HEAT RELEASE ESTIMATION AND PREDICTION OF WANKEL STRATIFIED-CHARGE COMBUSTION ENGINE

by

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ABSTRACT

The highly advanced Wankel stratified-charge combustion engine is the most promising future powerplant for general aviation. The advantages of the engine include low weight, high specific power density and multifuel capability without a loss in performance.

An one-zone heat release model for the stratified-charge Wankel engine was developed. The combustion chamber is modeled as an open thermodynamic system. The thermodynamic state of the chamber contents is represented by a linear approximation of the ratio of specific heats with temperature. The rate of heat released due to burning of the fuel was predicted by equating it to the rate of work transfer to the rotor, the rate of heat transfer to the walls, the enthalpy flux due to crevice flows across the combustion chamber boundary and the enthalpy flux due to fuel injection. Several sensitivity studies of the effects of these energy transfer mechanisms on the heat released were performed. To test the fuel-injection model, a heat release analysis was performed on Caterpillar diesel pressure data.

A cycle simulation in which a zero-dimensional one-zone combustion model was employed to predict the performance of a Wankel stratified-charge engine was developed. The performance model includes the effects of heat transfer, crevice and leakage flows and fuel-injection. The thermodynamic properties of the chamber contents were determined as a function of chamber temperature, pressure and average overall equivalence ratio. Unavailibility of Wankel stratified-charge engine data prevented calibration of the model. However, the effects on performance of heat transfer, crevice volumes and leakage were observed.

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CHAPTER 1.0 INTRODUCTION

The direct-injecton stratified-charge (DISC) engine combines the operating principals of the diesel and the spark-ignition engine. The DISC engine is the only spark-ignition engine with a thermal efficiency close to that of the diesel engine. The DISC engine has also demonstrated a wide fuel tolerance without a loss in performance. The disadvantage of the DISC engine is the high level of unburned hydrocarbons at light load operation. DISC engine research efforts are directed towards decreasing the level of unburned hydrocarbons at light load operation.

Stratified charge rotary engine development began at Curtiss-Wright during the mid 1960's [1]. Two prototype stratified charge military engines were designed and developed to the operational test stand phase. These engines displayed multi-fuel capability. However, neither engine matched the fuel economy of the reciprocating spark ignition engine or of the carbureted Cutriss-Wright automotive prototype engine developed during that time. Because of this, research efforts were terminated.

In 1973, research in the stratified rotary combustion engine recommenced. The Curtiss-Wright RC1-60, 60 cubic inch displacement, test engine was developed in 1974. Research efforts continued, analyzing the effects of nozzle configuration, increased rotor and housing temperature and increased compression ratio on brake specific fuel consumption with favorable results. In 1977, Curtiss-Wright began testing on the large 350 cubic inch displacement RC1-350 engine. Experimentation showed that the indicated specific fuel consumption decreased as the charge was made leaner.

Advantages of the stratified charge rotary engine include: high specific power density, multi-fuel capability, no balancing problems due to lack of reciprocating parts and low NO_x emissions. The problem which has plaqued the premixed spark-ignition Wankel engine is its low fuel economy. Despite the encouraging results on the fuel economy, the stratified-charge rotary combustion engine is not yet commercially produced.

The research carried out for this thesis focussed on the complete simulation of the performance of the stratified-charge Wankel engine. This research consisted of two phases. In phase one, "Heat Release Estimation", a heat release analysis of the contents of the engine combustion chamber is carried out to determine the rate of fuel chemical energy released using measured pressure data. The rate of burning of the fuel is estimated by equating it to the sum of the rate of change in sensible internal energy, the work transfer to the rotor and the rate of change of all possible energy loss mechanisms, such as heat transfer and enthalpy losses due to crevice flows across the system boundary. Phase two focussed on "Heat Release Prediction". The rate of fuel burning as an algebraic function of crankangle is specified, and the chamber pressure is calculated from a thermodynamic analysis of the contents of the Wankel engine chamber. In accomplishing the latter task, an existing premixed Wankel computer cycle simulation was modified for stratified charge application.

The remainder of this chapter provides a brief background as to the rationale of this research. Chapter two addresses the stratified charge combustion concept and improvements to the Wankel engine fuel economy through design and operation modifications. A description of the theory and modeling employed in the heat release analysis and the cycle simulation as well as a summary of the results and conclusions are found in chapters three and four respectively.

1.1 BACKGROUND

The turbocharged, turbo-compounded direct-injection stratified-charge Wankel combustion engine is the most promising future powerplant of general aviation. Studies performed by both Beech Aircraft Corporation [2] and Cessna Aircraft Corporation [3] under separate N.A.S.A. contract favored this highly advanced rotary engine concept over the highly advanced diesel, the highly advanced spark ignition and the turbine engine. The engines considered are conceptual designs sized to provide 250 hp under cruise condition at 25,000 feet altitude utilizing the most advanