4.1 Subroutine INPUT

Below is listed the input data set required by the Benson program. The variable names are also provided. The current version of the program has these varibles entered through a BLOCK DATA statement in the main program and then passed through a COMMON block into the program. READ statements are provided in the INPUT subroutine to read an external file to obtain these variables but these statements have been made into comment statements.

EQUIVD	RPM	PEXH	PAIR	TAIR	
CR	BORE	STROKE	CONROD	FPISTA	
EVO	EVC	AVO	AVC		
TWALL	WFUEL				
ACB	ACF				
ANNA	FMEPM				
NPCWF	DEL1	DEL2	DEL3	AAN(1)	AAN(2)
VALEXH					
CDE	NTEXH				
ALPHEX(1)	FEXH(1)				
ALPHEX(2)	FEXH(2)				

.
.
.

ALPHEX(NTEXH)	FEXH(NTEXH)
VALAIR	
CDA	WIDTHA

EQUIVD = Desired trapped equivalence ratio. If a specified fuel
          flow rate is desired, then EQUIVD should be set to zero
          and WFUEL set to the amount of fuel injected per cycle.
RPM   = Crankshaft speed, revolutions per minute.
PEXH   = Exhaust pressure, psia.
PAIR   = Intake manifold pressure, psia.
TAIR   = Intake manifold temperature, deg R.
CR   = Geometric Compression ratio
BORE   = Bore, inches.
STROKE = Stroke, inches
CONROD = Connecting rod length, inches.
FPISTA = Ratio of piston surface area to crossectional area of
          cylinder.
EVO   = Crankangle at which exhaust valve opens, deg ATDC.
EVC   = Crankangle at which exhaust valve closes, deg ATDC
AVO   = Crankangle at which intake port opens, deg ATDC
AVC   = Crankangle at which intake port closes, deg ATDC.
TWALL = Initial estimate of cylinder wall temperature, deg R.
WFUEL = Initial estimate of fuel injected be cycle, unless
               EQUIVD is zero in which case WFUEL is the actual fuel
          injected per cycle, Lbm.
ACB   = Start of combustion, degrees ATDC.
ACF   = End of combustion, degrees ATDC
ANNA   = Parameter for heat transfer model
FMEPM = Multiplier for friction model
NPCWF = Parameter for selection of combustion model
               If NPCWF = -1   Whitehouse-Way model used
               If NPCWF = 0 and DEL3 = 0.   AVL model used
               If NPCWF = 0 and DEL3 > 0.   Wiebe model used
               If NPCWF = 1   Watson model used
               If NPCWF = 2   User supplied model
DEL1   = Parameter for combustion model
DEL2   = Parameter for combustion model
DEL3   = Parameter for combustion model
AAN(1) = Injection rate parameter for Whitehouse-Way combustion
          model
AAN(2) = Injection rate parameter for Whitehouse-Way combustion
          model
VALEXH = Parameter which determines whether an exhaust valve or
          port is used
               If VALEXH = 0., exhaust ports are used
               If VALEXH = 10., exhaust valves are used
CDE   = Exhaust valve/port discharge coefficient
NTEXH = If an exhaust valve is used, NTEXH is the number of
          crankangle area combinations provided to specify the
          valve flow area
ALPHEX(I) = Array of crank positions at which valve flow area is
               specified.
FEXH(I) = Array of exhaust valve flow areas corresponding to
          ALPHEX(I).

VALAIR = Parameter which determines whether an intake port or
         valve is used
              If VALAIR = 0., intake ports are used.
              If VALAIR =10., intake valves are used.
CDA   = Intake port/valve discharge coefficient.
WIDTHA = If an intake port is used, this parameter specifies the
         fraction of the circumference which is taken up by port
         area.

4.2 Subroutine INPUT2

     Below is listed the input data set required by the Steady State Heat

Transfer Analysis. The variable names are provided below. The current

version of the program has these variables defined within the subroutine

INPUT2 although READ statements are provided to read these variables from an

external file. Currently these READ statements have been made into comment

statements.

TWEV	TWGH	TWGP	TWGC	TWEVG	
TC1	TC2	TC3			
NEXHV	DEXHV				
D1	D2	D3	D4	D5	D6
XXEVG	XXEVH	XXPSL			
XXPIS	XXPRG	XXHED			
XXPCR	XXRSL	XXSLV			
AEXVS	AEXST				
ASLEEV	APIST2				
APISTR	ARING1	ARING2			
CEXV	CHEAD	CSLEEV	CPIST	CRING	
HEXHP	HOILP	HCSL	HCHD		

TWEV = Initial estimate of the exhaust valve temperature, deg F.
TWGH = Initial estimate of the gas side head temperature, deg F.
TWGP = Initial estimate of the gas side piston temperature, deg F.
TWGC = Initial estimate of the gas side cylinder wall
        temperature, deg F.
TWEVG = Exhaust valve guide temperature, deg F.
TC1   = Piston cooling oil temperature, deg F.
TC2   = Cylinder wall coolant temperature, deg F.
TC3   = Head coolant temperature, deg F.
NEXHV = Number of exhaust valves

DEXHV = Diameter of exhaust valves, inches
D1   = Distance below piston surface of top ring groove, inches.
D2   = Depth of ring groove, inches.
D3   = Width of ring groove, inches.
D4   = Piston/cylinder wall clearance (piston is assumed centered in bore), inches.
D5   = Ring width, inches.
D6   = Ring depth, inches.
XXEVG = Heat transfer path length from exhaust valve to valve guide
XXEVH = Heat transfer path length from exhaust valve to valve seat
XXPSL = Heat transfer path length from piston to cylinder wall through lower rings and oil film
XXPIS = Heat transfer path length through piston
XXPRG = Heat transfer path length from piston rim to top compression ring
XXHED = Heat transfer path length through head
XXPCR = Heat transfer path length from piston crown to piston rim
XXRSL = Heat transfer path length from top compression ring to cylinder wall
XXSLV = Heat transfer path length through cylinder wall
AEXVS = Area of exhaust valve stem
AEXST = Exhaust valve seat contact area
ASLEEV = Characteristic area for heat transfer through cylinder wall
APIST2 = Surface area exposed to oil on underside of piston
APISTR = Characteristic area between piston crown and piston rim
ARING1 = Contact area between top compression ring and cylinder wall
ARING2 = Contact area between top compression ring and piston rim
CEXV = Thermal conductivity of exhaust valve
CHEAD = Thermal conductivity of head
CPIST = Thermal conductivity of piston
CRING = Thermal conductivity of ring
CSLEEV = Thermal conductivity of cylinder wall
HEXHP = Convection coefficient from back side of exhaust valve to gases in exhaust port
HOILP = Convection coefficient for cooling oil on backside of piston
HCSL = Convection coefficient for coolant on backside of cylinder wall
HCHD = Convection coefficient for coolant on backside of head

5.0 OUTPUT

The Benson program creates three output files containing the results of the engine simulation. The first file, written from UNIT 2, contains a summary of the input data and then the following results written for each iteration.

1. Fuel Flow
2. Scavenge Ratio
3. Trapping Efficiency
4. Scavenge Efficiency
5. Temperature Out (Exhaust)
6. Power
7. True Purity
8. Air Flow
9. Equivalence Ratio
10. Maximum Pressure
11. Maximum Temperature
12. Heat Loss (percent)

After the program has converged a summary of the heat transfer results is printed showing the metal part temperatures and the fraction of the heat transfer going to each part of the engine.

The second output file, UNIT 3, contains a listing of the cylinder pressure, temperature, specific heat ratio and volume as a function of crank angle for each iteration performed by the program. The last complete cycle of data corresponds to the cycle where the program converged.

The final output file, UNIT 4, contains a summary of the cycle data which is written at the end of each iteration. It includes the trapped pressure and temperature, the maximum pressure and temperature, the release pressure and temperature, the various gas exchange efficiencies described in section 7.1 and the indicated power. This data is printed for each iteration so the final listing corresponds to the listing for the converged cycle calculation.

6.0 SAMPLE CASES

6.1 Napier Nomad

The Napier Nomad was a combined cycle diesel engine developed during the early 1950's as a highly efficient aircraft engine. It is the most efficient aircraft engine ever flown, although the fuel economy of the Nomad did not provide sufficient advantage over the smaller, lighter gas turbine engine. In this example, the Benson program was combined with a simple compressor and turbine model to simulate the take-off performance of the Napier Nomad engine. Sufficient published data of the Nomad is available to confirm the analysis. The Nomad was liquid cooled, and the analysis was conducted assuming both oil and water cooling.

The input BLOCK DATA for this simulation is provided below. A summary of the results is presented in Table 6.1. A listing of the program which calls the Benson program including the turbomachinery is provided in Appendix 10.2.

```
DATA EQUIVD,RPM,PEXH,PAIR,TAIR /0.60,2050.,134.79,149.76,896./
 DATA CR,BORE,STROKE,CONROD,FPISTE,FPISTA /11.17,6.00,7.375,
1    14.75,1.,1.13/
 DATA EVO,EVC,AVO,AVC /105.,255.,130.,230./
 DATA TWALL,WFUEL /1460.,0.0001/
 DATA ACB,ACF /335.0,10./
 DATA ANNA,FMEPM /0.30,1.25/
 DATA NPCWF,DEL1,DEL2,DEL3,AAN(1),AAN(2) /-1,0.01457,0.667,0.4,
1  0.4,0.5/
 DATA VALEXH,CDE,WIDTHE /0.,0.85,0.20/
 DATA VALAIR,CDA,WIDTHA /0.,0.85,0.36/
```

Table 6.1

Napier Nomad

Specifications:

Two Stroke, Loop Scavenged

12 Cylinders   Bore: 6.00 inches   Stroke: 7.375 inches

Effective Compression Ratio: 8.00

At Takeoff Power: Speed: 2050 rpm   Mean Piston Speed: 2520 ft/min

Inlet Manifold Pressure: 89 psia

Inlet Manifold Temperature: 475 F

Compressor Efficiency: 0.85

Turbine Efficiency: 0.84

Under Takeoff Conditions

	Published Data	Benson Program (Water Cooled)	Benson Program (Oil Cooled)
BMEP	205 psi	205.1 psi	205.4 psi
Peak Pressure	2200 psi	2186 psi	2205 psi
Air Flow	13 lb/sec	13.03 lb/sec	13.00 lb/sec
Turbine Inlet Temp	1222 F	1162 F	1199 F
Diesel Power (12 cyl)	2660 hp	2654 hp	2658 hp
Turbine Power	2250 hp	2374 hp	2424 hp
Compressor Power	1840 hp	1858 hp	1854 hp
Total Shaft Power	3070 hp	3169 hp	3228 hp
Overall BSFC	0.345 lb/hp-hr	0.339 lb/hp-hr	0.329 lb/hp-hr
Percent Heat Loss	NA	13.8 %	10.2 %
Head Temp	NA	782 F	1498 F
Piston Temp	NA	834 F	1008 F
Sleeve Temp	NA	791 F	1224 F

6.2 Garrett CCE

The Garrett Turbine Engine Company, under Army contract, used the Benson

program to simulate a compound cycle engine suitable for use in a light

helicopter. The engine proposed by Garrett is a 6 cylinder, two stroke diesel

with two expansion turbines on the diesel exhaust. The first turbine drives

the compressor for the diesel intake air and the second is a power turbine

which is connected directly to the engine's output shaft. As in the above

example, the Benson program was combined with a simple compressor and turbine

model to simulate the Garrett design for a Compound Cycle Engine. Data for

the predicted performance was supplied by Garrett in the final contract

report. This data is compared below in Table 6.2 with the results of the

simulation for both water and oil cooling. The input data set is also

provided below. A listing of the main program used to simulate the Garrett

engine is provided in Appendix 10.3.

```
DATA EQUIVD,RPM,PEXH,PAIR,TAIR /0.68,6122.,134.79,149.76,896./
 DATA CR,BORE,STROKE,CONROD,FPISTE,FPISTA /9.1712,3.101,2.940,
1    7.168,1.,1.13/
 DATA EVO,EVC,AVO,AVC /90.,239.,126.,234./
 DATA TWALL,WFUEL /1460.,0.000145332/
 DATA ACB,ACF /345.,10.5/
 DATA ANNA,FMEPM /0.36,1.0/
 DATA NPCWF,DEL1,DEL2,DEL3,AAN(1),AAN(2) /-1,0.01457,0.667,0.4,
1  0.4,0.5/
 DATA VALEXH,CDE,NTEXH /10.,0.8864,13/
 DATA VALAIR,CDA,WIDTHA /0.,0.8,0.5542/
 DATA ALPHEX/0.00,10.97,25.00,31.61,41.00,52.25,72.89,90.95,104.00,
1  111.59,119.00,132.23,149.00,37*0./
 DATA FEXH/0.0,0.00093264,0.00364,0.00591222,0.00899,0.0106201,
1  0.01175263,0.01111131,0.00923,0.00717895,0.00461,0.00181743,0.,
2  37*0./
```

Table 6.2

Garrett CCE

Specifications:

Two Stroke, Uniflow Scavenged

6 Cylinders   Bore: 3.101 inches   Stroke: 2.940 inches

Effective Compression Ratio: 7.50

At Rated Power: Inlet Manifold Pressure: 149.79 psia

Inlet Manifold Temperature: 436 F

Compressor Efficiency: 0.79

Turbine Efficiency: 0.845, 0.848

Rated Power Conditions

	Published Data	Benson Program (Water Cooled)	Benson Program (Oil Cooled)
BMEP	400 psi	386.8 psi	386.5 psi
Peak Pressure	3364 psi	3401.1 psi	3429.2 psi
Air Flow	2.349 lb/sec	2.316 lb/sec	2.301 lb/sec
Turbine Inlet Temp	1752 F	1738 F	1785 F
Diesel Power (6 cyl)	824 hp	796.0 hp	795.5 hp
Turbine Power	226 hp	233.1 hp	248.6 hp
Fan Power	51 hp	51 hp	51 hp
Total Shaft Power	999 hp	978.1 hp	993.1 hp
Overall BSFC	0.328 lb/hp-hr	0.332 lb/hp-hr	0.323 lb/hp-hr
Percent Heat Loss	8.46 %	8.59 %	5.74 %
Head Temp	1244.3 F	1299.6 F	2078.3 F
Piston Temp	1279.3 F	1375.8 F	1571.3 F
Sleeve Temp	418.3 F	1344.8 F	1792.2 F

7.0 DOCUMENTATION OF SUBROUTINES

7.1 Subroutine BENSON

A simulation using the Benson program is initiated by a call to subroutine BENSON. There is no argument list for this subroutine. All data is passed into the subroutine through input files or COMMON blocks and all output data is written to the three output files discussed in Chapter 5.0.

Subroutine BENSON calls the input subroutines, the initialization subroutine, and then organizes the calls to CYLNDR and POWER to integrate the energy balance throughout the cycle. Examples of how BENSON is called from a main program are given in the Appendix for the sample cases of Chapter 6.0.

7.2 Subroutine BAL

This subroutine can be used for two purposes:

1. To find the enthalpy of combustion products given the fuel-air ratio and the temperature.

2. To find a final temperature of combustion products given an initial temperature and a rise in the enthalpy of the products.

For the combustion equation

$$A \cdot CH_n + [0.21\ O_2 + 0.79\ N_2] \rightarrow X_1\ N_2 + X_2\ O_2 + X_3\ CO_2 + X_4\ H_2O$$
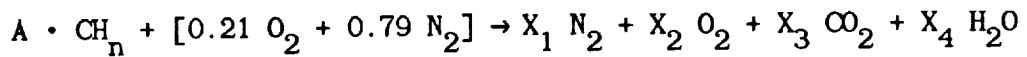
the number of moles of products, per mole of air, are given by the following equations.

$$X_1 = 0.79$$
$$X_2 = 0.21 - X_3 - \frac{1}{2} X_4$$

$$X_3 = \frac{\text{lb fuel}}{\text{lb air}} \cdot \frac{\text{lb C}}{\text{lb fuel}} \cdot \frac{\text{lb air}}{\text{mole air}} \cdot \frac{\text{mole C}}{\text{lb C}} = \frac{\text{mole C}}{\text{mole air}}$$

$$= \text{FZA} \cdot \text{CARBON} \cdot 28.85 / 12.01$$

$$X_4 = \frac{\text{lb fuel}}{\text{lb air}} \cdot \frac{\text{lb } H_2}{\text{lb fuel}} \cdot \frac{\text{lb air}}{\text{mole air}} \cdot \frac{\text{mole } H_2}{\text{lb } H_2} = \frac{\text{mole } H_2}{\text{mole air}}$$

$$= \text{FZA} \cdot (1 - \text{CARBON}) \cdot 28.85 / 2.016$$

These quantities can be used to calculate mole fractions by summing the total number of moles and dividing each term by the total.

To accomplish the first purpose of this subroutine the user specifies the temperature and fuel/air ratio of the mixture as well as the mass fraction of carbon in the fuel and the subroutine calculates the mole fractions of the product gas composition and then evaluates fourth order polynomial curve fits to JANAF table data to obtain the enthalpy of the gas mixture at the specified temperature [1].

For the case where the subroutine is intended to locate a temperature given an initial temperature and an increment of enthalpy, the subroutine first evaluates the enthalpy at the specified initial temperature and adds the enthalpy increment to obtain the enthalpy of the unknown state. Then the subroutine guesses a temperature and tests whether the enthalpy at this temperature is the same as the unknown. If not, the program adjusts the temperature and checks again. Newton's method is used to speed convergence. When the enthalpy matches within 0.01%, the subroutine returns to the calling program.

The argument list for subroutine BAL is

SUBROUTINE BAL(CARBON,FZA,T1,DELH,T2,GAM,H3)

where CARBON is the mass fraction of carbon in the fuel

FZA is the fuel/air mass ratio

T1 is the initial temperature when the subroutine is being used to
   locate a second unknown temperature.

DELH is the enthalpy increment.

T2 is the temperature at which the enthalpy is desired or is the
   unknown temperature.

GAM is the ratio of specific heats evaluated at T2.

H3 is the enthalpy at T2.

7.3 Subroutine CYLNDR

This subroutine integrates the energy equation described earlier for the
gas exchange portion of the cycle. The subroutine checks to see if the valves
or ports are open and, if so, integrates the energy equation. If the valves
are closed, then CYLNDR calls POWER to integrate the energy equation for the
compression-expansion portion of the cycle. When the subroutine is called the
first time step after the gas exchange has been completed, the subroutine
totals the mass added and removed from the cylinder and calculates the various
gas exchange efficiencies. These efficiencies are defined below.

Scavenging Efficiency: $\dfrac{\text{mass of delivered air retained in cylinder}}{\text{mass of trapped cylinder charge}}$

Purity: $\dfrac{\text{mass of air in trapped cylinder charge}}{\text{total mass of trapped cylinder charge}}$

Charging Efficiency based on Trapped Condition:

$$\dfrac{\text{mass of delivered air retained in cylinder}}{\text{Trapped volume x trapped density}}$$

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Charging Efficiency based on Inlet conditions and trapped volume:

$$\frac{\text{mass of delivered air retained in cylinder}}{\text{Trapped volume x inlet density}}$$

Charging Efficiency based on inlet conditions and swept volume:

$$\frac{\text{mass of delivered air retained in cylinder}}{\text{Swept volume x inlet density}}$$

Trapping Efficiency: $\dfrac{\text{mass of delivered air retained in cylinder}}{\text{total mass of air delivered to cylinder}}$

Scavenge Ratio based on swept volume:

$$\frac{\text{total mass of air delivered to cylinder}}{\text{Swept volume x inlet density}}$$

Scavenge Ratio based on trapped volume:

$$\frac{\text{total mass of air delivered to cylinder}}{\text{Trapped volume x inlet density}}$$

Relative Charging Efficiency based on trapped volume:

$$\frac{\text{total mass of trapped cylinder charge}}{\text{Trapped volume x inlet density}}$$

Relative Charging Efficiency based on swept volume:

$$\frac{\text{total mass of trapped cylinder charge}}{\text{Swept volume x inlet density}}$$

7.4 Subroutine CYLVOL

This subroutine takes the piston position and the piston velocity provided by STROK and calculates the cylinder volume and the rate of change of volume.

The volume at some crank position is equal to the sum of the volume displaced by the piston plus the displacement volume. The volume displaced by the piston is equal to the piston area times the distance between the top of the piston and its position at top dead center which is XSTROK as calculated by the subroutine STROK. The clearance volume can be expressed in terms of the compression ratio as

$$r = \frac{V_d + V_{cl}}{V_{cl}}$$

or

$$V_{cl} = \frac{V_d}{r - 1} = \frac{S \cdot AREA}{r - 1}$$

where V_{cl} is the clearance volume,

V_d is the displacement volume

S is the stroke

AREA is the piston area

r is the compression ratio

Thus, the volume in the cylinder can be expresed as

$$V = AREA \cdot XSTROK + \frac{S \cdot AREA}{r - 1}$$

or

$$V = AREA \cdot [XSTROK + \frac{S}{r - 1}]$$

The rate of change of the volume is equal to the derivative of this expression or in terms of DSTROK provided by the subroutine STROK,

$$\frac{dV}{d\theta} = AREA \cdot DSTROK$$

The argument list follows.

SUBROUTINE CYLVOL(FCYLG,XSTROK,STROKE,CRR,DSTROK,VCYLG,DVCYLG)

where FCYLG is the cross-sectional area of the cylinder

XSTROK is the piston position

STROKE is the engine stroke

CRR is the compression ratio

DSTROK is the piston velocity

VCYLG is the volume

DVCLYG is the rate of change of the volume

7.5 Subroutine ELIM

This subroutine is used to solve the system of nine linear algebraic equations developed by subroutine HTRANS for the metal part temperatures in the engine. The subroutine was copied from Gerald [8] and uses Gaussian elimination with partial pivoting. The argument list is as follows.

SUBROUTINE ELIM(AB,N,NP,NDIM)

where AB = Coefficient matrix augmented with vectors consisting of the right hand sides of the system equations (may be more than one set).

N = Number of equations.

NP = Total number of columns in the augmented matrix AB.

NDIM = First dimension of matrix AB in the calling program.

The solution vector(s) are returned in the augmentation columns of AB.

7.6 Subroutine FCLOSE

This subroutine closes the input/output files and states that the files created should be kept after completion of the program.

7.7 Subroutine FOPEN

This subroutine opens the input and output files which the Benson program reads from and writes to. Unit 1 is the input file and it is named DIESEL1.INP and units 2 through 5 are output files with names that can be specified by the user in the calling program. the user defined names are passed to FOPEN as 16 character names in the COMMON block named OPEN.

7.8 Subroutine HEADER

This subroutine writes titles and column headings to the output files and also writes out selected values of the input parameters so the particular run can be identified. The subroutine has no argument list and all data is passed into the subroutine through COMMON blocks /GEN/ and /CYL/.

7.9 Subroutine HTRANS

This subroutine executes the procedure described in Section 2.2 for calculating the engine part temperatures. The subroutine calculates the resistances described in that section and assembles the coefficient matrix for the system of algebraic equations for solution by subroutine ELIM. HTRANS also calculates the friction mean effective pressure due to the piston/ring friction so that the heat transfer terms associated with the dissipation of this friction can be added to the coefficient matrix. The terms for the crevice volume heat transfer are evaluated in subroutine POWER but are added to the coefficient matrix in HTRANS.

After solving the system equations by calling subroutine ELIM, the various heat transfer flow paths in the network diagram are summed to provide

a summary of the distribution of the heat transfer throughout the cylinder area. This data is provided to the main program through COMMON/HEAT1/ and COMMON/HEAT2/ and may be printed if desired.

7.10 Subroutine INITLZ

This subroutine is called early in the execution of the Benson program to perform a variety of tasks necessary to starting the calculations. If necessary, input variables are converted to the proper dimensions and then many of the variables are nondimensionalized. Variables used in summing calculations are assigned initial values of zero. The values of the polynomial coefficients used to calculate gas properties are assigned in this subroutine based on curve fits to the JANAF table data. The subroutine has no argument list and all data is passed into the subroutine through COMMON blocks /XXX/, /GEN/ and /CYL/.

7.11 Subroutine INPUT

This subroutine is used to supply the Benson program with input data about the specific engine application being simulated. The subroutine contains read statements for the essential data, however, these statements have been converted to comment statements and the data is either present as assignment statements in the subroutine or is assigned in the main calling program and then passed into the subroutine through COMMON/BNSN/. This was done so that the Benson program could be repeatedly called as a subroutine itself without having to reread the input data file for every run. INPUT has no argument list and all variables are passed through to the other subroutines

using COMMON blocks.

7.12 Subroutine INPUT2

This subroutine is used to supply the Benson program with input data for the detailed heat transfer calculations. The subroutine contains READ statements for the data, however, these statements have been converted to comment statements and the data is assigned directly to the variables by executable statements within the subroutine. To change the values of these parameters the subroutine must be edited and then recompiled. The format of the input data file and the variable name list are given in Section 3.2.

7.13 Subroutine MASSFL

Flow through the intake and exhaust ports and valves can be modeled as an adiabatic quasi-steady flow process. Potential energy effects are generally assumed negligible. With these assumptions, the energy balance for a control volume takes the following form.

$$h_1 + \frac{V_1^2}{2} = h_2 + \frac{V_2^2}{2}$$

where state 1 designates the upstream condition and state 2 is the condition at the minimum area section of the flow passage. Since state 1 is normally taken to be a stagnation condition, V_1 can be assumed to be zero. Thus,

$$V_2 = [2(h_1 - h_2)]^{1/2}$$

or for constant specific heat

$$V_2 = [2\,C_p\,(T_1 - T_2)]^{1/2}$$

Since the process is assumed isentropic, again for constant specific heats,

$$\frac{T_1}{T_2} = \left[\frac{P_1}{P_2}\right]^{\frac{\gamma-1}{\gamma}}$$

where γ is the ratio of specific heats, C_p/C_v.

Substituting this expression into the equation for V_2 gives

$$V_2 = \left[2\ C_p\ T_2\ \left[\left[\frac{P_1}{P_2}\right]^{\frac{\gamma-1}{\gamma}} - 1\right]\right]^{1/2}$$

if this velocity is divided by the speed of sound at state 2, $a_2 = \sqrt{\gamma RT}$, then a Mach number is obtained

$$U_m = \frac{V_2}{a_2} = \left[\left[\frac{2}{\gamma-1}\right]\left[\left[\frac{P_1}{P_2}\right]^{\frac{\gamma-1}{\gamma}} - 1\right]\right]^{1/2}$$

if this Mach number is greater than or equal to 1., then the flow through the valve or port is choked and the velocity at section 2 will be sonic. If the Mach number is less than 1. then the flow is not choked and the velocity at section 2 will be given by the above expression.

The mass flow rate through the valve or port can be obtained from the continuity equation

$$\dot{m} = \rho\ A\ V$$

When this equation is applied at section 2 the following expression for mass flow through the valve or port is obtained.

$$\dot{m} = \rho_2\ A_2\ a_2\ \left[\left[\frac{2}{\gamma-1}\right]\left[\left[\frac{P_1}{P_2}\right]^{\frac{\gamma-1}{\gamma}} - 1\right]\right]^{1/2}$$

In the Benson program, the expression for mass flow rate is non-dimensionalized using several defined reference quantities. A list of these quantities follows.

T_{ref} = Reference Temperature

P_{ref} = Reference Pressure

V_{ref} = Reference Volume

F_{ref} = Reference Area

X_{ref} = Reference length

D_{ref} = Reference diameter

a_{ref} = Reference speed of sound, $a_{ref} = \sqrt{\gamma RT}$

m_{ref} = Reference mass, $m_{ref} = \dfrac{P_{ref}V_{ref}}{R\,T_{ref}} = \dfrac{\gamma\,P_{ref}V_{ref}}{a_{ref}^2}$

Using these reference quantities, which are assigned internally in the program, the mass flow equation can be rearranged to obtain the form used in the Benson program.

$$\dot{m} = \rho_2\,A_2\,a_2\,U_m$$

but $\qquad \rho_2 = \rho_1\left[\dfrac{P_2}{P_1}\right] \qquad$ and $\qquad a_2 = \sqrt{\gamma RT_2}$

$$\dot{m} = \rho_1\left[\dfrac{P_2}{P_1}\right]A_2\,\sqrt{\gamma RT_2}\,U_m$$

Now, from the equation defining the Mach number,

$$\frac{P_2}{P_1} = \left[1 + \frac{\gamma-1}{\gamma}U_m^2\right]^{\frac{\gamma}{1-\gamma}}$$

So the mass flow can be arranged as

$$\dot{m} = \frac{\gamma\,P_1\,A_2\,U_m}{a_1\left[1 + \frac{\gamma-1}{\gamma}U_m^2\right]^{\frac{\gamma+1}{2(\gamma-1)}}}$$

The non-dimensional mass flow rate, WFLOW, is equal to

$$\text{WFLOW} = \frac{\dot{m}}{\left[\dfrac{m_{ref}\,V_{ref}}{F_{ref}\,a_{ref}}\right]} = \frac{\left[\dfrac{P_1}{P_{ref}}\right]\left[\dfrac{A_2}{A_{ref}}\right]\text{FM}}{\text{AO}\,\gamma_{ref}}$$

where $\text{AO} = \dfrac{a_1}{a_{ref}}$

and
$$FM = \frac{\gamma \ U_m}{\left[1 + \frac{\gamma-1}{2} U_m^2 \right]^{\frac{\gamma+1}{2(\gamma-1)}}}$$

if the flow is choked, the equation is the same but FM becomes

$$FM = \gamma \left[\left(\frac{2}{\gamma+1} \right)^{\frac{\gamma+1}{\gamma-1}} \right]^{1/2}$$

The argument for subroutine MASSFL follows.

SUBROUTINE MASSFL(FHOLE,RUP,RDP,AO,GR,G,WFLOW)

where FHOLE is the non-dimensional flow area, $\left[\frac{A_2}{A_{ref}} \right]$

RUP is the upstream pressure divided by the reference pressure

RDP is the downstream pressure divided by the reference pressure

AO is the ratio of the speed of sound at the upstream temperature

to the reference speed of sound.

GR is the reference value of γ, the ratio of specific heats

G is γ, the ratio of specific heats

WFLOW is the non-dimensional mass flow rate

7.14 Subroutine POWER

This subroutine integrates the energy balance equation for the compression-expansion portion of the cycle. The techniques used are the same as those described in detail in section 2.1 of this report.

Power is called by CYLNDR after the valves close indicating the start of the compression process. POWER calculates the gas properties at the start and end of each time step to obtain the internal energy and calculates the work and heat transfer. POWER also contains the combustion calculations resulting from the four combustion models. The amount of fuel burned is calculated and

multiplied by the constant volume heating value to obtain an effective heat release. This heat release is included in the energy balance. At the end of the expansion process, the indicated power and efficiency is calculated and printed to a file.

7.15 Subroutine SPLFIT

This subroutine is used to interpolate between discrete data provided to define a valve flow area curve. The calling program provides the X and Y arrays of discrete data and a value of X at which an interpolated Y is required and the subroutine fits a spline curve to the data and evaluates the spline at X. The relevant argument list follows.

SUBROUTINE SPLFIT (0,0,NP,0,0.,XKX,0,FY,0,X,Y,ITRP)

where NP is the number of points describing the curve

XKX(I) is the NP X-values defining the curve (25 points max). These points must be in ascending order

FY(I) is the array of NP Y-values defining the curve (corresponding to the X-values)

X is the X-value where the function value is required

Y is the calculate function value at the desired X-value

ITRP is an error indicator.

7.16 Subroutine SREA

This subroutine is used to calculate the surface area of the portion of the combustion chamber exposed to the combustion gases at a given crank position. This area will be the sum of the areas of the head surface, the

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piston surface and the instantaneous exposed cylinder wall surface. Each of these areas is calculated as follows.

$$\text{Head Area} = \text{FPISTE} \frac{\pi}{4} (\text{BORE})^2$$

$$\text{Piston Area} = \text{FPISTA} \frac{\pi}{4} (\text{BORE})^2$$

$$\text{Cylinder Wall Area} = \pi (\text{BORE}) L$$

where FPISTE = the ratio of the head surface area to the cylinder

cross-section

FPISTA = the ratio of the piston surface area to the cylinder

cross-section

BORE = the cylinder diameter

L = the distance between the current position of the piston and its

position at top dead center

Since the volume at any time is approximately equal to $\frac{\pi}{4} (\text{BORE})^2 L$ it is possible to express the cylinder wall surface area in terms of the volume as

$$\text{Cylinder wall area} = \pi (\text{BORE}) \frac{4}{\pi (\text{BORE})^2} = \frac{4V}{\text{BORE}}$$

Using this relation, the total surface area can be expressed as

$$\text{AREA} = \frac{4V}{\text{BORE}} + (\text{FPISTE} + \text{FPISTA}) \frac{\pi}{4} (\text{BORE})^2$$

The subroutine SREA evaluates this equation for a given set of input arguments. The argument list follows.

SUBROUTINE SREA (SAREA,FCYLL,DCYLL,XR,DR,FPISTA,FPISTE)

where SAREA is the total surface area

FCYLL is equal to $\frac{\pi}{4} (\text{BORE})^2$

DCYLL is the Bore

XR and DR are reference dimensions (assumed = 1. in the BENSON program)

7.17 Subroutine STROK

This subroutine calculates the piston position and the rate of change of piston position (piston velocity) for a specified engine geometry and at a specified crank angle. Ferguson [9] gives the following expression for the instantaneous cylinder volume for a reciprocating engine.

$$V = V_{cl} \left[1 + \frac{r-1}{2} \left[1 - \cos\theta + \frac{1}{\epsilon}[1-(1-\epsilon^2 \sin^2\theta)^{1/2}] \right] \right]$$

where V_{cl} is the clearance volume

r is the compression ratio

ϵ is a geometric ratio $= \frac{2\,L}{S}$

L is the connecting rod length

S is the stroke

θ is the crank angle

By defining the quantity FNN

$$FNN = \left[\frac{1}{\epsilon^2} - \sin^2\theta \right]^{1/2}$$

and recognizing that the compression ratio is equal to $\dfrac{V_d + V_{cl}}{V_{cl}}$ so that

$(r-1) = \dfrac{V_d}{V_{cl}}$ it can be shown that the volume can be expressed as

$$V = V_{cl} + \frac{V_d}{2} \left[1 - \cos\theta + \frac{1}{\epsilon} - FNN \right]$$

or

$$V = V_{cl} + \frac{\pi/4\ b^2\ S}{2} \left[1 - \cos\theta + \frac{1}{\epsilon} - FNN \right]$$

where b = bore

V_d = displacement volume

The subroutine STROK calculates the quantity

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$$X = \frac{S}{2}\left[1 - \cos\theta + \frac{1}{\epsilon} - FNN\right]$$

which is the distance between the top of the piston at the specified crank angle and its position at top dead center. Thus, at TDC, when $\theta = 0$, the value of $X = 0$. This value is provided in non-dimensional form by dividing by a reference length, XREF

$$XSTROK = \frac{X}{XREF} = \frac{S}{2\ XREF}\left[1 - \cos\theta + \frac{1}{\epsilon} - FNN\right]$$

The relation for the piston position can be differentiated with time to provide an expression for the piston velocity.

$$\frac{d[X]}{dt} = \frac{S}{2}\left[\frac{d(\cos\theta)}{dt} - \frac{d(FNN)}{dt}\right]$$

$$= \frac{S}{2}\left[\sin\theta + \frac{\sin 2\theta}{2\cdot FNN}\right]\frac{d\theta}{dt}$$

$$= \frac{S}{2}\left[\sin\theta + \frac{\sin 2\theta}{2\ FNN}\right]\cdot 2\pi\cdot REVENG$$

where REVENG is the engine speed in rev/sec.

The piston speed can be non-dimensionalized by introducing a non-dimensional time parameter, $ZREF = \frac{360\cdot XREF\cdot REVREF}{AREF}$ where REVREF is a reference engine speed and AREF is a reference speed of sound.

$$DSTROK = \frac{1}{AREF}\left[\frac{d[X]}{dt}\right] = \frac{\pi}{360}\ ZREF\ \left[\frac{REVENG}{REVREF}\right]\left[\frac{S}{XREF}\right]\left[\sin\theta + \frac{\sin 2\theta}{2\cdot FNN}\right]$$

The non-dimensional piston position and velocity supplied by subroutine STROK

are used by other routines in the Benson program to calculate such quantities as the cylinder volume and cylinder surface area.

The argument list follows.

SUBROUTINE STROK(XSTROK,DSTROK,THETAE,STROKE,CONROD,RPS,ZR)

where   XSTROK is the nondimensional piston position returned by STROK

DSTROK is the nondimensional piston velocity returned by STROK

THETAE is the crank position

STROKE is the stroke normalized by XREF

CONROD is the connecting rod length normalized by XREF

RPS is the rotational speed of the engine, normalized by dividing by the reference engine speed

ZR is the nondimensional time parameter (ZREF)

7.18 Subroutine UNITP

This subroutine is used to change the units of a pressure supplied as an input. The argument list follows.

SUBROUTINE UNITP (IA,IB,PP,PPB)

where IA and IB are used to designate the type of unit conversion desired, PP is the pressure which will be returned after having been multiplied by the appropriate conversion factor and PPB is the barometric pressure. PPB is required for conversions from gage pressure to absolute pressure. The values of IA and IB should be selected from the following choices.

IA	IB	Conversion
1	1	do nothing
1	2	do nothing
2	1	psia → bars (absolute)
2	2	bars (absolute) → psia
≠ 1,2	1	psig → bars (absolute)
≠ 1,2	2	bars (gage) → psia

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7.19 Subroutine UNITT

This subroutine is used to change the units of a temperature supplied as an input. The argument list follows.

SUBROUTINE UNITT (IA,IB,TT)

where IA and IB are used to designate the type of unit conversion desired and TT is the temperature which will be returned after having been multiplied by the appropriate conversion factor. The values of IA and IB should be selected from the following choices.

IA	IB	Conversion
1	2	None
2	2	°K → °C
3	2	°K → °R
≠ 1,2,3	2	°K → °F
1	≠ 2	None
2	≠ 2	°C → °K
3	≠ 2	°R → °K
≠ 1,2,3	≠ 2	°F → °K

7.20 Subroutine UNITW

This subroutine is used to change the units of a mass supplied as an argument. The argument list follows.

SUBROUTINE UNITW (IA,IB,WW)

where IA and IB are used to designate the type of unit conversion desired and is the mass which will be returned after having been multiplied by the appropriate conversion factor. The values of IA and IB should be selected from the following choices.

IA	IB	Conversion
1	2	None
1	≠ 2	None
≠ 1	2	kg → lbm
≠ 1	≠ 2	lbm → kg

8.0 CONCLUSION

8.1 Suggestions for Future Work

The major weakness of thermodynamic modeling diesel engines is the lack of a reliable and simple way to predict the heat transfer and heat release rates. Correlations are available for both these quantities and they are available in the Benson program, however, these correlations were developed under conditions very different from those present in the proposed Compound Cycle Engine. Experimental measurements at speeds above 6000 RPM and boost pressures above 100 psia are not currently available in the technical literature. These measurements must be made and used to verify the correlations before they can be used reliably at these conditions.

The current combustion models in the Benson program are of two types. The Watson model, the AVL model and the Wiebe model are simple functional models and cannot be used to understand the details of the diesel combustion. The Whitehouse-Way model is an attempt to include some of the physics of the fuel injection and combustion processes in a model and so it has the potential to provide the predictive information required for design. However, the Whitehouse-Way model is based on an out-of-date understanding of diesel combustion. This model treats the spray from a droplet perspective whereas more modern approaches recognize that the droplets vaporize very quickly after entering the combustion chamber (especially in a highly rated engine) and the subsequent combustion has the characteristics of a gaseous turbulent diffusion flame. The more successful modern diesel combustion models are based on this

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approach. A more modern combustion model should be added to the Benson program allowing the effects of parameters such as fuel injection pressure, injection duration, nozzle diameter, air swirl to be investigated.

Another useful feature that should be included in a model of the complete Compound Cycle Engine is second law thermodynamic analysis. Second law analysis is based on tracking the utilization and destruction of availability through the engine. Availability is defined as "the maximum amount of work that could be obtained by bringing a system into equilibrium with its surroundings." Availability enters the engine with the fuel and either leaves as work or is progressively destroyed by irreversible processes inside the engine. In contrast to conventional thermodynamic analysis which tracks energy through the system and cannot tell whether the energy could be profitably converted to work, second law analysis allows the sources of irreversibility in the engine to be identified and quantified so that their effect on the fuel efficiency of the engine can be determined.

8.2 Summary

This report documents the Benson Diesel Engine Simulation Program. This program is currently configured to simulate a loop or uniflow scavenged two stroke engine. The program can provide information about the effects of combustion timing, valve timing, heat release rate and other engine design and operating parameters. The program has been extended to include a more detailed heat transfer model that allows the prediction of metal part temperatures.

9.0 REFERENCES

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10.1 Variable Name List

ACB   = Start of Combustion
ACF   = End of Combustion
AIR   = An indicator of whether the intake valve/port is open or closed during the cycle (=0 when closed, =10 when open)
AIRVMX = Maximum flow area of intake valves/ports
ALPAIR = Array of crank positions corresponding to the intake valve flow areas given in FAIR, degrees.
ALPHAT = Cummulative total crankangle during integration.
ALPHEX = Array of crank positions corresponding to the exhaust valve flow areas given in FEXH, degrees.
ANGEND = Maximum number of crank degrees allowed before integration is terminated.
AAN(1) = Fuel injection parameters for Whitehouse-Way model.
AAN(2) = Fuel injection parameters for Whitehouse-Way model.
AVC   = Intake valve/port closing angle, degrees.
AVO   = Intake valve/port opening angle, degrees.
AREF   = Reference value for speed of sound (based on TREF).
ANNA, ANNB, ANNC = Parameter for Annand or Woschni Heat Transfer model.
BETA   = Parameter in Watson combustion model.
CARBON = Mass fraction of carbon in fuel.
CALVAL = Constant volume heat of combustion with water present as vapor in the products.
CD1, CD2 = Parameters in Watson combustion model.
CDA   = Discharge Coefficient for intake valve/port.
CDE   = Discharge Coefficient for exhaust valve/port.
CEFFYI = Charging efficiency based on inlet conditions and trapped volume.
CHEFFY = Charging efficiency based on trapped conditions.
CONDY   = Thermal Conductivity of cylinder contents.
CYCLE   = 2 for a two stroke engine, = 4 for a four stroke engine.
COEFFA, COEFFB, COEFFC, COEFFD = Coefficient for polynomial fit to JANAF tables.
CP1, CP2 = Parameter in Watson Combustion model.
CPT   = Specific heat at constant pressure.
CVT   = Specific heat at constant volume.
DEL1, DEL2, DEL3 = Parameter in either Wiebe or Whitehouse-Way combustion models.
DHEAT   = Heat transfer rate from cylinder during gas exchange.
DREF   = Reference diameter.

DZ   = Nondimensional time increment.
DQF   = Heat addition to cylinder due to combustion.
DQCR   = Heat transfer from cylinder due to radiation.
DQCY   = Heat transfer from cylinder due to convection.
ETI   = Internal energy of gases in cylinder at start of
          time step.
ETF   = Internal energy of gases in cylinder at end of time
          step.
EVC   = Exhaust valve/port opening angle, degrees.
EVO   = Exhaust valve/port closing angle, degrees.
EXH   = An indicator of whether the exhaust valve/port is open
          or closed during the cycle. (=0 when closed, =10 when
          open).
EXHVMX = Maximum flow area of exhaust valves/ports.
FCYL   = Crossectional area of cylinder.
FMEP1, FMEP2, FMEP3 = Parameters in FMEP correlation.
FMEPM   = Multiplier for FMEP correlation.
FPISTA = Ratio of surface area of piston top to crossectional
          area of cylinder.
FPISTE = Ratio of surface area of head exposed to combustion
          chamber to crossectional area of cylinder.
FAIR   = Array specifying the geometric intake valve flow area.
FEXH   = Array specifying the geometric exhaust valve flow area.
FREF   = A reference area used to normalize areas in the program.
FZA   = Fuel/air mass ratio.
GA   = Ratio of specific heats for air.
GE   = Ratio of Specific heats for exhaust products.
GREF   = Reference ratio of specific heats.
HEATG   = Total heat transfer during gas exchange.
HEATRF = Heat released due to combustion
HC1 ... HC8 = Integral of the convective coefficient times the
              area for steady state heat transfer analysis.
HCT1 ... HCT8 = Integral of the convective coefficient times
                the gas temperature times the area for steady
                state heat transfer analysis.
HTA   = Enthalpy of air entering cylinder
HTF   = Enthalpy of cylinder contents at end of time step.
NPCWF   = Parameter which determines which combustion model is
          used in the program
                when NPCWF.LT.0   Whitehouse-Way Model
                when NPCWF.EQ.0 and DEL3.EQ.0   AVL Model
                when NPCWF.EQ.0 and DEL3.GT.0   Wiebe Model
                when NPCWF.GT.0   Watson Model
NTAIR   = Number of points provided in ALPAIR and FAIR to specify
          the intake valve flow area. FAIR(NTAIR), ALPAIR(NTAIR)
NTEXH   = Number of points provided in ALPHEX and FEXH to specify
          the exhaust valve flow area. FEXH(NTEXH), ALPHEX(NTEXH)
PBARAB = Barometric pressure.
PI   = 3.141592654
PO2   = Partial pressure of oxygen.
PREF   = Reference pressure.

PORTED = 1 for loop scavenged, = 2 for uniflow scavenged.
PVEL   = Mean piston speed.
PURITY = Purity. Ratio of mass of air in trapped cylinder charge
          to total mass of trapped cylinder charge.
RELCHG = Relative charging efficiency based on trapped volume.
RELCHS = Relative charging efficiency based on swept volume.
REVENG = Engine speed, rev/sec.
REVREF = Reference engine speed, rev/sec.
REY   = Reynolds number of cylinder contents.
SCAEFF = Scavenging Efficiency
SCASW = Scavenge ratio based on swept volume.
SCAVR = Scavenge ratio based on trapped volume.
STOIC = Stoichiometric fuel/air ratio.
SURFC = Surface area of cylinder wall exposed to combustion.
SURFH = Surface area of head exposed to combustion chamber.
SURFP = Surface area of piston.
TAIR   = Temperature of air entering cylinder through intake.
TEXH   = Exhaust temperature (initial estimate specified as
          input)
TREF   = Reference temperature.
TREFF = Trapping Efficiency.
TWALL = Cylinder wall temperature.
VALAIR = 0 if engine has intake ports, = 10 if engine has intake
          valves.
VALEXH = 0 if engine has exhaust ports, = 10 if engine has
          exhaust valves.
VCYL   = Cylinder volume.
VEFFYI = Charging efficiency based on inlet conditions and
          swept volume.
VISCTY = Viscosity of cylinder contents.
WABU   = Mass of air required to burn fuel under stoichiometric
          conditions.
WAR   = Water to air ratio.
WCA   = Air retained in the cylinder.
WCAIR = Total mass of air trapped in cylinder.
WCHG   = Mass of air plus residual in cylinder per cycle.
WCO   = Total mass flow rate through exhaust valve.
WCYL   = Total mass in cylinder.
WCYLT = Trapped mass in cylinder.
WIDTHA = Fraction of cylinder circumference allocated for intake
          ports.
WIDTHE = Fraction of cylinder circumference allocated for exhaust
          ports.
WFUEL = Mass of fuel injected per cycle.
WMW   = Molecular weight.
WN(I) = Number of moles of species I.
WNA   = Number of moles of air trapped in cylinder.
WNI(I) = Number of moles of each species present at start of time
          step.
WNF(I) = Number of moles of each species present at end of time
          step.

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```
WNP     = Increase in number of moles in cylinder due to
          combustion (moles air - moles products).
WNR     = Number of moles of residual trapped in cylinder.
WNTF    = Total number of moles of gases in cylinder.
WRES    = Mass of residual gases in cylinder.
WTOT    = Total mass in cylinder, air+residual+fuel
```

10.2 Napier Nomad program listing

```
MAIN PROGRAM
  CHARACTER*16 FNAME1,FNAME2,FNAME3,FNAME4
  CHARACTER*2 INC1,INC2,INC3,INC4
  COMMON/BNSN/ EQUIVD,RPM,PEXH,PAIR,TAIR,
 1           CR,BORE,STROKE,CONROD,FPISTE,FPISTA,
 2           EVO,EVC,AVO,AVC,
 3           TWALL,WFUEL,
 4           ACB,ACF,
 5           ANNA,FMEPM,
 6           NPCWF,DEL1,DEL2,DEL3,AAN(2),
 7           VALEXH,CDE,NTEXH,WIDTHE,ALPHEX(50),FEXH(50),
 8           VALAIR,CDA,NTAIR,WIDTHA,ALPAIR(50),FAIR(50)
  COMMON/GEN/ALPHAT,ANGEND,ANGRES,AIRPO,EXHPO,IMOLS,
 1           APAIR,APEXH,AREF,AP(2),
 1           APN(2),CYCLE,DALPHA,
 1           DREF,DZ,FREF,
 1           IPOWER,IREV,GA,GE,GREF,IUNITL,
 1           IUNITP,IUNITT,IUNITK,IUNITW,IUNITQ,
 1           WAR,PBAR,PBARAB,
 1           PI,PREF,REVENG,REVREF,RPAIR,RPEXH,RP(2),
 1           RPN(2),STEP2,TEXH,TREF,VREF,WREF,XREF,
 1           Z,ZREF,HAIR,HREF,SCMULT,NC
  COMMON/COMB/ AIRFL,EQUIV,TEXHS,SHPS,FZA,HRD,SCASW,TREFF,SCAEFF,
 1    AIRVMX,EXHVMX,PORTED,STOIC,WOO,BLBACK,FUELF,BHP
  COMMON/OPEN/ FNAME1,FNAME2,FNAME3,FNAME4
  COMMON/TEMP/TWEV,TWGH,TWGP,TWGC,TWCR,TWPR,TWCP,TWCC,TWCH,TEXHP,
 1    TWEVG,TC1,TC2,TC3
  COMMON/HEAT1/ QF,QFPC,QC,QCPC,A1,A1PC,A2,A2PC,A3,A3PC,A4,A4PC,
 1    QCYL,QCYLPC
  COMMON/HEAT2/ QEVG,QEVGPC,QEXHP,QEXHPC,
 1    QTC1,QTC1PC,QTC2,QTC2PC,QTC3,QTC3PC,QOUT,QOUTPC
  FNAME1='FILE01.AAA      '
  FNAME2='FILE01.BBB      '
  FNAME3='FILE01.CCC      '
  FNAME4='FILE01.DDD      '
  INC1='02'
  INC2='03'
  INC3='04'
  INC4='05'
C
C  ASSUME COMPRESSOR PRESSURE RATIO AND PRESSURE RATIO ACROSS DIESEL
C
  P2P1=6.0544
  P6P5=1./1.171
C
C  INLET CONDITIONS
C
```

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```
      T1=518.7
      P1=14.7
C
C     COMPRESSOR OUTLET CONDITIONS
C
      ETACTT=0.85
      P2=P2P1*P1
      DUMMY=P2P1**0.2857 - 1.
      T2=T1*(DUMMY/ETACTT + 1.)
      WC=0.24*T1/ETACTT*DUMMY
C
C     LOSSES TO AFTERCOOLER/AFTERCOOLER INLET CONDITIONS
C
C     P3=0.98*P2
      P3=P2
      T3=T2
C
C     AFTERCOOLER EXIT CONDITIONS
C
      E=0.4
C     T4=T3-E*(T3-T1)
C     P4=0.98*P3
      T4=T3
      P4=P3
C
C     LOSSES TO DIESEL/DIESEL INLET CONDITIONS
C
      P5=P4
      T5=T4
      PAIR=P5
      TAIR=T5
      PEXH=P6P5*PAIR
C
C     RUN DIESEL PROGRAM
C
      CALL BENSON
C
C     EXHAUST CONDITIONS
C
      P6=PEXH
      T6=TEXHS
C
C     LOSSES TO HIGH PRESSURE TURBINE/TURBINE INLET CONDITIONS
C
      P7=0.98*P6
      T7=T6
C
C     TURBINE OUTLET CONDITIONS - WORK MATCHED TO COMPRESSOR REQUIREMENTS
C             ASSUMES 2% LOSS TO BEARING FRICTION
C
      ICHK=0
```

```
          T8=T7
          P8=14.7
       30 TM=(T8+T7)/2.
          CALL PROP(EQUIVD,TM,CPX,GX)
          ETAT1=0.84
          DUMMY=1.-(P8/P7)**((GX-1.)/GX)
          T8=T7*(1.-DUMMY*ETAT1)
          WT=ETAT1*CPX*T7*DUMMY*(FUELF+AIRFL)*3600./2544.
          IF(ICHK.EQ.1) GO TO 40
          ICHK=1
          GO TO 30
       40 CONTINUE
C
C
          TWCCF=TWCC*1.8-460.
          TWCPF=TWCP*1.8-460.
          TWCHF=TWCH*1.8-460.
          TWEVF=TWEV*1.8-460.
          TWGHF=TWGH*1.8-460.
          TWGPF=TWGP*1.8-460.
          TWPRF=TWPR*1.8-460.
          TWGCF=TWGC*1.8-460.
          TWCRF=TWCR*1.8-460.
C
          WRITE(2,1010)
     1010 FORMAT(/5X,'ENGINE PART TEMPERATURES',40X,'HEAT TRANSFER SUMMARY')
          WRITE(2,1011) TWGH,TWGHF,QF,QFPC
     1011 FORMAT(/2X,'GAS SIDE HEAD TEMPERATURE',7X,F8.1,' K',F11.1,' F',
         1    12X,'FRICTION GENERATED HEAT TRANSFER',3X,F10.3,F11.2,' %')
          WRITE(2,1012) TWGP,TWGPF,QC,QCPC
     1012 FORMAT(2X,'GAS SIDE PISTON CROWN TEMPERATURE',F7.1,' K',F11.1,
         1    ' F',12X,'CREVICE VOLUME HEAT TRANSFER',F17.3,F11.2,' %')
          WRITE(2,1013) TWGC,TWGCF,A1,A1PC
     1013 FORMAT(2X,'GAS SIDE SLEEVE TEMPERATURE',5X,F8.1,' K',F11.1,' F',
         1    12X,'HEAT TRANSFER TO CYLINDER WALL',F15.3,F11.2,' %')
          WRITE(2,1014) TWEV,TWEVF,A2,A2PC
     1014 FORMAT(2X,'EXHAUST VALVE TEMPERATURE',7X,F8.1,' K',F11.1,' F',
         1    12X,'HEAT TRANSFER TO PISTON',4X,F18.3,F11.2,' %')
          WRITE(2,1015) TWPR,TWPRF,A3,A3PC
     1015 FORMAT(2X,'PISTON RIM TEMPERATURE',10X,F8.1,' K',F11.1,' F',
         1    12X,'HEAT TRANSFER TO HEAD',6X,F18.3,F11.2,' %')
          WRITE(2,1016) TWCR,TWCRF,A4,A4PC
     1016 FORMAT(2X,'COMPRESSION RING TEMPERATURE',4X,F8.1,' K',F11.1,' F',
         1    12X,'HEAT TRANSFER TO EXHAUST VALVE',F15.3,F11.2,' %')
          WRITE(2,1017) TWCH,TWCHF,QCYL,QCYLPC
     1017 FORMAT(2X,'COOLANT SIDE HEAD TEMPERATURE',3X,F8.1,' K',F11.1,' F',
         1    12X,'TOTAL HEAT INPUT TO NETWORK',3X,F15.3,F11.2,' %')
          WRITE(2,1018) TWCP,TWCPF
     1018 FORMAT(2X,'OIL SIDE PISTON TEMPERATURE',5X,F8.1,' K',F11.1,' F')
          WRITE(2,1019) TWCC,TWCCF
     1019 FORMAT(2X,'COOLANT SIDE SLEEVE TEMPERATURE',F9.1,' K',F11.1,' F')
```

```
      WRITE(2,1002) QEVG,QEVGPC,QEXHP,QEXHPC,
     1    QTC1,QTC1PC,QTC2,QTC2PC,QTC3,QTC3PC,QOUT,QOUTPC
 1002 FORMAT(69X,'HEAT TRANSFER TO EXH VALVE GUIDE',3X,F10.3,F11.2,' %'/
     1 69X,'HEAT TRANSFER TO EXHAUST PORT GASES',F10.3,F11.2,' %'/
     2 69X,'HEAT TRANSFER TO PISTON COOLING OIL',F10.3,F11.2,' %'/
     3 69X,'HEAT TRANSFER TO SLEEVE COOLING OIL',F10.3,F11.2,' %'/
     4 69X,'HEAT TRANSFER TO HEAD COOLING OIL  ',F10.3,F11.2,' %'/
     5 69X,'TOTAL HEAT TRANSFER FROM NETWORK   ',F10.3,F11.2,' %')
C
      WC=-WC*(FUELF+AIRFL)*3600./2544.
      THP=BHP+WC+WT
      BSFC=FUELF/THP*3600.
      WRITE(2,1030) BHP,WC,WT,THP,BSFC
 1030 FORMAT(/3X,'DIESEL BRAKE POWER',F10.2,' HP'/
     1    3X,'COMPRESSOR POWER',F12.2,' HP'/3X,'TURBINE POWER',F15.2,
     2    ' HP'/3X,'TOTAL SHAFT POWER',F11.2,' HP'/3X,'BSFC',20X,F11.4)
C
      CALL FCLOSE
      STOP
      END
C
      BLOCK DATA
      COMMON/BNSN/ EQUIVD,RPM,PEXH,PAIR,TAIR,
     1             CR,BORE,STROKE,CONROD,FPISTE,FPISTA,
     2             EVO,EVC,AVO,AVC,
     3             TWALL,WFUEL,
     4             ACB,ACF,
     5             ANNA,FMEPM,
     6             NPCWF,DEL1,DEL2,DEL3,AAN(2),
     7             VALEXH,CDE,NTEXH,WIDTHE,ALPHEX(50),FEXH(50),
     8             VALAIR,CDA,NTAIR,WIDTHA,ALPAIR(50),FAIR(50)
C
      DATA EQUIVD,RPM,PEXH,PAIR,TAIR /0.60,2050.,134.79,149.76,896./
      DATA CR,BORE,STROKE,CONROD,FPISTE,FPISTA /11.17,6.00,7.375,
     1    14.75,1.,1.13/
      DATA EVO,EVC,AVO,AVC /105.,255.,130.,230./
      DATA TWALL,WFUEL /1460.,0.0001/
      DATA ACB,ACF /335.0,10./
      DATA ANNA,FMEPM /0.30,1.25/
      DATA NPCWF,DEL1,DEL2,DEL3,AAN(1),AAN(2) /-1,0.01457,0.667,0.4,
     1  0.4,0.5/
      DATA VALEXH,CDE,WIDTHE /0.,0.85,0.20/
      DATA VALAIR,CDA,WIDTHA /0.,0.85,0.36/
      END
C
      SUBROUTINE PROP(EQUIV,T,CPX,GX)
      IF(EQUIV.GT.0.) GO TO 10
      X1=0.
      X2=0.
      X3=0.21
      X4=0.79
```

```
      GO TO 20
10    CARBON=0.85561
      HC=12.011/1.008*(1.-CARBON)/CARBON
      ASTO=(2.+HC/2.)/2./0.21
      Y1=1.
      Y2=HC/2.
      Y3=ASTO/EQUIV*0.21 - 1. - HC/4.
      Y4=ASTO/EQUIV * 0.79
      YTOT=Y1+Y2+Y3+Y4
      X1=Y1/YTOT
      X2=Y2/YTOT
      X3=Y3/YTOT
      X4=Y4/YTOT
20    CP1=16.2-6.53E3/T+1.41E6/T**2
      CP2=19.86-597./SQRT(T)+7500./T
      CP3=11.515-172./SQRT(T)+1530./T
      CP4=9.47-3.47E3/T+1.16E6/T**2
      CPX=X1*CP1+X2*CP2+X3*CP3+X4*CP4
      AVM=X1*44.01+X2*18.016+X3*32.00+X4*28.01
      CPX=CPX/AVM
      RX=1545./778./AVM
      CVX=CPX-RX
      GX=CPX/CVX
      RETURN
      END
```

10.3 Garrett CCE program listing

```
       MAIN PROGRAM
       CHARACTER*16 FNAME1,FNAME2,FNAME3,FNAME4
       CHARACTER*2 INC1,INC2,INC3,INC4
       COMMON/BNSN/ EQUIVD,RPM,PEXH,PAIR,TAIR,
      1           CR,BORE,STROKE,CONROD,FPISTE,FPISTA,
      2           EVO,EVC,AVO,AVC,
      3           TWALL,WFUEL,
      4           ACB,ACF,
      5           ANNA,FMEPM,
      6           NPCWF,DEL1,DEL2,DEL3,AAN(2),
      7           VALEXH,CDE,NTEXH,WIDTHE,ALPHEX(50),FEXH(50),
      8           VALAIR,CDA,NTAIR,WIDTHA,ALPAIR(50),FAIR(50)
       COMMON/GEN/ALPHAT,ANGEND,ANGRES,AIRPO,EXHPO,IMOLS,
      1           APAIR,APEXH,AREF,AP(2),
      1           APN(2),CYCLE,DALPHA,
      1           DREF,DZ,FREF,
      1           IPOWER,IREV,GA,GE,GREF,IUNITL,
      1           IUNITP,IUNITT,IUNITK,IUNITW,IUNITQ,
      1           WAR,PBAR,PBARAB,
      1           PI,PREF,REVENG,REVREF,RPAIR,RPEXH,RP(2),
      1           RPN(2),STEP2,TEXH,TREF,VREF,WREF,XREF,
      1           Z,ZREF,HAIR,HREF,SCMULT,NC
       COMMON/COMB/ AIRFL,EQUIV,TEXHS,SHPS,FZA,HRD,SCASW,TREFF,SCAEFF,
      1     AIRVMX,EXHVMX,PORTED,STOIC,WCO,BLBACK,FUELF,BHP
       COMMON/OPEN/ FNAME1,FNAME2,FNAME3,FNAME4
       COMMON/TEMP/TWEV,TWGH,TWGP,TWGC,TWCR,TWPR,TWCP,TWCC,TWCH,TEXHP,
      1     TWEVG,TC1,TC2,TC3
       COMMON/HEAT1/ QF,QFPC,QC,QCPC,A1,A1PC,A2,A2PC,A3,A3PC,A4,A4PC,
      1     QCYL,QCYLPC
       COMMON/HEAT2/ QEVG,QEVGPC,QEXHP,QEXHPC,
      1     QTC1,QTC1PC,QTC2,QTC2PC,QTC3,QTC3PC,QOUT,QOUTPC
       FNAME1='FILE01.AAA       '
       FNAME2='FILE01.BBB       '
       FNAME3='FILE01.CCC       '
       FNAME4='FILE01.DDD       '
       INC1='02'
       INC2='03'
       INC3='04'
       INC4='05'
C
C     ASSUME COMPRESSOR PRESSURE RATIO AND PRESSURE RATIO ACROSS DIESEL
C
       P2P1=10.61
       P6P5=1./1.111
C
C     INLET CONDITIONS
C
       T1=518.7
```

```
            P1=14.7
C
C     COMPRESSOR OUTLET CONDITIONS
C
            ETACTT=0.79
            P2=P2P1*P1
            DUMMY=P2P1**0.2857 - 1.
            T2=T1*(DUMMY/ETACTT + 1.)
            WC=0.24*T1/ETACTT*DUMMY
C
C     LOSSES TO AFTERCOOLER/AFTERCOOLER INLET CONDITIONS
C
C           P3=0.98*P2
            P3=P2
            T3=T2
C
C     AFTERCOOLER EXIT CONDITIONS
C
            E=0.4
            T4=T3-E*(T3-T1)
            P4=0.98*P3
C
C     LOSSES TO DIESEL/DIESEL INLET CONDITIONS
C
            P5=P4*0.98
            T5=T4
            PAIR=P5
            TAIR=T5
            PEXH=P6P5*PAIR
C
C     RUN DIESEL PROGRAM
C
            CALL BENSON
C
C     EXHAUST CONDITIONS
C
            P6=PEXH
            T6=TEXHS
C
C     LOSSES TO HIGH PRESSURE TURBINE/TURBINE INLET CONDITIONS
C
            P7=0.98*P6
            T7=T6
C
C     AFTERBURNER OUTLET CONDITIONS
C
            F=0.0
            TIN=T6
            CALL TBURN(EQUIVD,F,TIN,TOUT)
            T7=TOUT
            XFUEL=F*(AIRFL+FUELF)
```

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```
C
C    TURBINE OUTLET CONDITIONS - WORK MATCHED TO COMPRESSOR REQUIREMENTS
C             ASSUMES 2% LOSS TO BEARING FRICTION
C
       ICHK=0
       T8=T7
   30  TM=(T8+T7)/2.
       CALL PROP(EQUIVD,TM,CPX,GX)
       ETAT1=0.845
       WT1=1.02*WC
       P8=P7*(1.-WT1/(ETAT1*CPX*T7))**(GX/(GX-1.))
       DUMMY=1.-(P8/P7)**((GX-1.)/GX)
       T8=T7*(1.-DUMMY*ETAT1)
       IF(ICHK.EQ.1) GO TO 40
       ICHK=1
       GO TO 30
   40  CONTINUE
C
C    LOSSES BETWEEN TURBINES/POWER TURBINE INLET CONDITIONS
C
       P9=0.98*P8
       T9=T8
C
C    POWER TURBINE OUTLET CONDITIONS
C
       ICHK=0
       T10=T9
   50  TM=(T9+T10)/2.
       CALL PROP(EQUIVD,TM,CPX,GX)
       WRITE(6,*) 'CPX,GX',CPX,GX
       P10=14.7
       ETAT2=0.848
       DUMMY=1.-(P10/P9)**((GX-1.)/GX)
       T10=T9*(1.-DUMMY*ETAT2)
       IF(ICHK.EQ.1) GO TO 60
       ICHK=1
       GO TO 50
   60  CONTINUE
       WT2=ETAT2*CPX*T9*DUMMY*(FUELF+AIRFL)*3600./2544.
C
       WRITE(6,*) 'T9,P9,T10,P10',T9,P9,T10,P10
C
       TWCCF=TWCC*1.8-460.
       TWCPF=TWCP*1.8-460.
       TWCHF=TWCH*1.8-460.
       TWEVF=TWEV*1.8-460.
       TWGHF=TWGH*1.8-460.
       TWGPF=TWGP*1.8-460.
       TWPRF=TWPR*1.8-460.
       TWGCF=TWGC*1.8-460.
       TWCRF=TWCR*1.8-460.
```

```
C
      WRITE(2,1010)
 1010 FORMAT(/5X,'ENGINE PART TEMPERATURES',40X,'HEAT TRANSFER SUMMARY')
      WRITE(2,1011) TWGH,TWGHF,QF,QFPC
 1011 FORMAT(/2X,'GAS SIDE HEAD TEMPERATURE',7X,F8.1,' K',F11.1,' F',
     1   12X,'FRICTION GENERATED HEAT TRANSFER',3X,F10.3,F11.2,' %')
      WRITE(2,1012) TWGP,TWGPF,QC,QCPC
 1012 FORMAT(2X,'GAS SIDE PISTON CROWN TEMPERATURE',F7.1,' K',F11.1,
     1   ' F',12X,'CREVICE VOLUME HEAT TRANSFER',F17.3,F11.2,' %')
      WRITE(2,1013) TWGC,TWGCF,A1,A1PC
 1013 FORMAT(2X,'GAS SIDE SLEEVE TEMPERATURE',5X,F8.1,' K',F11.1,' F',
     1   12X,'HEAT TRANSFER TO CYLINDER WALL',F15.3,F11.2,' %')
      WRITE(2,1014) TWEV,TWEVF,A2,A2PC
 1014 FORMAT(2X,'EXHAUST VALVE TEMPERATURE',7X,F8.1,' K',F11.1,' F',
     1   12X,'HEAT TRANSFER TO PISTON',4X,F18.3,F11.2,' %')
      WRITE(2,1015) TWPR,TWPRF,A3,A3PC
 1015 FORMAT(2X,'PISTON RIM TEMPERATURE',10X,F8.1,' K',F11.1,' F',
     1   12X,'HEAT TRANSFER TO HEAD',6X,F18.3,F11.2,' %')
      WRITE(2,1016) TWCR,TWCRF,A4,A4PC
 1016 FORMAT(2X,'COMPRESSION RING TEMPERATURE',4X,F8.1,' K',F11.1,' F',
     1   12X,'HEAT TRANSFER TO EXHAUST VALVE',F15.3,F11.2,' %')
      WRITE(2,1017) TWCH,TWCHF,QCYL,QCYLPC
 1017 FORMAT(2X,'COOLANT SIDE HEAD TEMPERATURE',3X,F8.1,' K',F11.1,' F',
     1   12X,'TOTAL HEAT INPUT TO NETWORK',3X,F15.3,F11.2,' %')
      WRITE(2,1018) TWCP,TWCPF
 1018 FORMAT(2X,'OIL SIDE PISTON TEMPERATURE',5X,F8.1,' K',F11.1,' F')
      WRITE(2,1019) TWCC,TWCCF
 1019 FORMAT(2X,'COOLANT SIDE SLEEVE TEMPERATURE',F9.1,' K',F11.1,' F')
      WRITE(2,1002) QEVG,QEVGPC,QEXHP,QEXHPC,
     1   QTC1,QTC1PC,QTC2,QTC2PC,QTC3,QTC3PC,QOUT,QOUTPC
 1002 FORMAT(69X,'HEAT TRANSFER TO EXH VALVE GUIDE',3X,F10.3,F11.2,' %'/
     1   69X,'HEAT TRANSFER TO EXHAUST PORT GASES',F10.3,F11.2,' %'/
     2   69X,'HEAT TRANSFER TO PISTON COOLING OIL',F10.3,F11.2,' %'/
     3   69X,'HEAT TRANSFER TO SLEEVE COOLING OIL',F10.3,F11.2,' %'/
     4   69X,'HEAT TRANSFER TO HEAD COOLING OIL  ',F10.3,F11.2,' %'/
     5   69X,'TOTAL HEAT TRANSFER FROM NETWORK   ',F10.3,F11.2,' %')
C
      FANP=51./6.
      THP=BHP+WT2-FANP
      BSFC=(FUELF+XFUEL)/THP*3600.
      WRITE(2,1030) BHP,WT2,FANP,THP,BSFC
 1030 FORMAT(/3X,'DIESEL BRAKE POWER',F10.2,' HP'/
     1   3X,'TURBINE POWER',F15.2,' HP'/
     2   3X,'FAN POWER      ',F15.2,
     3   ' HP'/3X,'TOTAL SHAFT POWER',F11.2,' HP'/3X,'BSFC',15X,F11.4)
      WRITE(6,*) 'BSFC = ',BSFC
C
      CALL FCLOSE
      STOP
      END
C
```

```
      BLOCK DATA
      COMMON/BNSN/ EQUIVD,RPM,PEXH,PAIR,TAIR,
     1             CR,BORE,STROKE,CONROD,FPISTE,FPISTA,
     2             EVO,EVC,AVO,AVC,
     3             TWALL,WFUEL,
     4             ACB,ACF,
     5             ANNA,FMEPM,
     6             NPCWF,DEL1,DEL2,DEL3,AAN(2),
     7             VALEXH,CDE,NTEXH,WIDTHE,ALPHEX(50),FEXH(50),
     8             VALAIR,CDA,NTAIR,WIDTHA,ALPAIR(50),FAIR(50)
C×××××××××××××××
      DATA EQUIVD,RPM,PEXH,PAIR,TAIR /0.68,6122.,134.79,149.76,896./
      DATA CR,BORE,STROKE,CONROD,FPISTE,FPISTA /9.1712,3.101,2.940,
     1    7.168,1.,1.13/
      DATA EVO,EVC,AVO,AVC /90.,239.,126.,234./
      DATA TWALL,WFUEL /1460.,0.000145332/
      DATA ACB,ACF /345.,10.5/
      DATA ANNA,FMEPM /0.36,1.0/
      DATA NPCWF,DEL1,DEL2,DEL3,AAN(1),AAN(2) /-1,0.01457,0.667,0.4,
     1  0.4,0.5/
      DATA VALEXH,CDE,NTEXH /10.,0.8864,13/
      DATA VALAIR,CDA,WIDTHA /0.,0.8,0.5542/
      DATA ALPHEX/0.00,10.97,25.00,31.61,41.00,52.25,72.89,90.95,104.00,
     1  111.59,119.00,132.23,149.00,37×0./
      DATA FEXH/0.0,0.00093264,0.00364,0.00591222,0.00899,0.0106201,
     1  0.01175263,0.01111131,0.00923,0.00717895,0.00461,0.00181743,0.,
     2  37×0./
      END
C
      SUBROUTINE PROP(EQUIV,T,CPX,GX)
      IF(EQUIV.GT.0.) GO TO 10
      X1=0.
      X2=0.
      X3=0.21
      X4=0.79
      GO TO 20
  10  CARBON=0.85561
      HC=12.011/1.008*(1.-CARBON)/CARBON
      ASTO=(2.+HC/2.)/2./0.21
      Y1=1.
      Y2=HC/2.
      Y3=ASTO/EQUIV×0.21 - 1. - HC/4.
      Y4=ASTO/EQUIV × 0.79
      YTOT=Y1+Y2+Y3+Y4
      X1=Y1/YTOT
      X2=Y2/YTOT
      X3=Y3/YTOT
      X4=Y4/YTOT
  20  CP1=16.2-6.53E3/T+1.41E6/T**2
      CP2=19.86-597./SQRT(T)+7500./T
      CP3=11.515-172./SQRT(T)+1530./T
```

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      CP4=9.47-3.47E3/T+1.16E6/T**2
      CPX=X1*CP1+X2*CP2+X3*CP3+X4*CP4
      AVM=X1*44.01+X2*18.016+X3*32.00+X4*28.01
      CPX=CPX/AVM
      RX=1545./778./AVM
      CVX=CPX-RX
      GX=CPX/CVX
      RETURN
      END
C
      SUBROUTINE TBURN(EQUIV,F,T1,T2)
      HV=18600.
      CALL PROP(EQUIV,T1,CP1,G1)
      T537=537.
      CALL PROP(EQUIV,T537,CPO,GO)
      CPAVE=(CP1+CPO)/2.
      DELH1=CPAVE*(T1-T537)
      DELH=DELH1+HV*F
C
      CARBON=0.85561
      STOIC=1./((CARBON/12.01+(1.-CARBON)/(1.008*4.))*(32.0+3.76*28.0))
      EQUIV2=(F+1.)*EQUIV + F/STOIC
C     WRITE(6,*) 'STOIC,EQUIV2',STOIC,EQUIV2
      TOLD=2300.
      CALL PROP(EQUIV2,TOLD,CP2,G2)
      T537=537.
      CALL PROP(EQUIV2,T537,CPO,GO)
      CPAVE=(CP2+CPO)/2.
      DELH2=CPAVE*(TOLD-T537)*(1.+F)
      ZOLD=DELH2-DELH
      TNEW=TOLD*1.05
   25 CALL PROP(EQUIV2,TNEW,CP2,G2)
      CPAVE=(CP2+CPO)/2.
      DELH2=CPAVE*(TNEW-T537)*(1.+F)
      ZNEW=DELH2-DELH
      DELT=ZNEW*(TNEW-TOLD)/(ZOLD-ZNEW)
      T2=TNEW+DELT
      WRITE(6,*) 'ZNEW,T2',ZNEW,T2
      IF(ABS(DELT).LT. 0.001) GO TO 50
      TOLD=TNEW
      TNEW=T2
      ZOLD=ZNEW
      GO TO 25
   50 WRITE(6,*) 'DELH,DELH2',DELH,DELH2
      RETURN
      END
C
C
```

10.4 Benson Program Listing

```
C   VARIABLE NAMES:
C      ACBB  = DUMMY VARIABLE USED TO STORE ACB, START OF COMBUSTION
C      ACFF  = DUMMY VARIABLE USED TO STORE ACF, END OF COMBUSTION
C      AIR   = AN INDICATOR OF WHETHER INTAKE VALVE/PORT IS OPEN OR
C              CLOSED DURING THE CYCLE (=0 WHEN CLOSED, =10 WHEN
C              OPEN.
C      ALPAIR = ARRAY OF CRANK POSITIONS CORRESPONDING TO THE INTAKE
C              VALVE FLOW AREAS GIVEN IN FAIR, DEGREES  (INPUT)
C      ALPHAT = CUMMULATIVE TOTAL CRANKANGLE DURING INTEGRATION
C      ALPHEX = ARRAY OF CRANK POSITIONS CORRESPONDING TO THE EXHAUST
C              VALVE FLOW AREAS GIVEN IN FEXH, DEGREES  (INPUT)
C      ANGEND = MAXIMUM NUMBER OF CRANK DEGREES ALLOWED BEFORE
C              INTEGRATION IS TERMINATED
C      AAN(1) = FUEL INJECTION PARAMETER FOR WHITEHOUSE-WAY MODEL

C      AAN(2) = FUEL INJECTION PARAMETER FOR WHITEHOUSE-WAY MODEL
C      ACB   = BEGINNING OF INJECTION WHEN NPCWF.LT.0
C              BEGINNING OF HEAT RELEASE WHEN NPCWF.GT.0
C      ACF   = END OF INJECTION WHEN NPCWF.LT.0
C              END OF HEAT RELEASE WHEN NPCWF.GT.0
C      AVC   = INTAKE VALVE/PORT OPENING ANGLE, DEGREES
C      AVO   = INTAKE VALVE/PORT CLOSING ANGLE, DEGREES
C      AREF  = REFERENCE VALUE FOR SPEED OF SOUND (BASED ON TREF)
C      ANNA  = PARAMETER FOR ANNAND OR WOSCHNI HEAT TRANSFER MODEL
C      ANNB  = PARAMETER FOR ANNAND OR WOSCHNI HEAT TRANSFER MODEL
C      ANNC  = PARAMETER FOR ANNAND OR WOSCHNI HEAT TRANSFER MODEL
C      BETA  = PARAMETER IN WATSON COMBUSTION MODEL
C      CARBON = MASS FRACTION OF CARBON IN FUEL
C      CD1   = PARAMETER IN WATSON COMBUSTION MODEL
C      CD2   = PARAMETER IN WATSON COMBUSTION MODEL
C      CYCLE = 2 FOR TWO CYCLE ENGINE, = 4 FOR FOUR CYCLE ENGINE
C      COEFFA = COEFFICIENT FOR POLYNOMIAL FIT TO JANAF TABLES
C      COEFFB = COEFFICIENT FOR POLYNOMIAL FIT TO JANAF TABLES
C      COEFFC = COEFFICIENT FOR POLYNOMIAL FIT TO JANAF TABLES
C      COEFFD = COEFFICIENT FOR POLYNOMIAL FIT TO JANAF TABLES
C      CP1   = PARAMETER IN WATSON COMBUSTION MODEL
C      CP2   = PARAMETER IN WATSON COMBUSTION MODEL
C      CYCLE = 2 FOR TWO STROKE ENGINE, = 4 FOR A FOUR STROKE ENGINE
C      SURFC = SURFACE AREA OF CYLINDER WALL EXPOSED TO COMBUSTION
C      DEL1  = PARAMETER FOR EITHER WIEBE OR WHITEHOUSE-WAY MODEL
C      DEL2  = PARAMETER FOR EITHER WIEBE OR WHITEHOUSE-WAY MODEL
C      DEL3  = PARAMETER FOR EITHER WIEBE OR WHITEHOUSE-WAY MODEL
C      DHEAT = HEAT TRANSFER RATE FROM CYLINDER DURING GAS EXCHANGE
C      DQF   = HEAT ADDITION TO CYLINDER DUE TO COMBUSTION
C      DQCR  = HEAT TRANSFER FROM CYLINDER DUE TO RADIATION
C      DQCY  = HEAT TRANSFER FROM CYLINDER DUE TO CONVECTION
C      ETI   = INTERNAL ENERGY OF GASES IN CYLINDER AT START OF
C              TIME STEP
C      ETF   = INTERNAL ENERGY OF GASES IN CYLINDER AT END OF
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C              TIME STEP
C      EVC  = EXHAUST VALVE/PORT OPENING ANGLE, DEGREES
C      EVO  = EXHAUST VALVE/PORT CLOSING ANGLE, DEGREES
C      EXH  = AN INDICATOR OF WHETHER THE EXHAUST VALVE/PORT IS OPEN
C              OR CLOSED DURING THE CYCLE. (=0 WHEN CLOSED, =10 WHEN
C              OPEN)
C      FCYL  = CROSSECTIONAL AREA OF CYLINDER
C      FMEP1 = PARAMETER IN FMEP CORRELATION
C      FMEP2 = PARAMETER IN FMEP CORRELATION
C      FMEP3 = PARAMETER IN FMEP CORRELATION
C      FPISTA = RATIO OF SURFACE AREA OF PISTON TOP TO CROSSECTIONAL
C              AREA OF CYLINDER
C      FPISTE = RATIO OF SURFACE AREA OF HEAD EXPOSED TO COMBUSTION
C              CHAMBER TO CROSSECTIONAL AREA OF CYLINDER
C      FAIR  = ARRAY SPECIFYING THE GEOMETRIC INTAKE VALVE FLOW AREA
C      FEXH  = ARRAY SPECIFYING THE GEOMETRIC EXHAUST VALVE FLOW AREA
C      FREF  = A REFERENCE AREA USED TO NORMALIZE AREAS IN THE PROGRAM
C      FZA   = FUEL/AIR MASS RATIO
C      GA    = RATIO OF SPECIFIC HEATS FOR AIR
C      GE    = RATIO OF SPECIFIC HEATS FOR EXHAUST PRODUCTS
C      GREF  = REFERENCE RATIO OF SPECIFIC HEATS (INPUT)
C      HEATG = TOTAL HEAT TRANSFER DURING GAS EXCHANGE
C      NPCWF = PARAMETER WHICH DETERMINES WHICH COMBUSTION MODEL IS
C              USED IN THE PROGRAM
C                  WHEN NPCWF.LT.0   WHITEHOUSE-WAY MODEL
C                  WHEN NPCWF.EQ.0 AND DEL3.EQ.0   AVL MODEL
C                  WHEN NPCWF.EQ.0 AND DEL3.GT.0   WIEBE MODEL
C                  WHEN NPCWF.GT.0   WATSON MODEL
C      NTAIR = NUMBER OF POINTS PROVIDED IN ALPAIR AND FAIR TO SPECIFY
C              THE INTAKE VALVE FLOW AREA. FAIR(NTAIR),ALPAIR(NTAIR)
C      NTEXH = NUMBER OF POINTS PROVIDED IN ALPHEX AND FEXH TO SPECIFY
C              THE EXHAUST VALVE FLOW AREA. FEXH(NTEXH),ALPHEX(NTEXH)
C      PO2   = PARTIAL PRESSURE OF OXYGEN
C      PORTED = 1 FOR LOOP SCAVENGED, = 2 FOR UNIFLOW SCAVENGED
C      STOIC = STOICHIOMETRIC FUEL/AIR RATIO
C      SURFP = SURFACE AREA OF PISTON
C      SURFH = SURFACE AREA OF HEAD EXPOSED TO COMBUSTION CHAMBER
C      TAIR  = TEMPERATURE OF AIR ENTERING CYLINDER THROUGH INTAKE
C      TEXH  = EXHAUST TEMPERATURE (INITIAL ESTIMATE SPECIFIED AS INPUT)
C      TREF  = REFERENCE TEMPERATURE (INPUT)
C
C      TWALL = CYLINDER WALL TEMPERATURE
C      VALAIR = 0 IF ENGINE HAS INTAKE PORTS, = 10 IF ENGINE HAS
C              INTAKE VALVES
C      VALEXH = 0 IF ENGINE HAS EXHAUST PORTS, = 10 IF ENGINE HAS
C              EXHAUST VALVES
C      WABU  = MASS OF AIR REQUIRED TO BURN FUEL UNDER STOICHIOMETRIC
C              CONDITIONS, MASS UNITS
C      WCA   = AIR RETAINED IN CYLINDER PER CYCLE, MASS UNITS
C      WCHG  = MASS OF AIR PLUS RESIDUAL IN CYLINDER PER CYCLE, MASS UNITS
C      WCO   = TOTAL MASS FLOW RATE THROUGH EXHAUST VALVE, MASS/TIME
C      WIDTHA = FRACTION OF CYLINDER BORE OCCUPIED BY INTAKE PORTS
C      WIDTHE = FRACTION OF CYLINDER BORE OCCUPIED BY EXHAUST PORTS
C      WFUEL = MASS OF FUEL INJECTED PER CYCLE, MASS UNITS
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C       WMW   = MOLECULAR WEIGHT
C       WN(I)  = NUMBER OF MOLES OF SPECIES I
C       WNA   = NUMBER OF MOLES OF AIR TRAPPED IN CYLINDER
C       WNI(I) = NUMBER OF MOLES OF EACH SPECIES PRESENT AT START OF
C               TIME STEP
C       WNF(I) = NUMBER OF MOLES OF EACH SPECIES PRESENT AT END OF
C               TIME STEP
C       WNP   = INCREASE IN NUMBER OF MOLES IN CYLINDER DUE TO
C               COMBUSTION (MOLS AIR —MOLES PRODUCTS)
C       WNR   = NUMBER OF MOLES OF RESIDUAL TRAPPED IN CYLINDER
C       WNTF  = TOTAL NUMBER OF MOLES OF GASES IN CYLINDER, GMOLES
C       WORKGA = WORK DONE WHEN VALVES ARE CLOSED
C       WORKGE = WORK DONE DURING GAS EXCHANGE
C       WRES  = MASS OF RESIDUAL GASES IN CYLINDER, MASS UNITS
C       WTOT  = TOTAL MASS IN CYLINDER, AIR+RESIDUAL+FUEL, MASS UNITS
C
C
C
      SUBROUTINE BENSON
C     CYLINDER PRESSURE, TEMPERATURE, VOLUME ON DIESEL3.OUT
C      IMPLICIT REAL(A—H,O—Z), INTEGER(I—N)
       COMMON/BNSN/ EQUIVZ,RPZ,PEXZ,PAIZ,TAIZ,
     1       CZ,BORZ,STROKZ,CONROZ,FPISTY,FPISTZ,
     2       EVOZ,EVCZ,AVOZ,AVCZ,
     3       TWALLZ,WFUEZ,
     4       ACBZ,ACFZ,
     5       ANNAZ,FMEPMZ,
     6       NPCWFZ,DEL1Z,DEL2Z,DEL3Z,AANZ(2),
     7       VALEXZ,CDEZ,NTEXHZ,WIDTZE,ALPHEZ(50),FEXHZ(50),
     8       VALAIZ,CDAZ,NTAIRZ,WIDTZA,ALPAIZ(50),FAIRZ(50)
       COMMON/XXX/ EQUIVD,RPM,PEXH,PAIR,TAIR,
     1       CR,BORE,STROKE,CONROD,FPISTE,FPISTA,
     2       EVO,EVC,AVO,AVC,
     3       TWALL,WFUEL,
     4       ACB,ACF,
     5       ANNA,FMEPM,
     6       NPCWF,DEL1,DEL2,DEL3,AAN(2),
     7       VALEXH,CDE,NTEXH,WIDTHE,ALPHEX(50),FEXH(50),
     8       VALAIR,CDA,NTAIR,WIDTHA,ALPAIR(50),FAIR(50)
       COMMON/GEN/ALPHAT,ANGEND,ANGRES,AIRPO,EXHPO,IMOLS,
     1       APAIR,APEXH,AREF,AP(2),
     1       APN(2),CYCLE,DALPHA,
     1       DREF,DZ,FREF,
     1       IPOWER,IREV,GA,GE,GREF,IUNITL,
     1       IUNITP,IUNITT,IUNITK,IUNITW,IUNITQ,
     1       WAR,PBARAB,
     1       PI,PREF,REVENG,REVREF,RPAIR,RPEXH,RP(2),
     1       RPN(2),STEP2,TEXH,TREF,VREF,WREF,XREF,
     1       Z,ZREF,HAIR,HREF,SCMULT,NC
       COMMON/CYL/ACSB,ALPHA,ALPHAE,ANNB,ANNC,AC,
     1       ACN,ACR,ALPHAC,
     1       CALVAL,CARBON,
     1       COEFFA(4),COEFFB(4),COEFFC(4),COEFFD(4),
     1       COEFFE(4),COEFFZ(4),CRANK,DCYL,DHEAT,
```

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      1        DRC,DVCYL,DWCIN,DWCP(2),DWCYL,
      1        FCYL,HEATG,
      1        PURITY,PVEL,PCR,PCYLT,
      1        PORTS,RC,RCN,RCR,SURFC,
      1        TCR,TCYLT,VSWEPT,
      1        VCYL,WCAIR,WCIN,
      1        WCOUT,WCYL,WMW(4),WPCNT(4),WCYLR,
      1        WN(4),WORKGA,WORKGE,XCRA,XSTA,
      1        NCD,WCYLT,DWCINT,
      1        TPIST,THEAD,TEXV,CID
      COMMON/COMB/AIRFL,EQUIV,TEXHS,SHPS,FZA,HRD,SCASW,TREFF,SCAEFF,
      + AIRVMX,EXHVMX,PORTED,STOIC,WCO,BLBACK,FUELF,BHP
      COMMON/HEAT/ NHEAT,QSLEV1,QPIST1,QHEAD1,QEXHV1,QTOT1,
      1        QSLEV2,QPIST2,QHEAD2,QEXHV2,QTOT2,
      2        HC1,HC2,HC3,HC4,HC5,HC6,HC7,HC8,
      3        HCT1,HCT2,HCT3,HCT4,HCT5,HCT6,HCT7,HCT8
      COMMON/STOP/ ISTOP
      WRITE(6,*) 'INSIDE BENSON'
      EQUIVD=EQUIVZ
      RPM=RPZ
      PEXH=PEXZ
      PAIR=PAIZ
      TAIR=TAIZ
      CR=CZ
      BORE=BORZ
      STROKE=STROKZ
      CONROD=CONROZ
      FPISTE=FPISTY
      FPISTA=FPISTZ
      EVO=EVOZ
      EVC=EVCZ
      AVO=AVOZ
      AVC=AVCZ
      TWALL=TWALLZ
      WFUEL=WFUEZ
      ACB=ACBZ
      ACF=ACFZ
      ANNA=ANNAZ
      FMEPM=FMEPMZ
      NPCWF=NPCWFZ
      DEL1=DEL1Z
      DEL2=DEL2Z
      DEL3=DEL3Z
      AAN(1)=AANZ(1)
      AAN(2)=AANZ(2)
      VALEXH=VALEXZ
      CDE=CDEZ
      NTEXH=NTEXHZ
      WIDTHE=WIDTZE
      VALAIR=VALAIZ
      CDA=CDAZ
      NTAIR=NTAIRZ
      WIDTHA=WIDTZA
      DO 444 I=1,50
```

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      ALPHEX(I)=ALPHEZ(I)
      FEXH(I)=FEXHZ(I)
      ALPAIR(I)=ALPAIZ(I)
  444 FAIR(I)=FAIRZ(I)
C
C
      ISTOP=0
      ZERO=0.0
      ONE=1.0
      PI=3.1415927
C
C   SELECT HEAT TRANSFER MODEL
C
      NHEAT=1
C
C   OPEN OUTPUT DATA FILES
C
      CALL FOPEN
      WRITE(6,*) 'RETURNED FROM FOPEN'
c
c  This section gets and prints the time and date of this run on the outputs
c
C     CALL GETTIM (IHOUR,IMINUT,IDUM1,IDUM2)
C     CALL GETDAT (IYEAR,IMONTH,IDAY)
C     DO 2 IZZZ=2,4
C       WRITE(IZZZ,1)IMONTH,IDAY,IYEAR,IHOUR,IMINUT
C   1   FORMAT(' DATE: ',I2,'/',I2,'/',I4,15X,'TIME: ',I2,':',I2)
C   2 CONTINUE
C
      TEXHS = 0.
      SHPS = 0.
      FZA = 0.
      EQUIV = .5
      AIRVMX = 0.
      EXHVMX = 0.
C
      CALL INPUT
      WRITE(6,*) 'RETURNED FROM INPUT'
C
      CALL INPUT2
      WRITE(6,*) 'RETURNED FROM INPUT2'
C
      CALL HEADER
      WRITE(6,*) 'RETURNED FROM HEADER'
C
      WRITE(3,2048)
 2048 FORMAT (4X, 5HANGLE,5X, 8HPRESSURE,3X,11HTEMPERATURE,4X,
     + 5HGAMMA,5X, 6HVOLUME,5X, 9HMEAN TEMP/)
      JJJJ=1
      Z=0.000
      CALL UNITP(IUNITP,1,PREF,PBARAB)
C SET UP TEMPERATURES TO S.I.UNITS
      CALL UNITT(IUNITT,1,TREF)
      AREF=SQRT(287.1*GREF*TREF)
```

```
C ENTER CALCULATION FIRST TIME
      XREF=1.
      DREF=1.
      FREF=1.
      VREF=1.
      WREF=GREF*PREF*VREF*1.0E5/AREF**2
      ZREF=360.0*XREF*REVREF/AREF
      REVENG=REVENG/REVREF
      CALL UNITT(IUNITT,1,TEXH)
      CALL UNITT(IUNITT,1,TAIR)
      CALL UNITP(IUNITP,1,PEXH,PBARAB)
      CALL UNITP(IUNITP,1,PAIR,PBARAB)
      CALL BAL(0.,0.,0.,0.,TAIR,GA,HAIR)
      CALL BAL(0.,0.,0.,0.,TREF,DUM,HREF)
      WRITE(6,*) 'ENTERING LOOP'
C
   6  RPEXH=PEXH/PREF
      RPAIR=PAIR/PREF
      APEXH=(SQRT(0.287E3*GE*TEXH))/AREF
      AAEXH=APEXH/RPEXH**((GE-1.0)/(2.0*GE))
      APAIR=(SQRT(0.287E3*GA*TAIR))/AREF
C
      DZ = STEP2/(ZREF*REVENG)
      Z = Z+DZ
      ALPHAT = Z*ZREF*REVENG
C
      IF (JJJJ.EQ.1) CALL INITLZ
C
      CALL CYLNDR(JJJJ)
C
C CHECK TO SEE IF CALCULATION IS COMPLETED
C
      IF(ISTOP.EQ.1) GO TO 999
C
C CHECK TO SEE IF MAXIMUM NUMBER OF ITERATIONS IS EXCEEDED
C
      IF(ALPHAT.GT.ANGEND) GO TO 7
      JJJJ=2
C REENTER CALCULATION AGAIN
      GO TO 6
    7 CONTINUE
      WRITE(6,*) 'MAXIMUM NUMBER OF ITERATIONS EXCEEDED'
c
c This section gets and prints the time and date of this run on the outputs
c
C     CALL GETTIM (IHOUR,IMINUT,IDUM1,IDUM2)
C     CALL GETDAT (IYEAR,IMONTH,IDAY)
C     DO 4 IZZZ=2,4
C       WRITE(IZZZ,3)IMONTH,IDAY,IYEAR,IHOUR,IMINUT
C   3   FORMAT(' DATE: ',I2,'/',I2,'/',I4,15X,'TIME: ',I2,':',I2)
C   4 CONTINUE
c
c
C999  CALL FCLOSE
```

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```
  999 CONTINUE
      RETURN
      END
C
      SUBROUTINE INITLZ
      COMMON/XXX/ EQUIVD,RPM,PEXH,PAIR,TAIR,
     1        CR,BORE,STROKE,CONROD,FPISTE,FPISTA,
     2        EVO,EVC,AVO,AVC,
     3        TWALL,WFUEL,
     4        ACB,ACF,
     5        ANNA,FMEPM,
     6        NPCWF,DEL1,DEL2,DEL3,AAN(2),
     7        VALEXH,CDE,NTEXH,WIDTHE,ALPHEX(50),FEXH(50),
     8        VALAIR,CDA,NTAIR,WIDTHA,ALPAIR(50),FAIR(50)
      COMMON/GEN/ALPHAT,ANGEND,ANGRES,AIRP0,EXHP0,IMOLS,
     1        APAIR,APEXH,AREF,AP(2),
     1        APN(2),CYCLE,DALPHA,
     1        DREF,DZ,FREF,
     1        IPOWER,IREV,GA,GE,GREF,IUNITL,
     1        IUNITP,IUNITT,IUNITK,IUNITW,IUNITQ,
     1        WAR,PBARAB,
     1        PI,PREF,REVENG,REVREF,RPAIR,RPEXH,RP(2),
     1        RPN(2),STEP2,TEXH,TREF,VREF,WREF,XREF,
     1        Z,ZREF,HAIR,HREF,SCMULT,NC
      COMMON/CYL/ACSB,ALPHA,ALPHAE,ANNB,ANNC,AC,
     1        ACN,ACR,ALPHAC,
     1        CALVAL,CARBON,
     1        COEFFA(4),COEFFB(4),COEFFC(4),COEFFD(4),
     1        COEFFE(4),COEFFZ(4),CRANK,DCYL,DHEAT,
     1        DRC,DVCYL,DWCIN,DWCP(2),DWCYL,
     1        FCYL,HEATG,
     1        PURITY,PVEL,PCR,PCYLT,
     1        PORTS,RC,RCN,RCR,SURFC,
     1        TCR,TCYLT,VSWEPT,
     1        VCYL,WCAIR,WCIN,
     1        WCOUT,WCYL,WMW(4),WPCNT(4),WCYLR,
     1        WN(4),WORKGA,WORKGE,XCRA,XSTA,
     1        NCD,WCYLT,DWCINT,
     1        TPIST,THEAD,TEXV,CID
      COMMON/COMB/AIRFL,EQUIV,TEXHS,SHPS,FZA,HRD,SCASW,TREFF,SCAEFF,
     + AIRVMX,EXHVMX,PORTED,STOIC,WCO,BLBACK,FUELF,BHP
C *******************************************************************
C  CONVERT TO SI UNITS
C *******************************************************************
   11 DCYL=DCYL/3.281
      XSTA=XSTA/3.281
      XCRA=XCRA/3.281
      IF(VALEXH.EQ.0.0) GO TO 15
      DO 14 N=1,NTEXH
   14 FEXH(N)=FEXH(N)/3.281**2
   15 IF(VALAIR.EQ.0.0) GO TO 17
      DO 16 N=1,NTAIR
   16    FAIR(N)=FAIR(N)/3.281**2
   17 CALL UNITP (IUNITP,1,PCYLT,PBARAB)
```

```
      CALL UNITT(IUNITT,1,TCYLT)
      IF (IUNITW.EQ.1) GO TO 22
      WFUEL=WFUEL/2.205
   22 CALL UNITT(IUNITT,1,TWALL)
      CALL UNITT(IUNITT,1,TPIST)
      CALL UNITT(IUNITT,1,THEAD)
      CALL UNITT(IUNITT,1,TEXV)
C ***********************************************************************
C  ENTER ENTHALPY AND VISCOSITY COEFFICIENTS, MOLECULAR WEIGHT
C  JANAF CURVE FIT 400 K TO 2400 K
C ***********************************************************************
      COEFFA(1)=3.00845
      COEFFA(2)=2.94628
      COEFFA(3)=3.29003
      COEFFA(4)=3.50953
      COEFFB(1)=6.15041E-4
      COEFFB(2)=1.03617E-3
      COEFFB(3)=2.69417E-3
      COEFFB(4)=6.54488E-4
      COEFFC(1)=-1.09800E-7
      COEFFC(2)=-3.39775E-7
      COEFFC(3)=-8.66074E-7
      COEFFC(4)=9.41722E-8
      COEFFD(1)=5.68186E-12
      COEFFD(2)=4.75627E-11
      COEFFD(3)=1.11529E-10
      COEFFD(4)=-3.43661E-11
      DO 49 I=1,4
   49 COEFFE(I)=8.3143*((COEFFA(I)-1.)*TREF+COEFFB(I)*TREF**2+
     + COEFFC(I)*TREF**3+COEFFD(I)*TREF**4)
      COEFFZ(1)=4.46E-7
      COEFFZ(2)=5.4E-7
      COEFFZ(3)=3.72E-7
      COEFFZ(4)=3.27E-7
      WMW(1)=28.016
      WMW(2)=32.000
      WMW(3)=44.010
      WMW(4)=18.016
      IMOLS=0
C  SET UP ANGLES FOR EACH CYLINDER
      ALPHAC=EVO-CRANK
      IF(ALPHAC.LT.0.) ALPHAC=ALPHAC+180.*CYCLE
C  SET UP NON-DIMENSIONAL PARAMETERS
      FCYL=(PI/4.0)*DCYL**2
   30 IF(VALEXH.EQ.0.0) GO TO 31
      DO 32 N=1,NTEXH
   32 FEXH(N)=FEXH(N)/FREF
      GO TO 33
   31 CONTINUE
      ZERO=0.0
   43 CALL STROK(EXHPO,ZERO,EVO,XSTA,XCRA,REVENG,ZREF)
   33 IF(VALAIR.EQ.0.0) GO TO 34
      DO 35 N=1,NTAIR
   35 FAIR(N)=FAIR(N)/FREF
```

```
      GO TO 36
   34 ZERO=0.0
      CALL STROK(AIRP0,ZERO,AVO,XSTA,XCRA,REVENG,ZREF)
   36 PVEL=2.0*XSTA*XREF*REVREF*REVENG
      WORKGA=0.
      WORKGE=0.
      HEATG=0.
      IMOLS=100
C
      CALL POWER (1,0)
C
   37 CONTINUE
      RCR=PCR/PREF
      ACR=SQRT(0.287E3*GE*TCR)/AREF
C *************************************************************
C  CALCULATE INITIAL CONDITIONS IN CYLINDER
C *************************************************************
      DST=1.0
      CALL STROK (XST,DST,EVO,XSTA,XCRA,REVENG,ZREF)
      CALL CYLVOL (FCYL,XST,XSTA,CR,DST,VCYL,DVCYL)
   39 VCYL=XSTA*FCYL
      DVCYL=0.0
   41 CONTINUE
      WCYL=GE*RCR*VCYL/(((ACR)**2)*GREF)
      WCYLR=WCYL
      DRC=0.
      RC=RCR
      AC=ACR
      WORKGA=0.0
      WORKGE=0.0
      HEATG=0.0
      WCIN=0.0
      SUMIMP=0.
      SUMCAP=0.
      WCOUT=0.0
      AIRNET=0.
      WCAIR=0.0
      DWCYL=0.0
      RETURN
      END


      SUBROUTINE CYLNDR(JJJJ)
      DIMENSION XMOL(4)
C     IMPLICIT REAL(A-H,O-Z), INTEGER(I-N)
      COMMON/XXX/ EQUIVD,RPM,PEXH,PAIR,TAIR,
     1         CR,BORE,STROKE,CONROD,FPISTE,FPISTA,
     2         EVO,EVC,AVO,AVC,
     3         TWALL,WFUEL,
     4         ACB,ACF,
     5         ANNA,FMEPM,
     6         NPCWF,DEL1,DEL2,DEL3,AAN(2),
     7         VALEXH,CDE,NTEXH,WIDTHE,ALPHEX(50),FEXH(50),
     8         VALAIR,CDA,NTAIR,WIDTHA,ALPAIR(50),FAIR(50)
      COMMON/GEN/ALPHAT,ANGEND,ANGRES,AIRP0,EXHP0,IMOLS,
```

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      1         APAIR,APEXH,AREF,AP(2),
      1         APN(2),CYCLE,DALPHA,
      1         DREF,DZ,FREF,
      1         IPOWER,IREV,GA,GE,GREF,IUNITL,
      1         IUNITP,IUNITT,IUNITK,IUNITW,IUNITQ,
      1         WAR,PBARAB,
      1         PI,PREF,REVENG,REVREF,RPAIR,RPEXH,RP(2),
      1         RPN(2),STEP2,TEXH,TREF,VREF,WREF,XREF,
      1         Z,ZREF,HAIR,HREF,SCMULT,NC
       COMMON/CYL/ACSB,ALPHA,ALPHAE,ANNB,ANNC,AC,
      1         ACN,ACR,ALPHAC,
      1         CALVAL,CARBON,
      1         COEFFA(4),COEFFB(4),COEFFC(4),COEFFD(4),
      1         COEFFE(4),COEFFZ(4),CRANK,DCYL,DHEAT,
      1         DRC,DVCYL,DWCIN,DWCP(2),DWCYL,
      1         FCYL,HEATG,
      1         PURITY,PVEL,PCR,PCYLT,
      1         PORTS,RC,RCN,RCR,SURFC,
      1         TCR,TCYLT,VSWEPT,
      1         VCYL,WCAIR,WCIN,
      1         WCOUT,WCYL,WMW(4),WPCNT(4),WCYLR,
      1         WN(4),WORKGA,WORKGE,XCRA,XSTA,
      1         NCD,WCYLT,DWCINT,
      1         TPIST,THEAD,TEXV,CID
       COMMON/COMB/AIRFL,EQUIV,TEXHS,SHPS,FZA,HRD,SCASW,TREFF,SCAEFF,
      + AIRVMX,EXHVMX,PORTED,STOIC,WCO,BLBACK,FUELF,BHP
       COMMON/CPURE/WCA,WCHG,IMIX
       COMMON/ENERGY/ UINITL,UFINAL,HOUT
       COMMON/TEMP/TWEV,TWGH,TWGP,TWGC,TWCR,TWPR,TWCP,TWCC,TWCH,TEXHP,
      1 TWEVG,TC1,TC2,TC3
       COMMON/INPT2/
      1 XXEVG,XXEVH,XXPSL,XXPIS,XXPRG,XXHED,XXPCR,XXRSL,XXSLV,
      2 AEXVS,AEXV,AEXST,AHEAD,ASLEEV,APIST1,APIST2,APISTR,ARING1,ARING2,
      3 CEXV,CHEAD,CSLEEV,CPIST,CRING,
      4 HEXHP,HOILP,HCSL,HCHD,NEXHV,DEXHV,
      5 D1,D2,D3,D4,D5,D6,VCV,APP,ARR,ASS
       COMMON/HEAT/ NHEAT,QSLEV1,QPIST1,QHEAD1,QEXHV1,QTOT1,
      1         QSLEV2,QPIST2,QHEAD2,QEXHV2,QTOT2,
      2         HC1,HC2,HC3,HC4,HC5,HC6,HC7,HC8,
      3         HCT1,HCT2,HCT3,HCT4,HCT5,HCT6,HCT7,HCT8
       COMMON/STOP/ ISTOP
       RPS=REVENG*REVREF
    2  CONTINUE
       ACN=AC
       RCN=RC
       NEX=1
       APN(NEX)=AP(NEX)
       RPN(NEX)=RP(NEX)
C   SET UP CRANK ANGLE
  101 ALPHAC=ALPHAC+DZ*ZREF*REVENG
       IF(ALPHAC.LT.180.0*CYCLE) GO TO 52
       ALPHAC=ALPHAC-180.0*CYCLE
   52 ALPHA=ALPHAC
       ALPHAE=ALPHA
```

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C *******************************************************************
C  TEST IF CYLINDER OPEN TO EXHAUST AFTER FIRST REVOLUTION
C         IF SO, START GAS EXCHANGE CALCULATIONS
C         IF NOT, GO TO STATEMENT 12 WHICH INITIALIZES
C         VARIABLES AND RETURNS TO MAIN
C *******************************************************************
      CRANK=CRANK-DZ*ZREF*REVENG
      IF(CRANK.LE.0.0) GO TO 102
  150 DWCP(NEX)=0.
  151 PORTS=0.0
      GO TO 12
C  SET UP CYLINDER CONDITIONS
  102 RC=RC+DZ*DRC
      WCYL=WCYL+DZ*DWCYL
C *******************************************************************
C  CALCULATE CYLINDER VOLUME, VOLUME CHANGE AND SURFACE AREA
C *******************************************************************
      DVCYLE=0.0
      DST=1.0
      CALL STROK (XST,DST,ALPHA,XSTA,XCRA,REVENG,ZREF)
      XHTA=XST
      CALL CYLVOL (FCYL,XST,XSTA,CR,DST,VCYL,DVCYL)
      FPISTE=1.0
      CALL SREA(SURFC,VCYL,FCYL,DCYL,XREF,DREF,
     1 FPISTA,FPISTE)
C  CALCULATE SURFACE AREA OF SLEEVE
      SURFC=SURFC-(FPISTA+FPISTE)*FCYL
C  CALCULATE SURFACE AREA OF PISTON
      SURFP=FPISTA*FCYL
C  CALCULATE SURFACE AREA OF EXHAUST VALVE(S)
      SURFE=FLOAT(NEXHV)*0.7854*DEXHV**2/(39.37)**2
C  CALCULATE SURFACE AREA OF HEAD
      SURFH=FPISTE*FCYL-SURFE
C  CALCULATE AC
      AC=SQRT(GE*RC*VCYL/(WCYL*GREF))
C *******************************************************************
C  TEST WHETHER PORTS AND VALVES ARE OPEN, IF SO, SET FLAGS
C *******************************************************************
      AIR=10.
      IF(ALPHA.GE.AVC .OR. ALPHA.LE.AVO) AIR=0.0
      EXH=10.
      IF(ALPHA.GE.EVC .OR. ALPHA.LE.EVO) EXH=0.0
C *******************************************************************
C     TEST WHETHER GAS EXCHANGE IS COMPLETE
C           IF SO, PRINT OUT MASS FLOW TOTALS
C               CALCULATE GAS EXCHANGE EFFICIENCIES
C               CALL POWER TO DO COMBUSTION CALCULATIONS
C *******************************************************************
C  HAS COMPRESSION STARTED YET?
      IF (ALPHA.LT.ACSB) GO TO 152
      DALPHA=DZ*ZREF*REVENG
C  IS THIS THE FIRST TIME STEP AFTER GAS EXCHANGE? IF SO, DO CALCULATIONS.
C       OTHERWISE, SKIP TO BOTTOM
      IF (ALPHA-ACSB.GT.DALPHA*0.99) GO TO 152
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C    IF (ALPHA-ACSB.GE.DALPHA) GO TO 152
C ***********************************************************
C  PRINT OUT MASS FLOW TOTALS
C ***********************************************************
      BAL2=-HEATG-WORKGA+HIN-HOUT-UINITL+UFINAL
      BAL2=BAL2/(WFUEL*CALVAL)*100.
      WRITE(6,2223) BAL2
 2223 FORMAT(2X,'GAS EXCHANGE ENERGY BALANCE',F8.4,' % OF FUEL ENERGY')
C
      BLBACK=1.-AIRNET/WCIN
      AIRFL=AIRNET*WREF*2.205*RPS*2./CYCLE
      IF(CYCLE.EQ.4.) GO TO 248
      IF(SCMULT.NE.1.) GO TO 247
      IF(PORTED.EQ.1.) GO TO 247
      SCASW=WCIN*WREF*.002871*TAIR/(PAIR*FCYL*XSTA)
      VEFFYI=1.-0.9811*EXP(-1.1201*SCASW)
      WCAIR=VEFFYI*PAIR*FCYL*XSTA/(WREF*.002871*TAIR)
      GO TO 248
  247 WCAIR=WCAIR*SCMULT
C
C  CALCULATE AND PRINT OUT THE TOTAL AIR SUPPLIED TO THE CYLINDER
C
  248 WCI=WCIN*WREF*2.0*RPS/CYCLE
      CALL UNITW(IUNITW,2,WCI)
      IF(IUNITW.EQ.2) GO TO 270
      WRITE(4,251)WCI
  251 FORMAT(35H TOTAL AIR SUPPLIED PER SECOND(KG)=,F11.6)
      GO TO 273
  270 WRITE(4,252)WCI
  252 FORMAT(35H TOTAL AIR SUPPLIED PER SECOND(LB)=,F11.6)
C
C  CALCULATE AND PRINT OUT THE MASS FLOW RATE THROUGH THE EXHAUST VALVE
C
  273 WCO=WCOUT*WREF*2.0*RPS/CYCLE
      CALL UNITW(IUNITW,2,WCO)
      IF(IUNITW.EQ.2) GO TO 271
      WRITE(4,253)WCO
  253 FORMAT(50H TOTAL MASS FLOW THROUGH EXH VALVE PER SECOND(KG)=,
     1    F11.6)
      GO TO 274
  271 WRITE(4,254)WCO
  254 FORMAT(50H TOTAL MASS FLOW THROUGH EXH VALVE PER SECOND(LB)=,
     1    F11.6)
C
C  CALCULATE AND PRINT OUT THE MASS OF AIR RETAINED IN THE CYLINDER
C
  274 WCA=WCAIR*WREF
      CALL UNITW(IUNITW,2,WCA)
      IF(IUNITW.EQ.2) GO TO 272
      WRITE(4,255)WCA
  255 FORMAT(34H TOTAL AIR RETAINED PER CYCLE(KG)=,F11.6)
      GO TO 275
  272 WRITE(4,256)WCA
  256 FORMAT(34H TOTAL AIR RETAINED PER CYCLE(LB)=,F11.6)
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C
  275 SCAVR=WCIN*WREF/((PAIR*1.0E5*VCYL*VREF)/
     1    (0.2871*1.0E3*TAIR))
       WRITE(4,257)SCAVR
  257 FORMAT(16H SCAVENGE RATIO=,F6.4)
       SCASW=WCIN*WREF/(PAIR*XSTA*XREF*PI*((DCYL*DREF)**2)/(4.
     1*TAIR*.00287))
       WRITE(4,261) SCASW
  261 FORMAT(33H SCAVENGE RATIO ON SWEPT VOLUME =,F6.4)
       CHEFFY=WCAIR*100.0/WCYL
       PURITY=CHEFFY/100.
       ONE=1.0000
       PURITY=AMIN1(PURITY,ONE)/(1.+WAR)
       CEFFYI=WCAIR*WREF*100.0/((PAIR*1.0E5*VCYL*VREF)/
     1    (0.2871*1.0E3*TAIR))
       VEFFYI=CEFFYI*VCYL/(XSTA*FCYL)
       WRITE(4,258)CHEFFY
       WRITE(4,259) CEFFYI
       WRITE(4,260) VEFFYI
  258 FORMAT(20H CHARGING EFFICIENCY,
     1        28H BASED ON TRAPPED CONDITION=,F6.2)
  259 FORMAT(20H CHARGING EFFICIENCY,
     1        43H BASED ON INLET CONDITION AND TRAPPED VOL.=,F6.2)
  260 FORMAT(20H CHARGING EFFICIENCY,
     1        41H BASED ON INLET CONDITION AND SWEPT VOL.=,F6.2)
       WSUPPL=WCIN*WREF
       WCA=WCAIR*WREF
       WCHG=WCYL*WREF
       WCA=AMIN1(WCA,WCHG)
       WDISP=PAIR*1.0E5*VCYL*VREF/(.2871*1.0E3*TAIR)
       WDISPS=PAIR*1.0E5*FCYL*FREF*XSTA*XREF/(.2871*1.0E3*TAIR)
       TREFF=WCA/WSUPPL*100.
       RELCHG=WCHG/WDISP*100.
       RELCHS=WCHG/WDISPS*100.
       SCAEFF=WCA/WCHG*100.
       WRITE(4,401)TREFF
       WRITE(4,402)RELCHG
       WRITE(4,404) RELCHS
       WRITE(4,403)SCAEFF
  401 FORMAT(23H TRAPPING EFFICIENCY = ,F6.2)
  402 FORMAT(32H RELATIVE CHARGING EFFICIENCY = ,F6.2)
  403 FORMAT(23H SCAVENGE EFFICIENCY = ,F6.2)
  404 FORMAT(47H RELATIVE CHARGING EFF BASED ON SWEPT VOLUME = ,F6.2)
       WRITE(4,405) STOIC
  405 FORMAT(33H STOICHIOMETRIC FUEL AIR RATIO = ,F6.4)
C ************************************************************
C  SET UP PARAMETERS FOR NEXT TIME
C ************************************************************
       WCIN=0.0
       WCOUT=0.0
       SUMIMP=0.
       SUMCAP=0.
       WCAIR=0.0
       AIRNET=0.
```

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C **************************************************************
C  CALCULATE TRAPPED PRESSURE AND TEMPERATURE
C **************************************************************
      N=1
      PCYLT=PREF*(RC-(RC-RCN)*(ALPHA-ACSB)/DALPHA)
      ACT=AC-(AC-ACN)*(ALPHA-ACSB)/DALPHA
      TCYLT=(GREF*TREF*ACT**2)/GE
      IF(IPOWER.EQ.0) GO TO 188
      IMOLS=100
C **************************************************************
C  CALL POWER TO DO COMBUSTION CALCULATIONS
C **************************************************************
      CALL POWER(1,1)
      IF(ISTOP.EQ.1) RETURN
C
  188 RCR=PCR/PREF
      ACR=SQRT(GE*TCR/(GREF*TREF))
      DST=1.0
      CALL STROK(XST,DST,EVO,XSTA,XCRA,REVENG,ZREF)
      CALL CYLVOL(FCYL,XST,XSTA,CR,DST,VCYL,DVCYL)
      WCYL=GE*RCR*VCYL/(((ACR)**2)*GREF)
      WORKGE=0.0
      WORKGA=0.0
      HEATG=0.0
      QSLEV2=0.
      QPIST2=0.
      QHEAD2=0.
      QEXHV2=0.
      HOUT=0.0
      HIN=0.0
      HOUT2=0.0
      HIN2=0.0
      HC5=0.
      HC6=0.
      HC7=0.
      HC8=0.
      HCT5=0.
      HCT6=0.
      HCT7=0.
      HCT8=0.
C  STORE RELEASE MASS
      WCYLR=WCYL
C  TEST IF BOTH AIR AND EXHAUST CLOSED
  152 IF(EXH.NE.0.0) GO TO 124
      IF(AIR.NE.0.0) GO TO 124
      GO TO 150
C **************************************************************
C  CALCULATE GAS EXCHANGE WORK
C **************************************************************
  124 WORKGA=WORKGA+0.5*PREF*VREF*(RC+RCN)*(DVCYL-DVCYLE)*DZ*100.
      WORKGE=WORKGE+0.5*PREF*VREF*(RC+RCN)*DVCYLE*DZ*100.
C **************************************************************
C  CALCULATE FLOW THROUGH VALVES/PORTS
C **************************************************************
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      PORTS=100.0
      IF(EXH.GT.0.0) GO TO 129
C  EXHAUST VALVE/PORT IS CLOSED, SET MASS FLOW EQUAL TO ZERO
      DWCP(NEX)=0.
      GO TO 126
C
C  EXHAUST VALVES/PORTS OPEN
C      CHECK WHETHER ENGINE HAS EXHAUST VALVES OR PORTS
C
  129 IF(VALEXH.NE.0.0) GO TO 140
C      ENGINE IS PORTED. CALCULATE PORT FLOW AREA AND NONDIMENSIONALIZE.
      XHTE=XHTA
  141 FEXHV=WIDTHE*PI*DCYL*(XHTE-EXHP0)
      FEXHV=FEXHV*DREF*XREF/FREF
      GO TO 542
C      ENGINE IS VALVED, USE SPLINE ROUTINE TO INTERPOLATE USER
C      SUPPLIED EXHAUST VALVE FLOW AREA DATA AT THIS CRANK POSITION
  140 CALL SPLFIT(0,0,NTEXH,0,0.0,ALPHEX,0,FEXH,0,ALPHA,FEXHV,ITRP)
  542 CONTINUE
  533 FEXHV=CDE*FEXHV
      EXHVMX = AMAX1(EXHVMX,FEXHV)
C
C  MASS FLOW EXHAUST
C
C      CHECK WHETHER FLOW IS IN OR OUT OF CYLINDER
C
      IF(RPEXH.LT.RC) GO TO 590
      CALL MASSFL (FEXHV,RPEXH,RC,APEXH,GREF,GE,DWCP(NEX))
      DWCP(NEX)=-DWCP(NEX)
      GO TO 547
  590 CALL MASSFL(FEXHV,RC,RPEXH,AC,GREF,GE,DWCP(NEX))
  547 CONTINUE
C  TEST FOR AIR PORTS
  126 IF(AIR.GT.0.0) GO TO 130
  127 DWCIN=0.0
      GO TO 147
C
C  INTAKE VALVES/PORTS OPEN
C      CHECK WHETHER ENGINE HAS INTAKE VALVES OR PORTS
C
  130 IF(VALAIR.NE.0.0) GO TO 144
C      ENGINE IS PORTED. CALCULATE PORT FLOW AREA AND NONDIMENSIONALIZE.
      FAIRV=WIDTHA*PI*DCYL*(XHTA-AIRP0)
      FAIRV=FAIRV*DREF*XREF/FREF
      GO TO 189
C      ENGINE IS VALVED, USE SPLINE ROUTINE TO INTERPOLATE USER
C      SUPPLIED INTAKE VALVE FLOW AREA DATA AT THIS CRANK POSITION
  144 CALL SPLFIT(0,0,NTAIR,0,0.0,ALPAIR,0,FAIR,0,ALPHA,FAIRV,ITRP)
  189 CONTINUE
  133 FAIRV=CDA*FAIRV
      AIRVMX = AMAX1(AIRVMX,FAIRV)
C  MASS FLOW AIR
      IF(RPAIR.LT.RC) GO TO 190
      CALL MASSFL (FAIRV,RPAIR,RC,APAIR,GREF,GA,DWCIN)
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      GO TO 147
  190 CALL MASSFL(FAIRV,RC,RPAIR,AC,GREF,GE,DWCIN)
      DWCIN=-DWCIN
      IF(NCD.EQ.1) DWCIN=0.
C ****************************************************************
C  MASS BALANCE
C ****************************************************************
  147 DWCYL=DWCIN-DWCP(NEX)
C
C  KEEP TRACK OF AMOUNT OF NEW AIR ADDED TO CYLINDER
C    ASSUMES CYLINDER CONTENTS ARE PERFECTLY MIXED
C
  177 IF ((ALPHA-EVO)-(DZ*ZREF*REVENG)) 170,171,171
  170 DZT=(ALPHA-EVO)/(ZREF*REVENG)
      GO TO 172
  171 DZT=DZ
C  TEST FLOW DIRECTION THROUGH AIR VALVE
  172 IF(DWCIN.GT.0.0) GO TO 174
C  OUTFLOW THROUGH AIR VALVE
C  TEST FLOW DIRECTION THROUGH EXHAUST VALVE
      IF(DWCP(NEX).GT.0.0) GO TO 173
C  OUTFLOW AIR VALVE,INFLOW EXH VALVE
      DWEAIR=WCAIR*DWCIN/WCYL
      WCAIR=WCAIR+DWEAIR*DZT
      GO TO 176
C  OUTFLOW AIR VALVE,OUTFLOW EXH VALVE
  173 DWEAIR=(DWCIN-DWCP(NEX))*WCAIR/WCYL
      WCAIR=WCAIR+DWEAIR*DZT
      GO TO 176
C  TEST FLOW DIRECTION THROUGH EXHAUST VALVE
  174 IF(DWCP(NEX).GT.0.0) GO TO 175
C  INFLOW AIR VALVE,INFLOW EXH VALVE
      DWEAIR=0.0
      WCAIR=WCAIR+DWCIN*DZT
      WCIN=WCIN+DWCIN*DZT
      GO TO 176
C  INFLOW AIR VALVE,OUTFLOW EXH VALVE
  175 DWEAIR=WCAIR*DWCP(NEX)/WCYL
      WCAIR=WCAIR+(DWCIN-DWEAIR)*DZT
      WCIN=WCIN+DWCIN*DZT
C  TOTAL MASS FLOW THROUGH EXHAUST VALVE
  176 WCOUT=WCOUT+DWCP(NEX)*DZT
C  TOTAL MASS FLOW THROUGH INTAKE VALVE
      AIRNET=AIRNET+DWCIN*DZT
C ****************************************************************
C  CALCULATE HEAT TRANSFER
C ****************************************************************
      TC=(GREF*TREF*AC**2)/GE
      TEXH=TC
      RHO=RC*PREF*1.0E2/(0.287*TC)
      WMOLS=RC*PREF*VCYL*VREF*1.0E2/(8.3143*TC)
      IF(IPOWER.NE.0) GO TO 160
      WN(1)=0.79*WMOLS
      WN(2)=0.21*WMOLS
```

```
      WN(3)=0.0
      WN(4)=0.0
      GO TO 168
  160 IF(IMOLS.EQ.0) GO TO 164
C CALCULATE PERCENT BY WT. OF CONSTITUENTS AT END OF POWER CYCLE
      WT=0.0
      DO 165 I=1,4
  165 WT=WT+WMW(I)*WN(I)
      DO 166 J=1,4
  166 WPCNT(J)=WMW(J)*WN(J)/WT
      IMOLS=0
C CALCULATE INSTANTANEOUS NO. OF MOLS. IN GAS EXCHANGE
  164 WN(1)=WREF*(0.767*WCAIR+WPCNT(1)
     1    *(WCYL-WCAIR))/WMW(1)
      WN(2)=WREF*(0.233*WCAIR+WPCNT(2)
     1    *(WCYL-WCAIR))/WMW(2)
      WN(3)=WREF*WPCNT(3)*(WCYL-WCAIR)/WMW(3)
      WN(4)=WREF*WPCNT(4)*(WCYL-WCAIR)/WMW(4)
C ***************************************************************
C CALCULATE HEAT TRANSFER DATA
C ***************************************************************
  168 CPT=0.0
      DO 161 I=1,4
  161 CPT=CPT+WN(I)*(COEFFA(I)+2.0*COEFFB(I)*TC+3.0*COEFFC(I)*TC**2
     1    +4.0*COEFFD(I)*TC**3)
      CPT=8.3143*CPT/(WCYL*WREF)
      SUMMOL=WN(1)+WN(2)+WN(3)+WN(4)
      RGAS=8.3143*SUMMOL/(WCYL*WREF)
      GE=CPT/(CPT-RGAS)
      SUMIMP=SUMIMP+TC*CPT*DWCP(1)*DZ
      SUMCAP=SUMCAP+CPT*DWCP(1)*DZ
      TAVG=1.8*SUMIMP/SUMCAP
      PRESS=14.5*PREF*RC
      TRANK=1.8*TC
      VOL=61032.7*VREF*VCYL
      WRITE(3,1020) ALPHA,PRESS,TRANK,GE,VOL
 1020 FORMAT (5(1X,E11.5))
      XSTIN=XST*39.372
C
C CALCULATE ENTHALPY OF AIR ENTERING CYLINDER
      HTA=0.0
      XMOL(1)=.79
      XMOL(2)=.21
      DO 21 I=1,2
   21 HTA=HTA+XMOL(I)*(8.3143*((COEFFA(I))*TAIR+COEFFB(I)*TAIR**2
     1    +COEFFC(I)*TAIR**3+COEFFD(I)*TAIR**4)-COEFFE(I))
      HTA=HTA/28.85
C CALCULATE ENTHALPY AND INTERNAL ENERGY OF CYLINDER CONTENTS AT
C     THE END OF THE TIME STEP
      HTF=0.0
      DO 91 I=1,4
      XMOL(I)=WN(I)/SUMMOL
   91 HTF=HTF+XMOL(I)*(8.3143*((COEFFA(I))*TC+COEFFB(I)*TC**2
     1    +COEFFC(I)*TC**3+COEFFD(I)*TC**4)-COEFFE(I))
```

```
      HTF=HTF*SUMMOL/(WREF*WCYL)
      ETF=HTF-8.3142*TC*SUMMOL/(WREF*WCYL)
C
      DHOUT=DWCP(1)*HTF*WREF*DZT
      HOUT=HOUT+DHOUT
      DHIN=DWCIN*HTA*WREF*DZT
      HIN=HIN+DHIN
C CALCULATE COEFFICIENTS FOR GAS VISCOSITY EQUATION
      A=0.0
      B=0.0
      DO 162 I=1,4
      A=WN(I)*COEFFZ(I)*SQRT(WMW(I))+A
  162 B=WN(I)*SQRT(WMW(I))+B
C ******************************************************************
C        CALCULATE HEAT TRANSFER DURING GAS EXCHANGE
C ******************************************************************
      IF(NHEAT.EQ.0) GO TO 777
      TWALL=TWGC
      TPIST=TWGP
      THEAD=TWGH
      TEXV=TWEV
  777 VISCTY=(A*TC**0.645)/B
      CONDY=CPT*VISCTY/0.7
      REY=RHO*PVEL*DCYL*DREF/VISCTY
      IF(ANNC.EQ.0) REY=REY*6.18
      H=(ANNA*CONDY*REY**ANNB)/(DCYL*DREF)
      DHEAT=SURFC*H*(TWALL-TC)*VREF*1000./AREF
      DHEAT=DHEAT+(SURFP*(TPIST-TC)+SURFH*(THEAD-TC)
     1 +SURFE*(TEXV-TC))*H*VREF*1000./AREF
C TOTAL HEAT TRANSFER DURING GAS EXCHANGE (KJ)
      HEATG=HEATG+DHEAT*DZ*1.0E-3
C
      DQSLEV=SURFC*H*(TWALL-TC)*VREF*1000./AREF
      DQPIST=SURFP*H*(TPIST-TC)*VREF*1000./AREF
      DQHEAD=SURFH*H*(THEAD-TC)*VREF*1000./AREF
      DQEXHV=SURFE*H*(TEXV-TC)*VREF*1000./AREF
      QSLEV2=QSLEV2+DQSLEV*DZ/1000.
      QPIST2=QPIST2+DQPIST*DZ/1000.
      QHEAD2=QHEAD2+DQHEAD*DZ/1000.
      QEXHV2=QEXHV2+DQEXHV*DZ/1000.
      QTOT2=QSLEV2+QPIST2+QHEAD2+QEXHV2
C
      HC5=HC5+H*SURFC*2.
      HC6=HC6+H*SURFP*2.
      HC7=HC7+H*SURFH*2.
      HC8=HC8+H*SURFE*2.
      HCT5=HCT5+H*SURFC*TC*2.
      HCT6=HCT6+H*SURFP*TC*2.
      HCT7=HCT7+H*SURFH*TC*2.
      HCT8=HCT8+H*SURFE*TC*2.
C ******************************************************************
C FIRST LAW OF THERMODYNAMICS
C ENERGY BALANCE AND PRESSURE CHANGE FOR GAS EXCHANGE
C ******************************************************************
```

92

```
      CVT=CPT-8.3143*SUMMOL/(WREF*WCYL)
      DTEMP=(DHEAT/1000.+WREF*(DWCIN*HTA-DWCP(1)*HTF-DWCYL
     + *ETF)-RC*PREF*DVCYL*VREF*100.)/(WREF*WCYL*CVT)
      DRC=RC*(DTEMP/TC+DWCYL/WCYL-DVCYL/VCYL)
C
   12 IF(PORTS.NE.0.0) GO TO 100
      RC=RCR
      AC=ACR
      DRC=0.0
      DWCYL=0.0
      DWCIN=0.0
  100 CONTINUE
    1 RETURN
      END
C
C
      SUBROUTINE ELIM(AB,N,NP,NDIM)
      DIMENSION AB(NDIM,NP)
C THIS SUBROUTINE SOLVES A SET OF LINEAR EQUATIONS.
C THE GAUSS ELIMINATION METHOD IS USED, WITH PARTIAL PIVOTING.
C MULTIPLE RIGHT HAND SIDES ARE PERMITTED, THEY SHOULD BE SUPPLIED
C AS COLUMNS THAT AUGMENT THE COEFFICIENT MATRIX
C PARAMETERS ARE -
C   AB   COEFFICIENT MATRIX AUGMENTED WITH R.H.S. VECTORS
C   N    NUMBER OF EQUATIONS
C   NP   TOTAL NUMBER OF COLUMNS IN THE AUGMENTED MATRIX
C   NDIM FIRST DIMENSION OF MATRIX AB IN THE CALLING PROGRAM.
C THE SOLUTION VECTOR(S) ARE RETURNED IN THE AUGMENTATION
C COLUMNS OF AB.
C     REFERENCE: APPLIED NUMERICAL ANALYSIS, 2ND EDITION
C              CURTIS F. GERALD    P. 132
C
C BEGIN THE REDUCTION
      NM1=N-1
      DO 35 I=1,NM1
C FIND THE ROW NUMBER OF THE PIVOT ROW.  WE WILL THEN
C INTERCHANGE ROWS TO PUT THE PIVOT ELEMENT ON THE DIAGONAL.
      IPVT=I
      IP1=I+1
      DO 10 J=IP1,N
      IF(ABS(AB(IPVT,I)) .LT. ABS(AB(J,I))) IPVT=J
   10 CONTINUE
C CHECK TO BE SURE THE PIVOT ELEMENT IS NOT TOO SMALL, IF SO
C PRINT A MESSAGE AND RETURN
      IF((ABS(AB(IPVT,I)) .LT. 1.E-5)) GO TO 99
C NOW INTERCHANGE, EXCEPT IF THE PIVOT ELEMENT IS ALREADY ON
C THE DIAGONAL, DON'T NEED TO.
      IF(IPVT.EQ.I) GO TO 25
      DO 20 JCOL = 1,NP
        SAVE=AB(I,JCOL)
        AB(I,JCOL)=AB(IPVT,JCOL)
        AB(IPVT,JCOL)=SAVE
   20 CONTINUE
C NOW REDUCE ALL ELEMENTS BELOW THE DIAGONAL IN THE I-TH ROW.  CHECK
```

```
C FIRST TO SEE IF A ZERO ALREADY PRESENT.  IF SO,
C CAN SKIP REDUCTION FOR THAT ROW.
  25 DO 32 JROW=IP1,N
     IF(AB(JROW,I).EQ.0) GO TO 32
     RATIO=AB(JROW,I)/AB(I,I)
     DO 30 KCOL=IP1,NP
     AB(JROW,KCOL) = AB(JROW,KCOL) —RATIO*AB(I,KCOL)
  30 CONTINUE
  32 CONTINUE
  35 CONTINUE
C WE STILL NEED TO CHECK A(N,N) FOR SIZE
     IF(ABS(AB(N,N)) .LT. 1.E—5) GO TO 99
C NOW WE BACK SUBSTITUTE
     NP1=N+1
     DO 50 KCOL=NP1,NP
     AB(N,KCOL)=AB(N,KCOL)/AB(N,N)
     DO 45 J=2,N
      NVBL=NP1—J
      L=NVBL+1
      VALUE=AB(NVBL,KCOL)
      DO 40 K=L,N
      VALUE=VALUE—AB(NVBL,K)*AB(K,KCOL)
  40    CONTINUE
     AB(NVBL,KCOL)=VALUE/AB(NVBL,NVBL)
  45 CONTINUE
  50 CONTINUE
     RETURN
C MESSAGE FOR A NEAR SINGULAR MATRIX
  99 WRITE(6,100)
 100 FORMAT(2X,'SOLUTION IS NOT FEASIBLE. A NEAR ZERO PIVOT WAS ENCOUN
    1TERED.')
     RETURN
     END




     SUBROUTINE POWER (N,IPUR)
     DIMENSION VCYLA(360),VCYLE(360),VCYLP(360),PCP(360),TCP(360),
    1        PRANG(360),CANG(2),PCFINT(2),WNI(4),WNF(4)
C    IMPLICIT REAL(A—H,O—Z) , INTEGER(I—N)
     COMMON/XXX/ EQUIVD,RPM,PEXH,PAIR,TAIR,
    1        CR,BORE,STROKE,CONROD,FPISTE,FPISTA,
    2        EVO,EVC,AVO,AVC,
    3        TWALL,WFUEL,
    4        ACB,ACF,
    5        ANNA,FMEPM,
    6        NPCWF,DEL1,DEL2,DEL3,AAN(2),
    7        VALEXH,CDE,NTEXH,WIDTHE,ALPHEX(50),FEXH(50),
    8        VALAIR,CDA,NTAIR,WIDTHA,ALPAIR(50),FAIR(50)
     COMMON/GEN/ALPHAT,ANGEND,ANGRES,AIRPO,EXHPO,IMOLS,
    1        APAIR,APEXH,AREF,AP(2),
    1        APN(2),CYCLE,DALPHA,
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```
     1        DREF,DZ,FREF,
     1        IPOWER,IREV,GA,GE,GREF,IUNITL,
     1        IUNITP,IUNITT,IUNITK,IUNITW,IUNITQ,
     1        WAR,PBARAB,
     1        PI,PREF,REVENG,REVREF,RPAIR,RPEXH,RP(2),
     1        RPN(2),STEP2,TEXH,TREF,VREF,WREF,XREF,
     1        Z,ZREF,HAIR,HREF,SCMULT,NC
      COMMON/CYL/ACSB,ALPHA,ALPHAE,ANNB,ANNC,AC,
     1        ACN,ACR,ALPHAC,
     1        CALVAL,CARBON,
     1        COEFFA(4),COEFFB(4),COEFFC(4),COEFFD(4),
     1        COEFFE(4),COEFFZ(4),CRANK,DCYL,DHEAT,
     1        DRC,DVCYL,DWCIN,DWCP(2),DWCYL,
     1        .FCYL,HEATG,
     1        PURITY,PVEL,PCR,PCYLT,
     1        PORTS,RC,RCN,RCR,SURFC,
     1        TCR,TCYLT,VSWEPT,
     1        VCYL,WCAIR,WCIN,
     1        WCOUT,WCYL,WMW(4),WPCNT(4),WCYLR,
     1        WN(4),WORKGA,WORKGE,XCRA,XSTA,
     1        NCD,WCYLT,DWCINT,
     1        TPIST,THEAD,TEXV,CID
      COMMON/COMB/AIRFL,EQUIV,TEXHS,SHPS,FZA,HRD,SCASW,TREFF,SCAEFF,
     + AIRVMX,EXHVMX,PORTED,STOIC,WCO,BLBACK,FUELF,BHP
      COMMON/TEMP/TWEV,TWGH,TWGP,TWGC,TWCR,TWPR,TWCP,TWCC,TWCH,TEXHP,
     1 TWEVG,TC1,TC2,TC3
      COMMON/HEAT/ NHEAT,QSLEV1,QPIST1,QHEAD1,QEXHV1,QTOT1,
     1        QSLEV2,QPIST2,QHEAD2,QEXHV2,QTOT2,
     2        HC1,HC2,HC3,HC4,HC5,HC6,HC7,HC8,
     3        HCT1,HCT2,HCT3,HCT4,HCT5,HCT6,HCT7,HCT8
      COMMON/INPT2/
     1 XXEVG,XXEVH,XXPSL,XXPIS,XXPRG,XXHED,XXPCR,XXRSL,XXSLV,
     2 AEXVS,AEXV,AEXST,AHEAD,ASLEEV,APIST1,APIST2,APISTR,ARING1,ARING2,
     3 CEXV,CHEAD,CSLEEV,CPIST,CRING,
     4 HEXHP,HOILP,HCSL,HCHD,NEXHV,DEXHV,
     5 D1,D2,D3,D4,D5,D6,VCV,APP,ARR,ASS
      COMMON/CV/ QCV,QCV1,QCV2,QCV3
      COMMON/FRIC/ QFRIC1,QFRIC2,QFRIC3
      COMMON/CPURE/WCA,WCHG,IMIX
      COMMON/ENERGY/ UINITL,UFINAL,HOUT
      COMMON/STOP/ ISTOP
      COMMON/WHTWY/ PSUM,RSUM,FUELS,TF,DA,XO2
C ***********************************************************************
C      SET UP ANGLES TO START CALCULATION
C ***********************************************************************
      RPS=REVENG*REVREF
      ANGLA=ACSB
      ANGLE=ACSB
      ANGLP=180.0*CYCLE-ACSB+EVO
      ANGLC=0.0
      K=1
      PRANG(1)=ACSB
C      SET UP COMBUSTION ANGLES
      ACBB=ACB
```

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      IF (ACBB.LT.180.0) ACBB=180.0*CYCLE+ACBB
      ACFF=ACF
      IF (NPCWF.EQ.0 .AND. DEL3.EQ.0.) HRD=15.+115.*EQUIV
      IF (NPCWF.EQ.0) ACFF=ACBB-180.*CYCLE+HRD
      IF (ACFF.LT.180.0) ACFF=180.0*CYCLE+ACFF
      IF (NPCWF.LT.0.0) HRD=ACFF-ACBB
C        CALCULATE TRAPPED VOLUME
      DST=0.0
      CALL STROK(XST,DST,ANGLA,XSTA,XCRA,REVENG,ZREF)
      CALL CYLVOL(FCYL,XST,XSTA,CR,DST,VCYLA(1),DVCY)
      FPISTE=1.0
      VCYLE(1)=0.0
      VCYLA(1)=VCYLA(1)*VREF
      VCYLE(1)=VCYLE(1)*VREF
      VCYLP(1)=VCYLA(1)+VCYLE(1)
      WORKA=0.0
      WORKE=0.0
      HEATRF=0.0
      DQCR=0.0
      DQCR1=0.0
      DQCR2=0.0
      DQCR3=0.0
      DQCR4=0.0
      ICOMB=0
      QHEAD1=0.
      QSLEV1=0.
      QPIST1=0.
      QEXHV1=0.
      QCV=0.
      HC1=0.
      HC2=0.
      HC3=0.
      HC4=0.
      HCT1=0.
      HCT2=0.
      HCT3=0.
      HCT4=0.
C ***********************************************************************
C        CALCULATE TRAPPED GAS COMPOSITION —NO.OF MOLS OF AIR(WNA),
C     NO. OF MOLS OF RESIDUALS(WNR),INCREASE IN MOLS OF PRODUCTS(WNP)
C ***********************************************************************
      VCYLT=VCYLP(1)
C CALCULATE TOTAL NUMBER OF MOLES OF GASES IN CYLINDER
      WNTF=PCYLT*VCYLT*100.0/(8.3143*TCYLT)
      IF (IPUR.EQ.0) GO TO 7
C CALCULATE MASS OF RESIDUAL
      WRES=WCHG-WCA
C CALCULATE TOTAL MASS IN CYLINDER (AIR+RESIDUAL+FUEL)
      WTOT=WCHG+WFUEL
C CALCULATE STOICHIOMETRIC MASS OF AIR REQUIRED TO BURN FUEL
      WABU=32.*(CARBON/12.01+(1.-CARBON)/4.032)*WFUEL/.233
      ZERO=0.0
      WAIR=WCA+WRES*MAX1(WCA-WABU,ZERO)/(WTOT-WRES)
      IF (WABU.GT.WCA) WRITE(4,8)
```

```
    8 FORMAT (17H *** WARNING *** ,32HBURNED AIR EXCEEDS AVAILABLE AIR)
    7 CONTINUE
C CALCULATE NUMBER OF MOLES OF AIR IN CYLINDER
      WNA=PURITY*WNTF
C CALCULATE NUMBER OF MOLES OF RESIDUAL IN CYLINDER
      WNR=WNTF-WNA
C CALCULATE INCREASE IN NUMBER OF MOLES OF DUE TO COMBUSTION
C      LB FUEL * (MOLES OF PRODUCTS-MOLES OF AIR)/LB FUEL
      WNP=WFUEL*(1.0-CARBON)/4.032
C CALCULATE NUMBER OF MOLS OF (1) NITROGEN, (2) OXYGEN,
C         (3) CARBON DIOXIDE, (4) WATER VAPOUR
      WNF(1)=0.79*WNA*(WNA+WNP+WNR)/(WNA+WNP)
      IF(WNF(1).LE.0.) WRITE(6,*) 'WNA,PURITY,WNTF,WNF(1)',WNA,PURITY,
     1  WNTF,WNF(1)
      WNF(4)=2.0*WNP*WNR/(WNA+WNP)
      WNF(3)=2.016*CARBON*WNF(4)/(12.01*(1.0-CARBON))
      WNF(2)=0.21*WNF(1)/0.79-WNF(3)-0.5*WNF(4)
C       TRAPPED MASS IN CYLINDER
      WMF=0.0
      DO 10 I=1,4
   10 WMF=WMF+WMW(I)*WNF(I)
      TRAF=28.85*WNA/WFUEL
      WAIR=WNF(2)*32./.233
      PURE=WAIR/WNTF/28.85
      WRITE(4,499) PURE
  499 FORMAT (14H TRUE PURITY =,F6.4)
      TRMF=WMF/WFUEL
      EAFR=32.*WNF(2)*100./(23.3*WFUEL)
      EQUIV=1./(STOIC*EAFR)
      WRITE(4,4) EQUIV
    4 FORMAT (21H EQUIVALENCE RATIO = ,F6.4)
      IF (EQUIVD.GT.0.) WFUEL=32.*WNF(2)*STOIC*EQUIVD/.233
      PSUM=0.
      RSUM=0.
      FUELS=0.
      DUR=0.
C       STORE TRAPPED PRESSURE, TEMPERATURE
      PCF=PCYLT
      PCP(1)=PCF
      CALL UNITP(IUNITP,2,PCP(1),PBARAB)
      TF=TCYLT
      TCP(1)=TF
      CALL UNITT(IUNITT,2,TCP(1))
C ***********************************************************************
C       CALCULATE INTERNAL ENERGY OF TRAPPED CONTENTS IN KJ
C ***********************************************************************
      ETF=0.0
      DO 11 I=1,4
   11 ETF=ETF+WNF(I)*(8.3143*((COEFFA(I)-1.0)*TF+COEFFB(I)*TF**2
     1   +COEFFC(I)*TF**3+COEFFD(I)*TF**4)-COEFFE(I))
      UINITL=ETF
C ***********************************************************************
C       START NEXT STEP
C ***********************************************************************
```

```
   23 K=K+1
      ANGLC=ANGLC+1.0
      ANGLA=ANGLA+1.0
      ANGLE=ANGLE+1.0
      PRANG(K)=ANGLA
      IF (PRANG(K).GE.(180.0*CYCLE)) PRANG(K)=PRANG(K)-180.0*CYCLE
      ETI=ETF
      PCI=PCF
      TI=TF
C      TEST IF COMBUSTION HAS STARTED
      IF (ANGLA.LE.ACBB) GO TO 12
C      COMBUSTION HAS STARTED --CALCULATE FUEL BURNT IN STEP
      IF (ICOMB.EQ.0) KC=K-1
      ICOMB=100
      CANG(1)=ANGLA-1.0
      CANG(2)=ANGLA
      DUR=ANGLA-ACBB
      ONE=1.000
      DA=AMIN1(DUR,ONE)
C
C CALCULATE PER CENT FUEL BURNED AT START AND END OF TIME STEP
C
      DO 25 I=1,2
C   WRITE(6,*) 'CANG(I),ACBB',CANG(I),ACBB
      ANG=CANG(I)-ACBB
      IF (ANG) 26,26,27
   26 PCFINT(I)=0.0
      GO TO 25
   27 IF(NPCWF.LT.0) GO TO 290
      IF(NPCWF.EQ.2) CALL BURNRT(ANGLA,ACB,ACF,WFUEL,DWFUEL)
C   WRITE(6,*) ANGLA,DWFUEL
      IF(NPCWF.EQ.2) GO TO 250
      TAU=ANG/HRD
C ********************************************************************
C      WIEBE COMBUSTION MODEL
C ********************************************************************
   29 IF(NPCWF.EQ.0) PCFINT(I)=100.*(1.-EXP(-DEL1*TAU**DEL2))
C ********************************************************************
C      WATSON COMBUSTION MODEL
C ********************************************************************
      BETA=1.-DEL1*EQUIV**DEL2/1.5E4**DEL3
      CP1=2.+1.25E-8*(1.5E4*REVREF*60.)**2.4
      CP2=5000.
      CD1=14.2/EQUIV**.644
      CD2=.79*CD1**.25
      IF (NPCWF.GT.0) PCFINT(I)=100.*(BETA*(1.-(1.-TAU**CP1)**CP2)+
     +(1.-BETA)*(1.-EXP(-CD1*TAU**CD2)))
      IF (NPCWF.GE.0) GO TO 25
C ********************************************************************
C      WHITEHOUSE-WAY COMBUSTION MODEL
C ********************************************************************
  290 PO2=PCF*WNF(2)/WNTF
      ZERO=0.0
      PO2=AMAX1(PO2,ZERO)
```

```
      DWFUEL=0.
C   RAMP FUEL INJECTION SCHEDULE ASSUMED
      TAU=DUR/HRD
      AA2=2.-AAN(1)*AAN(2)
      IF(TAU.LE.AAN(2)) FINJ=WFUEL*(AAN(1)*TAU+
     + ((AA2-AAN(1))/(2.*AAN(2)))*TAU**2)
      IF(TAU.GE.1.) GO TO 295
      IF(TAU.GT.AAN(2)) FINJ=WFUEL*((AAN(1)+AA2)*AAN(2)/2.+
     + (AA2/(1.-AAN(2))*(TAU-TAU**2/2.+AAN(2)**2/2.-AAN(2))))
  295 FINJ=AMIN1(FINJ,WFUEL)
      IF(DUR.GT.HRD) FINJ=WFUEL
      IF(FINJ.LE.PSUM) GO TO 250
      PREP=DEL1*FINJ**(1.-DEL2)*(FINJ-PSUM)**DEL2*PO2**DEL3
      PSUM=PSUM+PREP*DA
      PSUM=AMIN1(PSUM,FINJ)
      REACT=1.2E10*PO2*EXP(-1.5E4/TF)*(PSUM-RSUM)/(60.*REVREF*SQRT(TF))
      ZERO=0.0
      REACT=AMAX1(REACT,ZERO)
      RSUM=RSUM+REACT*DA
      IF(RSUM.LE.PSUM) DWFUEL=REACT*DA
      IF(RSUM.GT.PSUM) DWFUEL=PREP*DA
      IF(REACT.EQ.0.) DWFUEL=PSUM-FUELS
C MODIFIED BURNING RATE MODEL
      GO TO 250
C     ACF1=ACF+360.
C     ACB1=ACB+0.8*(ACF1-ACB)
C     IF(ANGLA.LT.ACB) DWFUEL=0.
C     IF(ANGLA.GT.ACB .AND. ANGLA.LE.ACB1) DWFUEL
C    1  =WFUEL*(2./(ACF1-ACB))*((ANGLA-ACB)/(ACB1-ACB))
C     IF(ANGLA.GT.ACB1 .AND. ANGLA.LT.ACF1) DWFUEL
C    1  =WFUEL*(2./(ACF1-ACB))*((ACF1-ANGLA)/(ACF1-ACB1))
C     IF(ANGLA.GE.ACF1) DWFUEL=0.
   25 CONTINUE
C **************************************************************
C      CALCULATE HEAT RELEASE DUE TO COMBUSTION OF FUEL
C **************************************************************
      DWFUEL=0.01*(PCFINT(2)-PCFINT(1))*WFUEL
  250 DQF=DWFUEL*CALVAL
      FUELS=FUELS+DWFUEL
C **************************************************************
C      CALCULATE NEW GAS COMPOSITION
C **************************************************************
C STORE OLD COMPOSITION
      WNTI=WNTF
      WMI=WMF
      DO 13 I=1,4
   13 WNI(I)=WNF(I)
C
      X=DWFUEL*(1.0-CARBON)/4.032
      Y=DWFUEL*CARBON/12.01
      WNTF=WNTI+X
      WMF=WMI+DWFUEL
      WM=0.5*(WMI+WMF)
      WNF(2)=WNI(2)-X-Y
```

99

```
      WNF(3)=WNI(3)+Y
      WNF(4)=WNI(4)+2.0*X
      DO 14 I=1,4
   14 WN(I)=0.5*(WNF(I)+WNI(I))
      GO TO 15
C *******************************************************************
C     COMBUSTION HAS NOT STARTED YET
C *******************************************************************
   12 DQF=0.0
      DQCR=0.0
      WNTI=WNTF
      WMI=WMF
      WM=WMF
      DO 16 I=1,4
      WNI(I)=WNF(I)
   16 WN(I)=WNF(I)
C *******************************************************************
C        CALCULATE CYLINDER VOLUME AND SURFACE AREA
C *******************************************************************
   15 DST=0.0
      CALL STROK(XST,DST,ANGLA,XSTA,XCRA,REVENG,ZREF)
      CALL CYLVOL(FCYL,XST,XSTA,CR,DST,VCYLA(K),DVCY)
      FPISTE=1.0
      VCYLE(K)=0.0
   17 VCYLP(K)=VCYLA(K)+VCYLE(K)
      CALL SREA(SURFC,VCYLP(K),FCYL,DCYL,XREF,DREF,
     1      FPISTA,FPISTE)
C CALCULATE SURFACE AREA OF CYLINDER EXPOSED TO COMBUSTION
      SURFC=SURFC-(FPISTA+FPISTE)*FCYL
      SURFC=SURFC*FREF
C CALCULATE SURFACE AREA OF PISTON (SQUARE METERS)
      SURFP=FPISTA*FCYL*FREF
C CALCULATE SURFACE AREA OF EXHAUST VALVE(S)
      SURFE=FLOAT(NEXHV)*0.7854*DEXHV**2/(39.37)**2
C CALCULATE SURFACE AREA OF HEAD EXPOSED TO COMBUSTION CHAMBER
      SURFH=FPISTE*FCYL*FREF -SURFE
C
      VCYLA(K)=VCYLA(K)*VREF
      VCYLE(K)=VCYLE(K)*VREF
      VCYLP(K)=VCYLP(K)*VREF
      IF (VCYLP(K).LT.VCYLP(K-1)) VOLMIN=VCYLP(K)
C     AVERAGE VOLUME AND DENSITY
      VC=0.5*(VCYLP(K)+VCYLP(K-1))
      RHO=WM/VC
C     ESTIMATE GAS TEMPERATURE AT END OF STEP
      TF=TI*(VCYLP(K-1)/VCYLP(K))**0.4+4.0*DQF/WM
C     CALCULATE AVERAGE GAS TEMPERATURE
   22 TM=0.5*(TI+TF)
C *******************************************************************
C     CALCULATE CONVECTIVE HEAT TRANSFER IN KJ
C        USE ANNAND CORRELATION IF ANNC.GT.0
C        USE WOSCHNI CORRELATION IF ANNC.EQ.0
C *******************************************************************
C CALCULATE CP FOR GAS MIXTURE
```

100

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      CPT=0.0
      DO 18 I=1,4
   18 CPT=CPT+WN(I)*(COEFFA(I)+2.0*COEFFB(I)*TM+3.0*COEFFC(I)*TM**2
    1   +4.0*COEFFD(I)*TM**3)
      CPT=8.3143*CPT/WM
C CALCULATE VISCOSITY OF GAS MIXTURE
      A=0.0
      B=0.0
      DO 19 I=1,4
      C=WN(I)*SQRT(WMW(I))
      A=A+COEFFZ(I)*C
   19 B=B+C
      VISCTY=(A*TM**0.645)/B
      IF(VISCTY.LE.0.) WRITE(6,*)'VISCTY,WN(I)S',VISCTY,WN
C CALCULATE THERMAL CONDUCTIVITY OF GAS MIXTURE (ASSUME PRANDTL = 0.7)
      CONDY=CPT*VISCTY/0.7
      REY=RHO*PVEL*DCYL*DREF/VISCTY
C    IF(REY.LE.0.) WRITE(6,*)'REY,RHO,PVEL,DCYL,DREF,VISCTY',
C   1  REY,RHO,PVEL,DCYL,DREF,VISCTY
      PMOT=PCYLT*(VCYLT/VCYLP(K))**1.32
      TERM1=2.28*PVEL
      TERM2=0.
      IF(ANGLA.GT.ACBB) TERM2=3.24E-3*.7854*DCYL**2*XSTA*TCYLT*
    +  (PCF-PMOT)/(PCYLT*VCYLT)
      IF(ANNC.EQ.0.) REY=REY*(TERM1+TERM2)/PVEL
      H=(ANNA*CONDY*REY**ANNB)/(DCYL*DREF)
C
C    UNITS: SURFC=SQUARE METERS
C        TM = DEG KELVIN
C        RPS = REV PER SECOND
C        DQCY = KJ/DEG CA
      HR1=0.
      HR2=0.
      HR3=0.
      HR4=0.
      IF (NHEAT.EQ.0) GO TO 777
      TWALL=TWGC
      TPIST=TWGP
      THEAD=TWGH
      TEXV=TWEV
  777 DQCY=(SURFC*H*(TM-TWALL))/(360.0*RPS)
      DQCY=DQCY+(SURFP*(TM-TPIST)+SURFH*(TM-THEAD)+SURFE*(TM-TEXV))*H/
    +  (360.*RPS)
C
      DQCY1=SURFC*H*(TM-TWALL)/(360.*RPS)
      DQCY2=SURFP*H*(TM-TPIST)/(360.*RPS)
      DQCY3=SURFH*H*(TM-THEAD)/(360.*RPS)
      DQCY4=SURFE*H*(TM-TEXV)/(360.*RPS)
      IF (ICOMB.EQ.0) GO TO 20
C ****************************************************************
C     RADIANT HEAT TRANSFER (AFTER START OF COMBUSTION ONLY)
C             -ANNAND CORRELATION ONLY -
C ****************************************************************
      DQCR=SURFC*ANNC*(TM**4-TWALL**4)/(360.*RPS)
```

```
      DQCR=DQCR+(SURFP*(TM**4-TPIST**4)+SURFH*(TM**4-THEAD**4)
     1 +SURFE*(TM**4-TEXV**4))*ANNC/(360.*RPS)
C
      HR1=ANNC*(TM**3+TM**2*TWALL+TM*TWALL**2+TWALL**3)
      HR2=ANNC*(TM**3+TM**2*TPIST+TM*TPIST**2+TPIST**3)
      HR3=ANNC*(TM**3+TM**2*THEAD+TM*THEAD**2+THEAD**3)
      HR4=ANNC*(TM**3+TM**2*TEXV +TM*TEXV**2 +TEXV**3)
C
      DQCR1=SURFC*ANNC*(TM**4-TWALL**4)/(360.*RPS)
      DQCR2=SURFP*ANNC*(TM**4-TPIST**4)/(360.*RPS)
      DQCR3=SURFH*ANNC*(TM**4-THEAD**4)/(360.*RPS)
      DQCR4=SURFE*ANNC*(TM**4-TEXV**4)/(360.*RPS)
   20 CONTINUE
C ************************************************************
C      PRESSURE AT END OF STEP
C ************************************************************
      PCF=PCI*VCYLP(K-1)*TF*WNTF/(VCYLP(K)*WNTI*TI)
C ************************************************************
C      WORK DONE BY GAS DURING TIME STEP IN KJ
C ************************************************************
      DWORKA=0.5*(PCF+PCI)*(VCYLA(K)-VCYLA(K-1))*100.0
      DWORKE=0.5*(PCF+PCI)*(VCYLE(K)-VCYLE(K-1))*100.0
C ************************************************************
C      INTERNAL ENERGY AT END OF TIME STEP
C ************************************************************
      ETF=0.0
      DO 21 I=1,4
   21 ETF=ETF+WNF(I)*(8.3143*((COEFFA(I)-1.0)*TF+COEFFB(I)*TF**2
     1    +COEFFC(I)*TF**3+COEFFD(I)*TF**4)-COEFFE(I))
      UFINAL=ETF
C
C ***** CALCULATE HEAT TRANSFER FROM CREVICE VOLUME *********
C
C  CREVICE VOLUME GAS TEMPERATURE  - DEG K
      TCV=(ASS*TWGC+APP*TWGP+ARR*TWCR)/(ASS+APP+ARR)
C  HEAT TRANSFER DUE TO INCOMING HOT GAS  - KJ/CRANKANGLE
      DQCV=GE/(GE-1.)*(TM/TCV-1.)*VCV*(PCF-PCI)*1.E2
      IF(PCF.LT.PCI) DQCV=0.0
C +++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
C ************************************************************
C      FIRST LAW OF THERMODYNAMICS.  FOR BALANCE, ERROR=0
C ************************************************************
C +++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
      ERROR=ETF-ETI-DQF+DQCY+DQCR+DWORKA+DWORKE+DQCV
      DERIV=0.0
      DO 24 I=1,4
   24 DERIV=DERIV+WNF(I)*8.3143*(COEFFA(I)-1.0+2.0*COEFFB(I)*TF
     1    +3.0*COEFFC(I)*TF**2+4.0*COEFFD(I)*TF**3)
C      SET NEW VALUE OF FINAL TEMPERATURE
      ERROR=ERROR/DERIV
```

```
      TF=TF-ERROR
C        TEST FOR ACCURACY OF ESTIMATE OF TF.   IF NOT ACCURATE ENOUGH
C           RETURN TO LABEL 22 WITH BETTER ESTIMATE OF TF AND REPEAT
C           CALCULATION
      IF(ABS(ERROR).GT.0.01) GOTO 22
C
      RGAS=8.3143*(WN(1)+WN(2)+WN(3)+WN(4))/WM
      GE=CPT/(CPT-RGAS)
      TEXH=TF
      PRESS=14.5*PCF
      TRANK=1.8*TEXH
      VOL=61032.7*VCYLA(K)
      PERCNT=100.*FUELS/WFUEL
      WRITE(3,1020) PRANG(K),PRESS,TRANK,GE,VOL
 1020 FORMAT (5(1X,E11.5))
      XSTIN=XST*39.372
C        ANSWER
      WORKA=WORKA+DWORKA
      WORKE=WORKE+DWORKE
      HEATRF=HEATRF+DQCY+DQCR
C
      QSLEV1=QSLEV1+DQCY1+DQCR1
      QPIST1=QPIST1+DQCY2+DQCR2
      QHEAD1=QHEAD1+DQCY3+DQCR3
      QEXHV1=QEXHV1+DQCY4+DQCR4
      QTOT1=QSLEV1+QPIST1+QHEAD1+QEXHV1
C
C SUM CREVICE VOLUME HEAT TRANSFER  (KJ)
C
      QCV=QCV+DQCV
C
C EVALUATE INTEGRALS USED IN CALCULATING EFFECTIVE GAS TEMPERATURES
C
      HC1=HC1+(H+HR1)*SURFC
      HC2=HC2+(H+HR2)*SURFP
      HC3=HC3+(H+HR3)*SURFH
      HC4=HC4+(H+HR4)*SURFE
      HCT1=HCT1+(H+HR1)*SURFC*TM
      HCT2=HCT2+(H+HR2)*SURFP*TM
      HCT3=HCT3+(H+HR3)*SURFH*TM
      HCT4=HCT4+(H+HR4)*SURFE*TM
C
      TCP(K)=TF
      CALL  UNITT(IUNITT,2,TCP(K))
      PCP(K)=PCF
      CALL  UNITP(IUNITP,2,PCP(K),PBARAB)
C ******************************************************************
C  TEST IF POWER CYCLE IS COMPLETE.   IF NOT RETURN TO LABEL 23
C ******************************************************************
      IF (ANGLC.LT.(ANGLP-0.1)) GO TO 23
C ******************************************************************
C       FINISH POWER CYCLE.   STORE RELEASE PRESSURE AND TEMPERATURE
C              AND CALCULATE INDICATED POWER
C ******************************************************************
```

```
      PCR=PCF
      TCR=TF
      WORKP=WORKA+WORKE
      WORKT=WORKP+WORKGA+WORKGE
      HEATT=HEATRF-HEATG
      CYCLES=RPS*2.0/CYCLE
      POWERA=WORKA*CYCLES
      POWERE=WORKE*CYCLES
      POWEGA=WORKGA*CYCLES
      POWEGE=WORKGE*CYCLES
      POWERT=WORKT*CYCLES
      VSWEPT=XSTA*FCYL*VREF
      PMIP=(WORKT/VSWEPT)*0.01
      HEATFL=WFUEL*CALVAL
C
C CHECK OVERALL ENERGY BALANCE (FOR COMPRESSION,COMB,EXPANSION)
C
      BALNCE= UFINAL-UINITL+HEATRF+WORKA-HEATFL+QCV
      PCBAL=BALNCE/HEATFL*100.
      WRITE(6,30) PCBAL
 30   FORMAT(2X,'COMP-EXP ENERGY BALANCE =',F8.4,' % OF FUEL ENERGY'/)
C
C        PRINT OUT ANSWERS
      WRITE(4,116) PRANG(1),PCP(1),TCP(1)
 116  FORMAT (6H ANGLE,F6.1,23H      TRAPPED PRESSURE,F7.1,
     1   26H     TRAPPED TEMPERATURE,F7.1)
      WRITE(4,117) PRANG(KC),PCP(KC),TCP(KC)
 117  FORMAT (6H ANGLE,F6.1,23H  COMPRESSION PRESSURE,F7.1,
     1   26H  COMPRESSION TEMPERATURE,F7.1)
C    I=0
C 33 I=I+1
C    IF (PCP(I)-PCP(I+1)) 33,33,34
C 34 WRITE(4,118) PRANG(I),PCP(I),TCP(I)
      TMAX=0.
      PMAX=0.
      DO 33 I=1,K
      PMAX=AMAX1(PMAX,PCP(I))
 33   TMAX=AMAX1(TMAX,TCP(I))
      WRITE(4,118) PRANG(I),PMAX,TMAX
 118  FORMAT (6H ANGLE,F6.1,23H      MAXIMUM PRESSURE,F7.1,
     1   '     MAXIMUM TEMPERATURE',F7.1)
      WRITE(4,119) PRANG(K),PCP(K),TCP(K)
 119  FORMAT (6H ANGLE,F6.1,23H      RELEASE PRESSURE,F7.1,
     1   26H     RELEASE TEMPERATURE,F7.1)
      WRITE(4,105) TRAF,EAFR,ACBB
 105  FORMAT (17H AIR-FUEL RATIO =,F6.2,
     1   30H   EFFECTIVE AIR-FUEL RATIO =,F6.2,
     1   24H   START OF COMBUSTION =,F7.2)
      X=VCYLT/VOLMIN
      XX = X
      Y=VCYLP(K)/VOLMIN
      WRITE(4,106) X,Y
 106  FORMAT (30H EFFECTIVE COMPRESSION RATIO =,F6.2,
```

1 32H   EFFECTIVE EXPANSION RATIO =,F6.2)

```
      IF (IUNITK.EQ.2) GO TO 38
      WRITE(4,107)
  107 FORMAT (20H  INDICATED POWER KW)
      X=POWERA+POWEGA
      WRITE(4,108) POWERA,POWEGA,X
  108 FORMAT (20HAIR    POWER CYCLE =,F8.2,17H   GAS EXCHANGE =,F8.2,
     1   10H   TOTAL =,F8.2)
   39 WRITE(4,111) POWERT,PMIP
  111 FORMAT (16HCOMBINED POWER =,F8.2,
     1   36H   MEAN INDICATED PRESSURE (BARS) =,F8.2)
      GO TO 40
   38 WRITE(4,112)
  112 FORMAT (23H  INDICATED HORSE POWER)
      A=POWERA*1.34
      B=POWEGA*1.34
      X=A+B
      WRITE(4,108) A,B,X
   41 A=POWERT*1.34
      B=PMIP*14.5
      AMEP=B
      IF (ALPHAT.LE.540.) GO TO 50
C
C   CALCULATE EXHAUST TEMPERATURE FROM ENERGY BALANCE
C
      FUELF=WFUEL*CYCLES*2.205
      FZA = FUELF/AIRFL
      YY = HEATT/HEATFL
      DELH=(FZA*CALVAL*(1.-YY-WORKT/HEATFL)+HAIR-HREF)/(1.+FZA)
      CALL BAL(CARBON,FZA,TREF,DELH,TEXHC,GAM,DUM)
      TEXHC=TEXHC*1.8
C
      YY = YY*100.
      SHP = A
      IF(ISTOP.NE.1) WRITE(2,1000) FUELF,SCASW,TREFF,SCAEFF,TEXHC,
     +     SHP,PURE,AIRFL,EQUIV,PMAX,TMAX,YY
 1000 FORMAT (F10.7,T13,F8.5,T25,F7.3,T37,F7.3,T47,F7.1,T56,F7.2,T65,
     +F7.4,T77,F8.5,T86,F7.4,T96,F7.1,T107,F7.1,T116,F7.2)
C
      WRITE(4,113) A,B
  113 FORMAT (17H COMBINED POWER =,F8.2,
     1   38H   MEAN INDICATED PRESSURE (P.S.I.) =,F8.2)
C
   40 A=100.0*HEATRF/HEATFL
      B=-100.0*HEATG/HEATFL
      X=100.0*HEATT/HEATFL
      WRITE(4,114) A,B,X
  114 FORMAT (35H PERCENT HEAT LOSS   POWER CYCLE =,F6.2,
     1   17H   GAS EXCHANGE =,F6.2,10H   TOTAL =,F6.2)
C
      Y=100.0*WORKT/HEATFL
      WRITE(4,115) Y
  115 FORMAT(31H INDICATED THERMAL EFFICIENCY = ,F6.2)
C
C
```

```
      CALL HTRANS
C
C
C ******** CONVERGENCE TEST *************************
C
      IF (ABS(SHP-SHPS).GT.SHP*.001) GO TO 45
      IF (ABS(TEXHC-TEXHS).GT.TEXHC*.001) GO TO 45
      IF (EQUIVD.GT.0..AND.ABS(EQUIV-EQUIVD).GT..001) GO TO 45
C
      IF(ISTOP.EQ.1) RETURN
      ISTOP=1
C
      APIST=.7854*(3.281*DCYL*DREF)**2*144.
      AIRVMX = AIRVMX*1550.15*FREF
      EXHVMX = EXHVMX*1550.15*FREF
      EXHAP=EXHVMX/APIST
      AIRAP=AIRVMX/APIST
      WRITE(2,2900) XX,EXHAP,AIRAP,GAM
 2900 FORMAT(1X,28HEFFECTIVE COMPRESSION RATIO ,F8.4,5X,
     +16HEXHVMX/APISTON=  ,F9.4,5X,16HAIRVMX/APISTON= ,F9.4,5X,4HGE= ,
     + F7.4/)
      WRITE(2,1010) AMEP,GA,BLBACK,Y
 1010 FORMAT(1X,39HINDICATED MEAN EFFECTIVE PRESSURE (PSI) ,F11.4,4X,
     + 3HGA=,F8.5,4X,18HBLOWBACK FRACTION=,F9.5,4X,
     + 20HINDICATED THERM EFF=,F6.2)
C ***************************************************************
C     ENGINE FRICTION CALCULATION
C ***************************************************************
      VPSTN=PVEL*3.281*60.
      FMEP1=12.964
      FMEP2=0.0030476
      FMEP3=0.65476E-6
      FMEP=FMEP1+VPSTN*(FMEP2+VPSTN*FMEP3)
      FMEP=FMEP*FMEPM
      FHP=FMEP*XSTA*XREF*3.281*APIST*REVREF*2./(550.*CYCLE)
      BHP=SHP-FHP
      BSFC=3600.*FUELF/BHP
C
      WRITE(2,1012)VPSTN,FMEP,BHP,BSFC
 1012 FORMAT(1X,'PISTON MEAN VELOCITY (FPM)',F9.2,4X,
     + 'FRICTION MEAN EFFECTIVE PRESSURE (PSI)',F9.4,4X,
     + 'BRAKE HP=',F7.2,4X,'BSFC=',F8.5/)
   45 CONTINUE
      SHPS = SHP
      TEXHS = TEXHC
   50 CONTINUE
      RETURN
      END
C
      SUBROUTINE MASSFL(FHOLE,RUP,RDP,A0,GR,G,WFLOW)
C    IMPLICIT REAL(A-H,O-Z), INTEGER(I-N)
C    SUBROUTINE TO CALCULATE MASS FLOW RATE OF A COMPRESSIBLE
C    FLUID THROUGH A PASSAGE
C
```

```fortran
C     FHOLE =
C     RUP = RATIO OF UPSTREAM PRESSURE TO REFERENCE PRESSURE
C     RDP = RATIO OF DOWNSTREAM PRESSURE TO REFERENCE PRESSURE
C     A0 = RATIO OF SPEED OF SOUND OF FLUID TO REFERENCE SPEED OF
C         SOUND
C     GR = REFERENCE VALUE OF GAMMA, THE RATIO OF SPECIFIC HEATS
C     G = GAMMA, THE RATIO OF SPECIFIC HEATS
C     WFLOW = MASS FLOW RATE OF FLUID THROUGH PASSAGE (NON-DIMENSIONALIZED)
C
C
C     CALCULATE MACH NUMBER OF FLOW THROUGH PASSAGE TO DETERMINE
C     WHETHER FLOW IS CHOKED
C
      UM=SQRT((2.0/(G-1.0))*(((RUP/RDP)**((G-1.0)/G))-1.0))
      IF(UM.LT.1.0) GO TO 1
C
C     FLOW IS CHOKED
C
      FM=G*SQRT((2.0/(G+1.0))**((G+1.0)/(G-1.0)))
      GO TO 2
C
C     FLOW IS NOT CHOKED
C
    1 FM=G*UM/(1.0+((G-1.0)/2.0)*UM**2)**((G+1.0)/(2.0*(G-1.0)))
C
C     CALCULATE MASS FLOW RATE
C
    2 WFLOW=FHOLE*RUP*FM/(GR*A0)
      RETURN
      END
C
      SUBROUTINE HTRANS
C
C     HEAT TRANSFER CALCULATIONS
C
      COMMON/XXX/ EQUIVD,RPM,PEXH,PAIR,TAIR,
     1        CR,BORE,STROKE,CONROD,FPISTE,FPISTA,
     2        EVO,EVC,AVO,AVC,
     3        TWALL,WFUEL,
     4        ACB,ACF,
     5        ANNA,FMEPM,
     6        NPCWF,DEL1,DEL2,DEL3,AAN(2),
     7        VALEXH,CDE,NTEXH,WIDTHE,ALPHEX(50),FEXH(50),
     8        VALAIR,CDA,NTAIR,WIDTHA,ALPAIR(50),FAIR(50)
      COMMON/GEN/ALPHAT,ANGEND,ANGRES,AIRP0,EXHP0,IMOLS,
     1        APAIR,APEXH,AREF,AP(2),
     1        APN(2),CYCLE,DALPHA,
     1        DREF,DZ,FREF,
     1        IPOWER,IREV,GA,GE,GREF,IUNITL,
     1        IUNITP,IUNITT,IUNITK,IUNITW,IUNITQ,
     1        WAR,PBARAB,
     1        PI,PREF,REVENG,REVREF,RPAIR,RPEXH,RP(2),
     1        RPN(2),STEP2,TEXH,TREF,VREF,WREF,XREF,
     1        Z,ZREF,HAIR,HREF,SCMULT,NC
```

```
      COMMON/CYL/ACSB,ALPHA,ALPHAE,ANNB,ANNC,AC,
     1          ACN,ACR,ALPHAC,
     1          CALVAL,CARBON,
     1          COEFFA(4),COEFFB(4),COEFFC(4),COEFFD(4),
     1          COEFFE(4),COEFFZ(4),CRANK,DCYL,DHEAT,
     1          DRC,DVCYL,DWCIN,DWCP(2),DWCYL,
     1          FCYL,HEATG,
     1          PURITY,PVEL,PCR,PCYLT,
     1          PORTS,RC,RCN,RCR,SURFC,
     1          TCR,TCYLT,VSWEPT,
     1          VCYL,WCAIR,WCIN,
     1          WCOUT,WCYL,WMW(4),WPCNT(4),WCYLR,
     1          WN(4),WORKGA,WORKGE,XCRA,XSTA,
     1          NCD,WCYLT,DWCINT,
     1          TPIST,THEAD,TEXV,CID
      COMMON/COMB/AIRFL,EQUIV,TEXHS,SHPS,FZA,HRD,SCASW,TREFF,SCAEFF,
     + AIRVMX,EXHVMX,PORTED,STOIC,WCO,BLBACK,FUELF,BHP
      COMMON/TEMP/TWEV,TWGH,TWGP,TWGC,TWCR,TWPR,TWCP,TWCC,TWCH,TEXHP,
     1 TWEVG,TC1,TC2,TC3
      COMMON/HEAT1/ QF,QFPC,QC,QCPC,A1,A1PC,A2,A2PC,A3,A3PC,
     1 A4,A4PC,QCYL,QCYLPC
      COMMON/HEAT2/ QEVG,QEVGPC,QEXHP,QEXHPC,
     1 QTC1,QTC1PC,QTC2,QTC2PC,QTC3,QTC3PC,QOUT,QOUTPC
      COMMON/HEAT/ NHEAT,QSLEV1,QPIST1,QHEAD1,QEXHV1,QTOT1,
     1          QSLEV2,QPIST2,QHEAD2,QEXHV2,QTOT2,
     2          HC1,HC2,HC3,HC4,HC5,HC6,HC7,HC8,
     3          HCT1,HCT2,HCT3,HCT4,HCT5,HCT6,HCT7,HCT8
      COMMON/INPT2/
     1 XXEVG,XXEVH,XXPSL,XXPIS,XXPRG,XXHED,XXPCR,XXRSL,XXSLV,
     2 AEXVS,AEXV,AEXST,AHEAD,ASLEEV,APIST1,APIST2,APISTR,ARING1,ARING2,
     3 CEXV,CHEAD,CSLEEV,CPIST,CRING,
     4 HEXHP,HOILP,HCSL,HCHD,
     5 D1,D2,D3,D4,D5,D6,VCV,APP,ARR,ASS
      COMMON/CV/ QCV,QCV1,QCV2,QCV3
      COMMON/FRIC/ QFRIC1,QFRIC2,QFRIC3
      DIMENSION A(9,10),AFAHR(9)
      RPS=REVENG*REVREF
C
C CALCULATE EFFECTIVE GAS TEMPERATURES
C
      TEG1=HCT1/HC1
      TEG2=HCT2/HC2
      TEG3=HCT3/HC3
      TEG4=HCT4/HC4
      TEG5=HCT5/HC5
      TEG6=HCT6/HC6
      TEG7=HCT7/HC7
      TEG8=HCT8/HC8
C
      HTOT1=HC1+HC5
      HTOT2=HC2+HC6
      HTOT3=HC3+HC7
      HTOT4=HC4+HC8
      HTTT1=HCT1+HCT5
```

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      HTTT2=HCT2+HCT6
      HTTT3=HCT3+HCT7
      HTTT4=HCT4+HCT8
C
      TTEG1=HTTT1/HTOT1
      TTEG2=HTTT2/HTOT2
      TTEG3=HTTT3/HTOT3
      TTEG4=HTTT4/HTOT4
C
C  CALCULATE RESISTANCES FROM NETWORK MODEL
C
      R1=XXEVG/(AEXVS*CEXV)
      R2=1./(HEXHP*AEXV)
      R3=XXEVH/(AEXST*CEXV)
      R4=XXHED/(AHEAD*CHEAD)
      R5=1./(HCHD*AHEAD)
      R6=XXPIS/(APIST1*CPIST)
      R7=1./(HOILP*APIST2)
      R8=XXPSL/(ASLEEV*CPIST)
      R9=XXPCR/(APISTR*CPIST)
      R10=XXRSL/(ARING1*CRING)
      R11=XXSLV/(ASLEEV*CSLEEV)
      R12=XXPRG/(ARING2*CRING)
      R13=1./(HCSL*ASLEEV)
C
C  WRITE(6,*)'R(S)',R1,R2,R3,R4,R5,R6,R7,R8,R9,R10,R11,R12,R13
C
      R14=360./HTOT1
      R15=360./HTOT2
      R16=360./HTOT3
      R17=360./HTOT4
C
      RX1=360.*RPS/HC1
      RX2=360.*RPS/HC2
      RX3=360.*RPS/HC3
      RX4=360.*RPS/HC4
      RY1=360.*RPS/HC5
      RY2=360.*RPS/HC6
      RY3=360.*RPS/HC7
      RY4=360.*RPS/HC8
C
      QX1=(TEG1-TWALL)/RX1
      QX2=(TEG2-TPIST)/RX2
      QX3=(TEG3-THEAD)/RX3
      QX4=(TEG4-TEXV)/RX4
      QY1=(TEG5-TWALL)/RY1
      QY2=(TEG6-TPIST)/RY2
      QY3=(TEG7-THEAD)/RY3
      QY4=(TEG8-TEXV)/RY4
C
C  WRITE(6,*) QX1,QY1,QSLEV1,QSLEV2
C  WRITE(6,*) QX2,QY2,QPIST1,QPIST2
C  WRITE(6,*) QX3,QY3,QHEAD1,QHEAD2
C  WRITE(6,*) QX4,QY4,QEXHV1,QEXHV2
```

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C
C
C  HEAT TRANSFER IN KJ/CYCLE
C
      QCYL1=QSLEV1-QSLEV2
      QCYL2=QPIST1-QPIST2
      QCYL3=QHEAD1-QHEAD2
      QCYL4=QEXHV1-QEXHV2
C    .
      QTOT1=QSLEV1+QPIST1+QHEAD1+QEXHV1
      QTOT2=QSLEV2+QPIST2+QHEAD2+QEXHV2
C
C  CHECK CALCULATIONS
C
      QC1=(TTEG1-TWALL)/R14/RPS
      QC2=(TTEG2-TPIST)/R15/RPS
      QC3=(TTEG3-THEAD)/R16/RPS
      QC4=(TTEG4-TEXV)/R17/RPS
C    WRITE(6,*) 'QCYL1,QC1',QCYL1,QC1
C    WRITE(6,*) 'QCYL2,QC2',QCYL2,QC2
C    WRITE(6,*) 'QCYL3,QC3',QCYL3,QC3
C    WRITE(6,*) 'QCYL4,QC4',QCYL4,QC4
      QTOT=QCYL1+QCYL2+QCYL3+QCYL4
      QCTOT=QC1+QC2+QC3+QC4
C    WRITE(6,*) 'QTOT,QCTOT',QTOT,QCTOT
      QPC=QCTOT/WFUEL/CALVAL*100.
      WRITE(6,*) 'HEAT LOSS AS A PERCENTAGE OF FUEL INPUT:',QPC
C
C  **** CALCULATE HEAT GENERATION DUE TO FRICTION ****
C
C        PISTON/RING FMEP FROM BISHOP'S EQUATION
C       BISHOP, J.N. "EFFECTS OF DESIGN VARIABLES ON FRICTION AND
C       ECONOMY," SAE PAPER 812A, (1964)
C
C  MEAN PISTON SPEED (M/S)
      STROKE=XSTA
      BORE=DCYL
      CM=2.*STROKE*RPS
C  OIL DENSITY  (KG/M**3)
      DENOIL=55.31*16.018
C  OIL VISCOSITY  (KG/M-SEC)  AT 200 DEG F
      VISOIL=250.E-5*1.4878
C  REYNOLDS NUMBER
      RE=CM*DENOIL*BORE/VISOIL
C  FMEP, FROM BISHOP  (PA)
      FMEPB=(6.2E4*CR**0.2/RE)*DENOIL*CM**2
C    WRITE(6,*)'FMEPB,RE,CM',FMEPB,RE,CM
C  FRICTION TORQUE  (N-M)
      FRICT=FMEPB*BORE*BORE*STROKE/8.
C  FRICTION POWER LOSS  (KW)
      FRICP=FRICT*2.*3.1415926*RPS/1000.
      FRICHP=FRICP/0.7456
C    WRITE(6,*) 'PISTON/RING FRICTION HP',FRICHP
C  FRICTION HEAT GENERATION TERMS  (KW)
```

```
      CFRIC1=0.5
      CFRIC2=0.5
      QFRIC1=CFRIC1*CFRIC2*FRICP
      QFRIC2=(1.-CFRIC2)*FRICP
      QFRIC3=(1.-CFRIC1)*CFRIC2*FRICP
C
C     ***** CREVICE VOLUME CALCULATIONS *******
C
C CREVICE VOLUME HEAT TRANSFER IN KW
C
      QCV1=QCV*ARR/(ARR+ASS+APP)*RPS
      QCV2=QCV*ASS/(ARR+ASS+APP)*RPS
      QCV3=QCV*APP/(ARR+ASS+APP)*RPS
C
C GENERATE COEFFICIENT MATRIX FOR SOLUTION OF SYSTEM OF EQUATIONS
C
      DO 100 I=1,9
      DO 100 J=1,10
 100  A(I,J)=0.
C
      A(1,1)=-1./R13-1./R11
      A(1,8)=1./R11
      A(1,10)=-TC2/R13
C
      A(2,2)=-1./R7-1./R6
      A(2,6)=1./R6
      A(2,10)=-TC1/R7
C
      A(3,3)=-1./R5-1./R4
      A(3,5)=1./R4
      A(3,10)=-TC3/R5
C
      A(4,4)=-1./R1-1./R2-1./R3-1./R17
      A(4,5)=1./R3
      A(4,10)=-TWEVG/R1-TEXHP/R2-TTEG4/R17
C
      A(5,5)=-1./R4-1./R3-1./R16
      A(5,3)=1./R4
      A(5,4)=1./R3
      A(5,10)=-TTEG3/R16
C
      A(6,6)=-1./R8-1./R9-1./R6-1./R15
      A(6,8)=1./R8
      A(6,7)=1./R9
      A(6,2)=1./R6
      A(6,10)=-QFRIC3-TTEG2/R15
C
      A(7,7)=-1./R9-1./R12
      A(7,6)=1./R9
      A(7,9)=1./R12
      A(7,10)=-QCV3
C
      A(8,8)=-1./R11-1./R10-1./R8-1./R14
      A(8,1)=1./R11
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      A(8,9)=1./R10
      A(8,6)=1./R8
      A(8,10)=-QCV2-QFRIC2-TTEG1/R14
C
      A(9,9)=-1./R10-1./R12
      A(9,8)=1./R10
      A(9,7)=1./R12
      A(9,10)=-QCV1-QFRIC1
C
C  SOLVE SYSTEM OF EQUATIONS TO GET METAL TEMPERATURES
C  SOLUTION VECTOR IS LOCATED IN COLUMN 10 OF COEFFICIENT MATRIX
C   TEMPERATURES ARE IN KELVIN
C
      CALL ELIM(A,9,10,9)
C
      TWCC=A(1,10)
      TWCP=A(2,10)
      TWCH=A(3,10)
      TWEV=A(4,10)
      TWGH=A(5,10)
      TWGP=A(6,10)
      TWPR=A(7,10)
      TWGC=A(8,10)
      TWCR=A(9,10)
C
      DO 200 I=1,9
  200 AFAHR(I)=A(I,10)*1.8-460.
C   WRITE(6,1000) (A(I,10),AFAHR(I),I=1,9)
 1000 FORMAT(2X,'COOLANT SIDE SLEEVE TEMPERATURE',F9.1,' K',F11.1,' F'/
     1 2X,'OIL SIDE PISTON TEMPERATURE',5X,F8.1,' K',F11.1,' F'/
     2 2X,'COOLANT SIDE HEAD TEMPERATURE',3X,F8.1,' K',F11.1,' F'/
     3 2X,'EXHAUST VALVE TEMPERATURE',7X,F8.1,' K',F11.1,' F'/
     4 2X,'GAS SIDE HEAD TEMPERATURE',7X,F8.1,' K',F11.1,' F'/
     5 2X,'GAS SIDE PISTON CROWN TEMPERATURE',F7.1,' K',F11.1,' F'/
     6 2X,'PISTON RIM TEMPERATURE',10X,F8.1,' K',F11.1,' F'/
     7 2X,'GAS SIDE SLEEVE TEMPERATURE',5X,F8.1,' K',F11.1,' F'/
     8 2X,'COMPRESSION RING TEMPERATURE',4X,F8.1,' K',F11.1,' F'/)
C
C  CHECK ENERGY BALANCE ON HEAT TRANSFER NETWORK
C
C  — ENERGY IN —
      QF=QFRIC1+QFRIC2+QFRIC3
      QC=QCV1+QCV2+QCV3
      A1=(TTEG1-TWGC)/R14
      A2=(TTEG2-TWGP)/R15
      A3=(TTEG3-TWGH)/R16
      A4=(TTEG4-TWEV)/R17
      QCYL=QF+QC+A1+A2+A3+A4
      QFPC=QF/QCYL*100.
      QCPC=QC/QCYL*100.
      A1PC=A1/QCYL*100.
      A2PC=A2/QCYL*100.
      A3PC=A3/QCYL*100.
      A4PC=A4/QCYL*100.
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      QCYLPC=100.
C  — ENERGY OUT —
      QEVG=(TWEV—TWEVG)/R1
      QEXHP=(TWEV—TEXHP)/R2
      QTC1=(TWCP—TC1)/R7
      QTC2=(TWCC—TC2)/R13
      QTC3=(TWCH—TC3)/R5
      QOUT=QEVG+QEXHP+QTC1+QTC2+QTC3
      QEVGPC=QEVG/QOUT*100.
      QEXHPC=QEXHP/QOUT*100.
      QTC1PC=QTC1/QOUT*100.
      QTC2PC=QTC2/QOUT*100.
      QTC3PC=QTC3/QOUT*100.
      QOUTPC=100.
C     PRINT OUT HEAT TRANSFER SUMMARY
C
C     WRITE(6,*) '    HEAT TRANSFER SUMMARY —KW'
C     WRITE(6,1001) QF,QFPC,QC,QCPC,
C   1 A1,A1PC,A2,A2PC,A3,A3PC,A4,A4PC,QCYL,QCYLPC
 1001 FORMAT(2X,'FRICTION GENERATED HEAT TRANSFER',3X,F10.3,F11.2,' %'/
     1 2X,'CREVICE VOLUME HEAT TRANSFER',F17.3,F11.2,' %'/
     2 2X,'HEAT TRANSFER TO CYLINDER WALL',F15.3,F11.2,' %'/
     3 2X,'HEAT TRANSFER TO PISTON',4X,F18.3,F11.2,' %'/
     4 2X,'HEAT TRANSFER TO HEAD',6X,F18.3,F11.2,' %'/
     5 2X,'HEAT TRANSFER TO EXHAUST VALVE',F15.3,F11.2,' %'/
     6 2X,'TOTAL HEAT INPUT TO NETWORK',3X,F15.3,F11.2,' %'/)
C     WRITE(6,1002) QEVG,QEVGPC,QEXHP,QEXHPC,
C   1 QTC1,QTC1PC,QTC2,QTC2PC,QTC3,QTC3PC,QOUT,QOUTPC
 1002 FORMAT(2X,'HEAT TRANSFER TO EXH VALVE GUIDE',3X,F10.3,F11.2,' %'/
     1 2X,'HEAT TRANSFER TO EXHAUST PORT GASES',F10.3,F11.2,' %'/
     2 2X,'HEAT TRANSFER TO PISTON COOLING OIL',F10.3,F11.2,' %'/
     3 2X,'HEAT TRANSFER TO SLEEVE COOLING OIL',F10.3,F11.2,' %'/
     4 2X,'HEAT TRANSFER TO HEAD COOLING OIL ',F10.3,F11.2,' %'/
     5 2X,'TOTAL HEAT TRANSFER FROM NETWORK  ',F10.3,F11.2,' %')
C
      RETURN
      END
C
      SUBROUTINE INPUT2
      COMMON/INPT2/
     1 XXEVG,XXEVH,XXPSL,XXPIS,XXPRG,XXHED,XXPCR,XXRSL,XXSLV,
     2 AEXVS,AEXV,AEXST,AHEAD,ASLEEV,APIST1,APIST2,APISTR,ARING1,ARING2,
     3 CEXV,CHEAD,CSLEEV,CPIST,CRING,
     4 HEXHP,HOILP,HCSL,HCHD,NEXHV,DEXHV,
     5 D1,D2,D3,D4,D5,D6,VCV,APP,ARR,ASS
      COMMON/XXX/ EQUIVD,RPM,PEXH,PAIR,TAIR,
     1       CR,BORE,STROKE,CONROD,FPISTE,FPISTA,
     2       EVO,EVC,AVO,AVC,
     3       TWALL,WFUEL,
     4       ACB,ACF,
     5       ANNA,FMEPM,
     6       NPCWF,DEL1,DEL2,DEL3,AAN(2),
     7       VALEXH,CDE,NTEXH,WIDTHE,ALPHEX(50),FEXH(50),
     8       VALAIR,CDA,NTAIR,WIDTHA,ALPAIR(50),FAIR(50)
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      COMMON/GEN/ALPHAT,ANGEND,ANGRES,AIRP0,EXHP0,IMOLS,
     1       APAIR,APEXH,AREF,AP(2),
     1       APN(2),CYCLE,DALPHA,
     1       DREF,DZ,FREF,
     1       IPOWER,IREV,GA,GE,GREF,IUNITL,
     1       IUNITP,IUNITT,IUNITK,IUNITW,IUNITQ,
     1       WAR,PBARAB,
     1       PI,PREF,REVENG,REVREF,RPAIR,RPEXH,RP(2),
     1       RPN(2),STEP2,TEXH,TREF,VREF,WREF,XREF,
     1       Z,ZREF,HAIR,HREF,SCMULT,NC
      COMMON/CYL/ACSB,ALPHA,ALPHAE,ANNB,ANNC,AC,
     1       ACN,ACR,ALPHAC,
     1       CALVAL,CARBON,
     1       COEFFA(4),COEFFB(4),COEFFC(4),COEFFD(4),
     1       COEFFE(4),COEFFZ(4),CRANK,DCYL,DHEAT,
     1       DRC,DVCYL,DWCIN,DWCP(2),DWCYL,
     1       FCYL,HEATG,
     1       PURITY,PVEL,PCR,PCYLT,
     1       PORTS,RC,RCN,RCR,SURFC,
     1       TCR,TCYLT,VSWEPT,
     1       VCYL,WCAIR,WCIN,
     1       WCOUT,WCYL,WMW(4),WPCNT(4),WCYLR,
     1       WN(4),WORKGA,WORKGE,XCRA,XSTA,
     1       NCD,WCYLT,DWCINT,
     1       TPIST,THEAD,TEXV,CID
      COMMON/COMB/AIRFL,EQUIV,TEXHS,SHPS,FZA,HRD,SCASW,TREFF,SCAEFF,
     +  AIRVMX,EXHVMX,PORTED,STOIC,WCO,BLBACK,FUELF,BHP
      COMMON/TEMP/TWEV,TWGH,TWGP,TWGC,TWCR,TWPR,TWCP,TWCC,TWCH,TEXHP,
     1  TWEVG,TC1,TC2,TC3
      PI=3.141592654
C  BORE AND STROKE IN FEET
      BORE=DCYL
      STROKE=XSTA
C
C  OPEN DATA FILE FOR HEAT TRANSFER INPUT
C
      OPEN (10, FILE='DIESEL10.INP',STATUS='OLD')
C
C  READ IN INITIAL ESTIMATES OF METAL TEMPERATURES  (DEG F)
C
C   READ(10,*) TWEV,TWGH,TWGP,TWGC,TWEVG
      TWEV=1000.
      TWGH=1000.
      TWGP=1000.
      TWGC=1000.
      TWEVG=1000.
C
C  READ IN OIL AND COOLANT TEMPERATURES  (DEG F)
C
C   READ(10,*) TC1,TC2,TC3
      TC1=200.
      TC2=200.
      TC3=200.
C
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```
C   CONVERT FROM FAHRENHEIT TO KELVIN
C
      TWEV=(TWEV+460.)/1.8
      TWGH=(TWGH+460.)/1.8
      TWGP=(TWGP+460.)/1.8
      TWGC=(TWGC+460.)/1.8
      TWEVG=(TWEVG+460.)/1.8
      TC1=(TC1+460.)/1.8
      TC2=(TC2+460.)/1.8
      TC3=(TC3+460.)/1.8
C
C   READ IN EXHAUST VALVE PARAMETERS AND CALCULATE EXHAUST VALVE AREA
C         DEXHV IN INCHES, AEXV IN SQUARE INCHES
C   READ(10,*) NEXHV,DEXHV
      NEXHV=4
      DEXHV=1.
      AEXV=FLOAT(NEXHV)*0.785398*DEXHV**2
C
C   READ IN PISTON RING/GROOVE DIMENSIONS  (INCHES)
C
C   READ(10,*) D1,D2,D3,D4,D5,D6
      D1=0.375
      D2=0.130
      D3=0.130
      D4=0.005
      D5=0.125
      D6=0.125
C
C   READ IN CONDUCTION PATH LENGTHS  (INCHES)
C
C   READ(10,*) XXEVG,XXEVH,XXPSL
C   READ(10,*) XXPIS,XXPRG,XXHED
C   READ(10,*) XXPCR,XXRSL,XXSLV
      XXEVG=0.
      XXEVH=0.
      XXPSL=0.
      XXPIS=0.
      XXPRG=0.
      XXHED=0.
      XXPCR=0.
      XXRSL=0.
      XXSLV=0.2
C
C   XXEVH=0.93
C   XXPIS=2.00
C   XXHED=0.800
C   XXSLV=0.750
C
C   CHECK FOR ZEROS, IF SO, USE DEFAULTS
C
      IF(XXEVG.LE.1.E-6) XXEVG=3.
      IF(XXEVH.LE.1.E-6) XXEVH=DEXHV/3.
      IF(XXPSL.LE.1.E-6) XXPSL=(BORE*12.)/3.
      IF(XXPIS.LE.1.E-6) XXPIS=0.5
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      IF(XXPRG.LE.1.E-6) XXPRG=D5
      IF(XXHED.LE.1.E-6) XXHED=0.25
      IF(XXPCR.LE.1.E-6) XXPCR=0.25
      IF(XXRSL.LE.1.E-6) XXRSL=D6
      IF(XXSLV.LE.1.E-6) XXSLV=0.25
C
C  CONVERT FROM INCHES TO METERS
C
      XXEVG=XXEVG/39.372
      XXEVH=XXEVH/39.372
      XXPSL=XXPSL/39.372
      XXPIS=XXPIS/39.372
      XXPRG=XXPRG/39.372
      XXHED=XXHED/39.372
      XXPCR=XXPCR/39.372
      XXRSL=XXRSL/39.372
      XXSLV=XXSLV/39.372
C
C  READ IN HEAT TRANSFER AREAS   (SQUARE INCHES)
C
C     READ(10,*) AEXVS,AEXST
C     READ(10,*) ASLEEV,APIST2
C     READ(10,*) APISTR,ARING1,ARING2
      AEXVS=0.
      AEXST=0.
      ASLEEV=0.
      APIST2=0.
      APISTR=0.
      ARING1=0.
      ARING2=0.
      APIST1=FPISTA*PI/4.*BORE**2 * 144.
      AHEAD=PI/4.*BORE**2*144. -AEXV
C
C  CHECK FOR ZEROS, IF SO, USE DEFAULTS
C
      IF(AEXVS.LE.1.E-9) AEXVS=FLOAT(NEXHV)*PI/4.*(0.25)**2
      IF(AEXST.LE.1.E-9) AEXST=FLOAT(NEXHV)*PI*DEXHV*0.050
      IF(ASLEEV.LE.1.E-9) ASLEEV=PI*BORE*(STROKE/4.)*144.
      IF(APIST2.LE.1.E-9) APIST2=APIST1
      IF(APISTR.LE.1.E-9) APISTR=PI*BORE*12.*0.5
      IF(ARING1.LE.1.E-9) ARING1=PI*BORE*12.*D5
      IF(ARING2.LE.1.E-9) ARING2=PI/4.*((BORE*12.-2.*D4)**2
     1   -(BORE*12.-2.*D6)**2)
C
C  CONVERT FROM SQUARE INCHES TO SQUARE METERS
C
      AEXVS =AEXVS /39.372**2
      AEXV  =AEXV  /39.372**2
      AEXST =AEXST /39.372**2
      ASLEEV=ASLEEV/39.372**2
      APIST1=APIST1/39.372**2
      APIST2=APIST2/39.372**2
      APISTR=APISTR/39.372**2
      ARING1=ARING1/39.372**2
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      ARING2=ARING2/39.372**2
      AHEAD = AHEAD/39.372**2
C
C   READ IN THERMAL CONDUCTIVITIES — BTU/(HR—FT—R)
C
C    READ(10,*) CEXV,CHEAD,CSLEEV,CPIST,CRING
      CEXV=24.
      CHEAD=22.
      CSLEEV=22.
      CPIST=60.
      CRING=24.8
C
C   CONVERT FROM BTU/(HR—FT—R) TO KW/(M—K)
C
      TT=1.054*3.281*1.8/3600.
      CEXV=CEXV*TT
      CHEAD=CHEAD*TT
      CSLEEV=CSLEEV*TT
      CPIST=CPIST*TT
      CRING=CRING*TT
C
C   READ IN CONVECTIVE COEFFICIENTS — BTU/(HR—FT**2—R)
C
C    READ(10,*) HEXHP,HOILP,HCSL,HCHD
C
C   CONVERT FROM BTU/(HR—FT**2—R) TO KW/(M**2—K)
C
      HEXHP=10.
      HOILP=900.
      HCSL=200.
      HCHD=200.
C    HOILP=900.
C    HCSL=2000.
C    HCHD=2000.
C    HOILP=900.
C    HCSL=1600.
C    HCHD=1600.
      TT=1.054*3.281**2*1.8/3600.
      HEXHP=HEXHP*TT
      HOILP=HOILP*TT
      HCSL=HCSL*TT
      HCHD=HCHD*TT
C
C   CONVERT FROM INCHES TO METERS
C
      D1=D1/39.372
      D2=D2/39.372
      D3=D3/39.372
      D4=D4/39.372
      D5=D5/39.372
      D6=D6/39.372
C
C   CALCULATE CREVICE VOLUME CHARACTERISTICS
C
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      BORE=DCYL/3.281
      VCV=PI/4.*(BORE**2-(BORE-2.*D4)**2)*D1
     1   + PI/4.*(BORE**2-(BORE-2.*D4-2.*D2)**2)*(D3-D5)
     2   + PI/4.*((BORE-2.*D6)**2-(BORE-2.*D4-2.*D2)**2)*D5
      APP=PI*(BORE-2.*D4)*D1
     1   + PI/4.*((BORE-2.*D4)**2-(BORE-2.*D4-2.*D2)**2)
      ARR=PI/4.*(BORE**2-(BORE-2.*D6)**2)+PI*(BORE-2.*D6)*D5
      ASS=PI*BORE*(D1+D3-D5)
C
      CLOSE (10,STATUS='KEEP')
C
      RETURN
      END
C
      SUBROUTINE BURNRT(ANGLA,ACB,ACF,WFUEL,DWFUEL)
C MODIFIED BURNING RATE MODEL -SAWTOOTH SHAPE
      ACF1=ACF+360.
      ACB1=ACB+0.8*(ACF1-ACB)
      IF(ANGLA.LT.ACB) DWFUEL=0.
      IF(ANGLA.GT.ACB .AND. ANGLA.LE.ACB1) DWFUEL
     1   =WFUEL*(2./(ACF1-ACB))*((ANGLA-ACB)/(ACB1-ACB))
      IF(ANGLA.GT.ACB1 .AND. ANGLA.LT.ACF1) DWFUEL
     1   =WFUEL*(2./(ACF1-ACB))*((ACF1-ANGLA)/(ACF1-ACB1))
      IF(ANGLA.GE.ACF1) DWFUEL=0.
      RETURN
      END


      SUBROUTINE SPLFIT(JJ,IJ,NP,OPT,ANGROT,XKX,IXLGR,FY,IYLGR,X,Y,ITRP)
C
C-------SUBROUTINE SPLFIT IS A GENERALIZED SPLINE CURVE FIT PROGRAM
C
C-------THE INPUT PARAMETERS ARE
C   JJ -OVERALL FLOW ITERATION NUMBER
C   IJ -INTERVAL NUMBER
C   NP -THE NUMBER OF POINTS DESCRIBING THE CURVE
C       (A MINIMUM OF 3 POINTS ARE REQUIRED)
C   OPT -OPTION FOR COORDINATE SYSTEM ROTATION (INTEGER)
C       (USE ONLY FOR REGULAR CARTESIAN COORDINATE SYSTEM)
C       0 -NO ROTATION
C       1 -ROTATION (MUST SPECIFY ANGROT)
C   ANGROT -COORDINATE ROTATION ANGLE (DEGREES)
C       (DUMMY VALUE IF OPT=0)
C   XKX(I) -THE NP X-VALUES DEFINING THE CURVE (25 MAX)
C       (MUST BE IN ASCENDING ORDER)
C   IXLGR -LOGARITHMIC X-AXIS INDICATOR
C       0 -CARTESIAN COORDINATE AXIS
C       1 -LOGARITHMIC COORDINATE AXIS
C   FY(I) -THE NP Y-VALUES DEFINING THE CURVE
C       (CORRESPONDING TO THE X-VALUES)
C   IYLGR -LOGARITHMIC Y-AXIS INDICATOR
C       0-CARTESIAN COORDINATE AXIS
C       1 -LOGARITHMIC COORDINATE AXIS
C-------NOTE : THE FUNCTION SLOPES AT THE END POINTS ARE EVALUATED FROM THE FIRST
C       TWO AND LAST TWO DATA INPUT POINTS.  THESE POINTS MUST THUS BE
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C           SELECTED TO GIVE A GOOD SLOPE REPRESENTATION
C      X —THE X VALUE WHERE THE FUNCTION VALUE IS DESIRED
C
C———————THE OUTPUT PARAMETERS ARE
C      Y —THE FUNCTION VALUE AT THE DESIRED X—VALUE
C      ITRP —TRAP FOR NON—CONVERGENCE
C
       REAL MAT(25,51),L(25),FCT(25),MKM1,MK,LK,LR(25)
       DIMENSION XKX(25),XK(25),FY(25),F(25)
       DIMENSION XKR(25),FR(25)
       INTEGER OPT
C
       ITRP=0
       N=NP—1
       NP1=N+1
       NP2=N+2
       NP3=N+3
       NM1=N—1
       NTOT=(NP1+NP2)
       DO 5 I=1,NP
       XK(I)=XKX(I)
       F(I)=FY(I)
     5 CONTINUE
C———————CHANGE COORDINATES FOR LOGARITHMIC AXES
       IF(IXLGR .EQ. 0)GOTO 210
       DO 200 I=1,NP
       IF(XK(I) .GT. 0.0)GOTO 198
       ITRP=1
       WRITE(6,606)
       GO TO 1010
   198 CONTINUE
       XK(I)=ALOG10(XK(I))
   200 CONTINUE
       IF(X .LE. 0.0)X=1.E—5
       X=ALOG10(X)
   210 CONTINUE
       IF(IYLGR .EQ. 0)GOTO 230
       DO 220 I=1,NP
       IF(F(I) .GT. 0.0)GOTO 202
       ITRP=1
       WRITE(6,608)
       GO TO 1010
   202 CONTINUE
       F(I)=ALOG10(F(I))
   220 CONTINUE
   230 CONTINUE
C
       IF(OPT .EQ. 0)GO TO 15
       ANGROT=ANGROT*3.141593/180.
       CAN=COS(ANGROT)
       SAN=SIN(ANGROT)
C
       DO 10 I=1,NP1
       XKR(I)=XK(I)*CAN + F(I)*SAN
```

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      FR(I)=F(I)*CAN -XK(I)*SAN
   10 CONTINUE
   15 CONTINUE
C
      DO 20 I=1,N
      IF(OPT .EQ. 0)GO TO 20
      LR(I)=XKR(I+1)-XKR(I)
   20 L(I)=XK(I+1)-XK(I)
C-------GET SLOPES AT THE END POINTS
      YPFST=(F(2)-F(1))/(XK(2)-XK(1))
      YPLST=(F(NP1)-F(N))/(XK(NP1)-XK(N))
      IF(OPT .EQ. 1)YPFSTR=(FR(2)-FR(1))/(XKR(2)-XKR(1))
      IF(OPT .EQ. 1)YPLSTR=(FR(NP1)-FR(N))/(XKR(NP1)-XKR(N))
C-------INITIALIZE THE MATRIX TO ZERO
      DO 30 I=1,NP1
      DO 30 J=1,NP2
   30 MAT(I,J)=0.
C-------ADD THE IDENTITY MATRIX TO GET THE OVERALL MATRIX
      DO 40 J=NP3,NTOT
      DO 40 I=1,NP1
      MAT(I,J)=0.
      IF((J-I) .EQ. (NP1 + 1))GOTO 35
      GO TO 40
   35 MAT(I,J)=1.
   40 CONTINUE
C
      MAT(1,1)=L(1)/3.
      MAT(1,2)=L(1)/6.
      MAT(1,NP2)=(F(2)-F(1))/L(1)-YPFST
      MAT(NP1,N)=L(N)/6.
      MAT(NP1,NP1)=L(N)/3.
      MAT(NP1,NP2)=YPLST-(F(NP1)-F(N))/L(N)
      IF(OPT .EQ. 1)MAT(1,1)=LR(1)/3.
      IF(OPT .EQ. 1)MAT(1,2)=LR(1)/6.
      IF(OPT .EQ. 1)MAT(1,NP2)=(FR(2)-FR(1))/LR(1)-YPFSTR
      IF(OPT .EQ. 1)MAT(NP1,N)=LR(N)/6.
      IF(OPT .EQ. 1)MAT(NP1,NP1)=LR(N)/3.
      IF(OPT .EQ. 1)MAT(NP1,NP2)=YPLSTR-(FR(NP1)-FR(N))/LR(N)
C
      DO 50 I=2,N
      IM1=I-1
      IM2=I-2
      IP1=I+1
      MAT(I,IM1)=L(IM1)/6.
      MAT(I,I)=(L(IM1)+L(I))/3.
      MAT(I,IP1)=L(I)/6.
      MAT(I,NP2)=(F(IP1)-F(I))/L(I) -(F(I)-F(IM1))/L(IM1)
      IF(OPT .EQ. 1)MAT(I,IM1)=LR(IM1)/6.
      IF(OPT .EQ. 1)MAT(I,I)=(LR(IM1)+LR(I))/3.
      IF(OPT .EQ. 1)MAT(I,IP1)=LR(I)/6.
   50 IF(OPT .EQ. 1)MAT(I,NP2)=(FR(IP1)-FR(I))/LR(I)-(FR(I)-FR(IM1))/LR(-
     *IM1)
C-------MAKE THE PIVOT ELEMENT THE LARGEST ELEMENT
      NSW=0
```

```
      DO 70 J=1,NP1
      IF(J .EQ. NP1)GO TO 75
      DO 70 I=J,N
      IP=I+1
      IF(ABS(MAT(IP,J)) .LT. ABS(MAT(J,J)))GO TO 70
      NSW=NSW+1
      DO 60 JS=1,NTOT
      STOR=MAT(J,JS)
      MAT(J,JS)=MAT(IP,JS)
      MAT(IP,JS)=STOR
   60 CONTINUE
   70 CONTINUE
   75 CONTINUE
C------REDUCE ELEMENTS IN PIVOT COLUMN TO ZERO, EXCEPT PIVOT
      DO 110 J=1,NP1
      DO 80 IR=1,NP1
   80 FCT(IR)=MAT(IR,J)/MAT(J,J)
      FCT(J)=0.
      DO 100 IZER=1,NP1
      DO 90 JZER=J,NTOT
      MAT(IZER,JZER)=MAT(IZER,JZER)-FCT(IZER)*MAT(J,JZER)
   90 CONTINUE
  100 CONTINUE
  110 CONTINUE
C------GET THE DETERMINANT
      DET=1.0
      DO 120 K=1,NP1
  120 DET=DET*MAT(K,K)
      DET=DET*((-1.)**NSW)
C------TRAP SINGULARITY
      IF(ABS(MAT(NP1,NP1)) .LT. 1.E-7 .AND. ABS(DET) .LT. 1.E-7)GOTO 122
      GO TO 125
  122 WRITE(6,602)LJ,JJ
      ITRP=1
      GO TO 1010
  125 CONTINUE
C------DIVIDE EACH ROW BY IT'S PIVOT
      DO 130 IPIV=1,NP1
      DIV=MAT(IPIV,IPIV)
      DO 130 JPIV=1,NTOT
      MAT(IPIV,JPIV)=MAT(IPIV,JPIV)/DIV
  130 CONTINUE
C------FOR A GIVEN X, FIND THE XK THAT BRACKET IT AND CALCULATE GENERATED F
      IND=0
      IF(X .LE. XK(1))IND=1
      IF(IND .EQ. 1)Y=F(1)
      IF(IND .EQ. 1)GO TO 1000
      IF(X .GE. XK(NP1))IND=2
      IF(IND .EQ. 2)Y=F(NP1)
      IF(IND .EQ. 2)GO TO 1000
C
      DO 140 I=2,NP1
      IND=0
      IF(X .EQ. XK(I))Y=F(I)
```

```
      IF(X .EQ. XK(I))GO TO 1000
      IF(XK(I-1) .LT. X .AND. XK(I) .GT. X)GO TO 135
      GO TO 140
  135 CONTINUE
      IM1=I-1
      MKM1=MAT(IM1,NP2)
      MK=MAT(I,NP2)
      XXM=XK(I-1)
      XX=XK(I)
      FK=F(I)
      FKM1=F(I-1)
      LK=XK(I)-XK(I-1)
      IF(OPT .EQ. 1)XXM=XKR(I-1)
      IF(OPT .EQ. 1)XX=XKR(I)
      IF(OPT .EQ. 1)FK=FR(I)
      IF(OPT .EQ. 1)FKM1=FR(I-1)
      IF(OPT .EQ. 1)LK=XKR(I)-XKR(I-1)
      GO TO 142
  140 CONTINUE
  142 CONTINUE
C
      IF(OPT .EQ. 0)GO TO 160
      ANGRT1=ANGROT
      ANGRT2=ANGROT
      ANGRT3=ANGROT
      ANGRT4=ANGROT
      Y1L=(MKM1*(XX-XXM)**3)/(6.*LK)+(FKM1/LK-LK*MKM1/6.)*(XX-XXM)
      Y2L=(1.0/TAN(ANGRT1))*XXM-X/SIN(ANGRT2)
      IF(Y1L .GT. Y2L)INDC=1
      IF(Y2L .GT. Y1L)INDC=-1
      INDCP=INDC
      INDCPI=-INDCP
      DELXR=(XX-XXM)/10.
      XR=XXM
C
      DO 150 I=1,30
      XR=XR+DELXR
      IF(XR .GT. XX)GO TO 152
      TERM1=(MKM1*(XX-XR)**3)/(6.*LK)
      TERM2=(MK*(XR-XXM)**3)/(6.*LK)
      TERM3=(FK/LK-MK*LK/6.)*(XR-XXM)
      TERM4=(FKM1/LK-LK*MKM1/6.)*(XX-XR)
      Y1=TERM1+TERM2+TERM3+TERM4
      Y2=(1.0/TAN(ANGRT3))*XR-X/SIN(ANGRT4)
      IF(Y1 .GT. Y2)INDC=1
      IF(Y2 .GT. Y1)INDC=-1
      CRIT=ABS(Y1-Y2)/ABS(Y1)
      IF(CRIT .LE. 1.E-4)GO TO 155
      IF(INDC .EQ. INDCPI)DELXR=-DELXR/10.
      IF(INDC .EQ. INDCPI)INDCP=INDCPI
      IF(INDC .EQ. INDCPI)INDCPI=-INDCP
  150 CONTINUE
C
      GO TO 155
```

```
  152 WRITE(6,604)I,IJ,JJ
      ITRP=1
      GO TO 1010
  155 CONTINUE
      ANGINV=-ANGROT
      SANI=SIN(ANGINV)
      CANI=COS(ANGINV)
      Y=Y1*CANI -XR*SANI
C-------X=XR*CANI + Y1*SANI
      GO TO 1000
  160 CONTINUE
      TERM1=(MKM1*(XX-X)**3)/(6.*LK)
      TERM2=(MK*(X-XXM)**3)/(6.*LK)
      TERM3=(FK/LK-MK*LK/6.)*(X-XXM)
      TERM4=(FKM1/LK-LK*MKM1/6.)*(XX-X)
      Y=TERM1+TERM2+TERM3+TERM4
C-------FORMAT STATEMENTS
  602 FORMAT(/,1X,44HABORT -SINGULAR MATRIX IN SUBROUTINE SPLFIT,/,   -
     *1X,11HIN INTERVAL,I3,24H, OVERALL FLOW ITERATION,I3,/)
  604 FORMAT(/,1X,62HABORT -COORDINATE ROTATION CALCULATIONS HAVE NOT C-
     *ONVERGED IN,I4,1X,31HITERATIONS IN SUBROUTINE SPLFIT,/,        -
     *1X,11HIN INTERVAL,I3,24H, OVERALL FLOW ITERATION,I3,/)
  606 FORMAT(/,1X,61HABORT -NEGATIVE NUMBER SPECIFIED IN LOGARITHMIC X-
     *AXIS ARRAY,/)
  608 FORMAT(/,1X,61HABORT -NEGATIVE NUMBER SPECIFIED IN LOGARITHMIC Y-
     *AXIS ARRAY,/)
 1000 CONTINUE
      IF(IXLGR .EQ. 1)X=(10.0)**(X)
      IF(IYLGR .EQ. 1)Y=(10.0)**(Y)
 1010 CONTINUE
      RETURN
      END
C
      SUBROUTINE UNITP(IA,IB,PP,PPB)
C     IMPLICIT REAL(A-H,O-Z),INTEGER(I-N)
      IF(IB.EQ.2) GO TO 1
      IF(IA.EQ.1) GO TO 2
      IF(IA.EQ.2) GO TO 3
      PP=(PP+PPB)/14.5
      GO TO 2
    3 PP=PP/14.5
    2 RETURN
    1 IF(IA.EQ.1) GO TO 4
      IF(IA.EQ.2) GO TO 5
      PP=(PP+PPB)*14.5
      GO TO 4
    5 PP=PP*14.5
    4 RETURN
      END
C
      SUBROUTINE UNITT(IA,IB,TT)
C     IMPLICIT REAL(A-H,O-Z), INTEGER(I-N)
      IF(IB.EQ.2) GO TO 1
      IF(IA.EQ.1) GO TO 2
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      IF(IA.EQ.2) GO TO 3
      IF(IA.EQ.3) GO TO 4
      TT=(TT+460.0)/1.8
      GO TO 2
    3 TT=TT+273.0
      GO TO 2
    4 TT=TT/1.8
    2 RETURN
    1 IF(IA.EQ.1) GO TO 5
      IF(IA.EQ.2) GO TO 6
      IF(IA.EQ.3) GO TO 7
      TT=1.8*TT-460.0
      GO TO 5
    6 TT=TT-273.0
      GO TO 5
    7 TT=1.8*TT
    5 RETURN
      END
C
      SUBROUTINE UNITW(IA,IB,WW)
C     IMPLICIT REAL(A-H,O-Z), INTEGER(I-N)
      IF(IB.EQ.2) GO TO 1
      IF(IA.EQ.1) GO TO 2
      WW=WW/2.205
    2 RETURN
    1 IF(IA.EQ.1) GO TO 3
      WW=WW*2.205
    3 RETURN
      END
C
      SUBROUTINE STROK(XSTROK,DSTROK,THETAE,STROKE,CONROD,RPS,ZR)
C     IMPLICIT REAL(A-H,O-Z), INTEGER(I-N)
      CONRAT=2.0*CONROD/STROKE
      PI=3.14159
      THETA=THETAE*PI/180.0
      FNN=SQRT(CONRAT**2-SIN(THETA)**2)
      IF(DSTROK.EQ.0.0) GO TO 1
      DSTROK=(PI/360.0)*ZR*RPS*STROKE*(SIN(THETA)+SIN(2.0*THETA)/
     1     (2.0*FNN))
    1 XSTROK=0.5*STROKE*(1.0+CONRAT-COS(THETA)-FNN)
      RETURN
      END
C
      SUBROUTINE CYLVOL(FCYLG,XSTROK,STROKE,CRR,DSTROK,VCYLG,DVCYLG)
C     IMPLICIT REAL(A-H,O-Z), INTEGER (I-N)
      VCYLG=FCYLG*(XSTROK+STROKE/(CRR-1.0))
      DVCYLG=FCYLG*DSTROK
      RETURN
      END
C
      SUBROUTINE SREA(SAREA,VCYLL,FCYLL,DCYLL,XR,DR,F1,F2)
C     IMPLICIT REAL(A-H,O-Z), INTEGER(I-N)
      SAREA=4.0*VCYLL*XR/(DCYLL*DR)+(F1+F2)*FCYLL
      RETURN
```

```
      END
C
      SUBROUTINE BAL(CARBON,FZA,T1,DELH,T2,GAM,H3)
C     OVERALL ENERGY BALANCE
C     FZA=OVERALL FUEL/AIR RATIO
C     T=TEMPERATURE, K
C     DELH=ENTHALPY CHANGE, KJ/KG
      DIMENSION X(4)
C     IMPLICIT REAL(A-H,O-Z),INTEGER (I-N)
      COMMON/JANAF/ A(4),B(4),C(4),D(4)
      X(1)=.79
      X(3)=FZA*CARBON*28.85/12.01
      X(4)=FZA*(1.-CARBON)*28.85/2.016
      X(2)=.21-X(3)-.5*X(4)
      SUM=X(1)+X(2)+X(3)+X(4)
      X(1)=X(1)/SUM
      X(2)=X(2)/SUM
      X(3)=X(3)/SUM
      X(4)=X(4)/SUM
      IF (DELH.EQ.0.) GO TO 15
      H1=0.
      DO 5 I=1,4
5     H1=H1+X(I)*8.3143*(A(I)*T1+B(I)*T1**2+C(I)*T1**3+D(I)*T1**4)
      H2=H1+DELH*(FZA+1.)*28.85/SUM
      T2=T1+100.
15    H2C=0.
      DO 10 I=1,4
10    H2C=H2C+X(I)*8.3143*(A(I)*T2+B(I)*T2**2+C(I)*T2**3+D(I)*T2**4)
      H3=H2C*SUM/(28.85*(1.+FZA))
      CP=0.
      DO 20 I=1,4
20    CP=CP+X(I)*8.3143*(A(I)+2.*B(I)*T2+3.*C(I)*T2**2+4.*D(I)*T2**3)
      GAM=CP/(CP-8.3143)
      IF(DELH.EQ.0.) RETURN
      IF(ABS(H2C-H2).LE.H2*.0001) GO TO 25
      T2=T2+(H2-H2C)/CP
      GO TO 15
25    RETURN
      END
C
      SUBROUTINE FOPEN
      CHARACTER*16 FNAME1,FNAME2,FNAME3,FNAME4
      COMMON/OPEN/ FNAME1,FNAME2,FNAME3,FNAME4
      OPEN (1, FILE='DIESEL1.INP',STATUS='OLD')
      OPEN (2, FILE=FNAME1,STATUS='NEW')
      OPEN (3, FILE=FNAME2,STATUS='NEW')
      OPEN (4, FILE=FNAME3,STATUS='NEW')
      RETURN
      END
C
      SUBROUTINE FCLOSE
      CLOSE (1,STATUS='KEEP')
      CLOSE (2,STATUS='KEEP')
      CLOSE (3,STATUS='KEEP')
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      CLOSE (4,STATUS='KEEP')
      RETURN
      END
C
      SUBROUTINE INPUT
C    IMPLICIT REAL(A-H,O-Z), INTEGER(I-N)
      DIMENSION TITLE(20)
      COMMON/XXX/ EQUIVD,RPM,PEXH,PAIR,TAIR,
     1          CR,BORE,STROKE,CONROD,FPISTE,FPISTA,
     2          EVO,EVC,AVO,AVC,
     3          TWALL,WFUEL,
     4          ACB,ACF,
     5          ANNA,FMEPM,
     6          NPCWF,DEL1,DEL2,DEL3,AAN(2),
     7          VALEXH,CDE,NTEXH,WIDTHE,ALPHEX(50),FEXH(50),
     8          VALAIR,CDA,NTAIR,WIDTHA,ALPAIR(50),FAIR(50)
      COMMON/GEN/ALPHAT,ANGEND,ANGRES,AIRP0,EXHP0,IMOLS,
     1          APAIR,APEXH,AREF,AP(2),
     1          APN(2),CYCLE,DALPHA,
     1          DREF,DZ,FREF,
     1          IPOWER,IREV,GA,GE,GREF,IUNITL,
     1          IUNITP,IUNITT,IUNITK,IUNITW,IUNITQ,
     1          WAR,PBARAB,
     1          PI,PREF,REVENG,REVREF,RPAIR,RPEXH,RP(2),
     1          RPN(2),STEP2,TEXH,TREF,VREF,WREF,XREF,
     1          Z,ZREF,HAIR,HREF,SCMULT,NC
      COMMON/CYL/ACSB,ALPHA,ALPHAE,ANNB,ANNC,AC,
     1          ACN,ACR,ALPHAC,
     1          CALVAL,CARBON,
     1          COEFFA(4),COEFFB(4),COEFFC(4),COEFFD(4),
     1          COEFFE(4),COEFFZ(4),CRANK,DCYL,DHEAT,
     1          DRC,DVCYL,DWCIN,DWCP(2),DWCYL,
     1          FCYL,HEATG,
     1          PURITY,PVEL,PCR,PCYLT,
     1          PORTS,RC,RCN,RCR,SURFC,
     1          TCR,TCYLT,VSWEPT,
     1          VCYL,WCAIR,WCIN,
     1          WCOUT,WCYL,WMW(4),WPCNT(4),WCYLR,
     1          WN(4),WORKGA,WORKGE,XCRA,XSTA,
     1          NCD,WCYLT,DWCINT,
     1          TPIST,THEAD,TEXV,CID
      COMMON/COMB/AIRFL,EQUIV,TEXHS,SHPS,FZA,HRD,SCASW,TREFF,SCAEFF,
     +  AIRVMX,EXHVMX,PORTED,STOIC,WCO,BLBACK,FUELF,BHP
      COMMON/CPURE/WCA,WCHG,IMIX
      WRITE(4,10)
      WRITE(2,10)
   10 FORMAT ('BENSON DIESEL ENGINE MODEL'/)
C    READ(1,20) TITLE
C    WRITE(4,21) TITLE
C    WRITE(2,21) TITLE
C 20 FORMAT(20A4)
C 21 FORMAT(1X,20A4)
C
      IPOWER=10
```

```
      CYCLE=2.
      ANGEND=7200.
      PORTED=2.
      COOLED=2.
      IF (PORTED.EQ.0.) PORTED = 1.
C
      IUNITP=2
      IUNITT=3
      IUNITL=2
      IUNITW=2
      IUNITK=2
      IUNITQ=3
C
C     READ(1,*) EQUIVD,RPM,PEXH,PAIR,TAIR
C     WRITE(2,*) EQUIVD,RPM,PEXH,PAIR,TAIR
      REVENG=RPM/60.
      PBARAB=14.7
      PREF=14.7
      TREF=518.7
      GREF=1.4
      REVREF=REVENG
C
      TEXH=2100.
      GE=1.33
      GA=1.4
      WAR=0.
C
      STEP2=2.
C
C     READ(1,*) CR,BORE,STROKE,CONROD,FPISTA
C     WRITE(2,*) CR,BORE,STROKE,CONROD,FPISTA
      DCYL=BORE/12.
      XSTA=STROKE/12.
      XCRA=CONROD/12.
C
C     READ(1,*) EVO,EVC,AVO,AVC
C     WRITE(2,*) EVO,EVC,AVO,AVC
      ACSB=EVC
      IF(AVC.GT.EVC) ACSB=AVC
C
C     READ(1,*) TWALL,WFUEL
C     WRITE(2,*) TWALL,WFUEL
      PURITY=0.9
      PCYLT=185.
      TCYLT=1290.
      CRANK=0.
      NCD=0
C
C     READ(1,*) ACB,ACF
C     WRITE(2,*) ACB,ACF
      TPIST=TWALL
      THEAD=TWALL
      TEXV=TWALL
C
```

```
      CALVAL=42515.
C     READ(1,*) ANNA,FMEPM
C     WRITE(2,*) ANNA,FMEPM
      SCMULT=1.1
      ANNB=0.7
      ANNC=0.327E-10
C WOSCHNI HEAT LOSS MODEL ASSUMED WHEN ANNB=0.8 AND ANNC=0.
      IF(SCMULT.EQ.0.) SCMULT=1.
      IF(FMEPM.EQ.0.) FMEPM=1.
C
      CARBON=0.85561
C     READ(1,*) NPCWF,DEL1,DEL2,DEL3,AAN(1),AAN(2)
C     WRITE(2,*) NPCWF,DEL1,DEL2,DEL3,AAN(1),AAN(2)
C AAN(1), ANN(2) FUEL INJECTION CONSTANTS FOR WHITEHOUSE-WAY MODEL
      IF(AAN(1).EQ.0.) AAN(1)=1.
      IF(AAN(2).EQ.0.) AAN(2)=1.
      IF(DEL1.EQ.0.) DEL1=6.9
      IF(DEL2.EQ.0.) DEL2=2.1
      STOIC=1./((CARBON/12.01+(1.-CARBON)/(1.008*4.))*(32.0+3.76*28.0))
C     AVL HEAT RELEASE MODEL USED WHEN NPCWF = 0, DEL3=0.
C     WIEBE HEAT RELEASE MODEL USED WHEN NPCWF=0, DEL3 .GT. 0.
C     WHITEHOUSE-WAY MODEL USED WHEN NPCWF .LT. 0
C     WATSON MODEL USED WHEN NPCWF.GT.0
      IF (NPCWF.GT.0) HRD=125.0
      IF (NPCWF.EQ.0) HRD=DEL3
C
C     READ(1,*) VALEXH
C     WRITE(2,*) VALEXH
      IF(VALEXH.EQ.0.0) GO TO 8
C
C     READ(1,*) CDE,NTEXH
C     WRITE(2,*) CDE,NTEXH
C
C     READ(1,*) (ALPHEX(N),FEXH(N),N=1,NTEXH)
C     WRITE(2,191) (ALPHEX(N),FEXH(N),N=1,NTEXH)
  191 FORMAT(1X,2E10.3)
      DO 192 N=1,NTEXH
  192 ALPHEX(N)=ALPHEX(N)+EVO
      GO TO 9
C
    8 CONTINUE
C     READ(1,*) CDE,WIDTHE
C     WRITE(2,*) CDE,WIDTHE
C
    9 CONTINUE
C     READ(1,*) VALAIR
C     WRITE(2,*) VALAIR
      IF(VALAIR.EQ.0.0) GO TO 200
C
C     READ(1,*) CDA,NTAIR
C     WRITE(2,*) CDA,NTAIR
C
C     READ(1,*) (ALPAIR(N),FAIR(N),N=1,NTAIR)
C     WRITE(2,*) (ALPAIR(N),FAIR(N),N=1,NTAIR)
```

```fortran
      DO 193 N=1,NTAIR
  193 ALPAIR(N)=ALPAIR(N)+AVO
      GO TO 201
C
  200 CONTINUE
C     READ(1,*) CDA,WIDTHA
C     WRITE(2,*) CDA,WIDTHA
C
  201 RETURN
      END
C
      SUBROUTINE HEADER
      COMMON/XXX/ EQUIVD,RPM,PEXH,PAIR,TAIR,
     1          CR,BORE,STROKE,CONROD,FPISTE,FPISTA,
     2          EVO,EVC,AVO,AVC,
     3          TWALL,WFUEL,
     4          ACB,ACF,
     5          ANNA,FMEPM,
     6          NPCWF,DEL1,DEL2,DEL3,AAN(2),
     7          VALEXH,CDE,NTEXH,WIDTHE,ALPHEX(50),FEXH(50),
     8          VALAIR,CDA,NTAIR,WIDTHA,ALPAIR(50),FAIR(50)
      COMMON/GEN/ALPHAT,ANGEND,ANGRES,AIRP0,EXHP0,IMOLS,
     1          APAIR,APEXH,AREF,AP(2),
     1          APN(2),CYCLE,DALPHA,
     1          DREF,DZ,FREF,
     1          IPOWER,IREV,GA,GE,GREF,IUNITL,
     1          IUNITP,IUNITT,IUNITK,IUNITW,IUNITQ,
     1          WAR,PBARAB,
     1          PI,PREF,REVENG,REVREF,RPAIR,RPEXH,RP(2),
     1          RPN(2),STEP2,TEXH,TREF,VREF,WREF,XREF,
     1          Z,ZREF,HAIR,HREF,SCMULT,NC
      COMMON/CYL/ACSB,ALPHA,ALPHAE,ANNB,ANNC,AC,
     1          ACN,ACR,ALPHAC,
     1          CALVAL,CARBON,
     1          COEFFA(4),COEFFB(4),COEFFC(4),COEFFD(4),
     1          COEFFE(4),COEFFZ(4),CRANK,DCYL,DHEAT,
     1          DRC,DVCYL,DWCIN,DWCP(2),DWCYL,
     1          FCYL,HEATG,
     1          PURITY,PVEL,PCR,PCYLT,
     1          PORTS,RC,RCN,RCR,SURFC,
     1          TCR,TCYLT,VSWEPT,
     1          VCYL,WCAIR,WCIN,
     1          WCOUT,WCYL,WMW(4),WPCNT(4),WCYLR,
     1          WN(4),WORKGA,WORKGE,XCRA,XSTA,
     1          NCD,WCYLT,DWCINT,
     1          TPIST,THEAD,TEXV,CID
      COMMON/COMB/AIRFL,EQUIV,TEXHS,SHPS,FZA,HRD,SCASW,TREFF,SCAEFF,
     +     AIRVMX,EXHVMX,PORTED,STOIC,WCO,BLBACK,FUELF,BHP
      COMMON/CPURE/WCA,WCHG,IMIX
      WRITE(3,2048)
 2048 FORMAT(4X,'ANGLE',5X,'PRESSURE',3X,'TEMPERATURE',4X,
     1 'GAMMA',5X,'VOLUME',5X,'MEAN TEMP'/)
C
      NC=1
```

130

```
      WRITE(2,1027)
      WRITE(2,1028) TWALL,WFUEL,ACB,ACF,TPIST,THEAD,WAR
1027 FORMAT(43X,'WALL',7X,'FUEL',8X,'COMBUSTION',5X,'PISTON',4X,
    + 'CHAMB'/ 11X,13X,13X,6X,'TEMP',5X,
    +    'PER CYCLE',4X,'START FINISH',5X,'TEMP    TEMP',5X,'WAR'/)
1028 FORMAT (39X,       F9.1,E13.3,F9.1,F7.1,F10.1,F9.1,3X,F6.4)
1035 FORMAT (14H CYLINDER BORE,F8.4/7H STROKE,F9.4/
    1      50H SURFACE AREA PISTON / CYLINDER CROSS SECTION AREA,F8.4
    2      /22H CONNECTING ROD LENGTH,F9.4)
      DCYL12=DCYL*12
      XSTA12=XSTA*12
      XCRA12=XCRA*12
      CID=.7854*DCYL12**2*XSTA12
      WRITE(2,1035) DCYL12,XSTA12,FPISTA,XCRA12
      WRITE(2,1038) CR,CID
1038 FORMAT (26H NOMINAL COMPRESSION RATIO,F8.4,5X,'SWEPT VOLUME (IN3)'
    +,F8.3)
      WRITE(2,1040) EVO,EVC,AVO,AVC,ACSB,AAN(1),AAN(2)
1040 FORMAT (/12H PORT TIMING//4H EVO,F7.1/4H EVC,F7.1/4H AVO,F7.1/
    1      4H AVC,F7.1/32H ANGLE COMPRESSION STROKE BEGINS,F7.1,5X,
    1'AAN(1)= ',F6.3,5X,'AAN(2)= ',F6.3)
      IF (VALEXH.GT.5.) GO TO 85
      WRITE(2,1042) WIDTHE
1042 FORMAT (28H PERCENTAGE PORT WIDTH (EXH),F9.4)
      GO TO 86
   85 WRITE(2,1043) CDE
1043 FORMAT (26HCOEFFICIENT CD (EXH) VALVE,F7.4)
   86 IF (VALAIR.GT.5.) GO TO 87
      WRITE(2,1044) WIDTHA
1044 FORMAT (27HPERCENTAGE PORT WIDTH (AIR),F9.4)
      GO TO 88
   87 WRITE(2,1045) CDA
1045 FORMAT (25HCOEFFICIENT CD (AIR) PORT,F7.4)
   88 SPEED=REVENG*60.
      WRITE(2,2047) SPEED,PAIR,TAIR,PEXH
2047 FORMAT(11HSPEED (RPM),F10.2,5X,26HSUPPLY AIR PRESSURE (PSIA),
    + F8.2,5X,19HSUPPLY AIR TEMP (R),F8.2,5X,23HEXHAUST PRESSURE (PSIA)
    + ,F8.2/)
      WRITE(2,1049) CALVAL,CARBON,DEL1,DEL2,DEL3
1049 FORMAT(22HCALORIFIC VALUE(KJ/KG),F10.2,4X,
    1      15HCARBON FRACTION,F8.5,4X,5HDEL1 ,F6.4,4X,5HDEL2 ,F6.4,
    +4X,5HDEL3 ,F6.4)
      WRITE(2,1051) ANNA,FMEPM,ANNB
1051 FORMAT (1H ,8HANNAND A,F7.4,49X,
    +    5X,'FMEPM= ',F5.3,/9H ANNAND B,F7.4)
      WRITE(2,1052) ANNC
      WRITE(2,3000)
3000 FORMAT(/1X, 9HFUEL FLOW,2X, 9HSCAV RAT.,3X, 8HTRAPPING,3X,
    + 8HSCAVENGE,2X, 8HTEMP OUT,3X, 5HPOWER,5X, 4HTRUE,5X, 8HAIR FLOW,
    + 3X, 5HEQUIV,5X, 5HP MAX,6X, 5HT MAX,4X, 7HPERCENT)
      WRITE(2,3010)
3010 FORMAT(2X, 6HLB/SEC,5X, 6HSW VOL,7X, 3HEFF,8X, 3HEFF,9X, 1HR,8X,
    + 2HHP,5X, 6HPURITY,5X, 6HLB/SEC,15X, 4HPSIA,8X, 1HR,5X,
    + 9HHEAT LOSS/)
```

```
 1052 FORMAT(1H ,8HANNAND C,E12.4,2X,16H KW/(M**2)(K**4))
      RETURN
      END
C
      BLOCK DATA
C  FOURTH ORDER POLYNOMIAL CURVE FIT TO JANAF TABLE DATA
C  IN THE RANGE 400 K TO 2400 K
C  THIS DATA CAN BE USED TO FIND ENTHALPY, INTERNAL ENERGY, AND
C  SPECIFIC HEAT USING THE FOLLOWING EQUATIONS
C      H(I) = R (A(I)*T + B(I)*T**2 + C(I)*T**3 + D(I)*T**4)
C      U(I) = R ( (A(I)-1.)*T + B(I)*T**2 + C(I)*T**3 + D(I)*T**4)
C      CP(I) = R (A(I) + 2*B(I)*T + 3*C(I)*T**2 + 4*D(I)**3)
C
C  WHERE H(I) IS THE SENSIBLE MOLAR ENTHALPY OF SPECIES I,  J/GMOL
C      U(I) IS THE SENSIBLE MOLAR ENTHALPY OF SPECIES I,  J/GMOL
C      CP(I) IS THE MOLAR SPECIFIC HEAT AT CONSTANT PRESSURE, J/GMOL-K
C
      COMMON/JANAF/ A(4),B(4),C(4),D(4)
      DATA A/3.00845,2.94628,3.29003,3.50953/
      DATA B/6.15041E-4,1.03617E-3,2.69417E-3,6.54488E-4/
      DATA C/-1.09800E-7,-3.39775E-7,-8.66074E-7,9.41722E-8/
      DATA D/5.68186E-12,4.75627E-11,1.11529E-10,-3.43661E-11/
      END
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15. Supplementary Notes

16. Abstract

This report documents the Benson Diesel Engine Simulation Program and explains how it can be used to predict the performance of diesel engines. This program was obtained from the Garrett Turbine Engine Company but has been extensively modified since that time. The program is a thermodynamic simulation of the diesel engine cycle which uses a single zone combustion model. It can be used to predict the effect of changes in engine design and operating parameters such as valve timing, speed and boost pressure. The most significant change made to this program is the addition of a more detailed heat transfer model to predict metal part temperatures. This report contains a description of the sub-models used in the Benson program, a description of the input parameters and sample program runs.

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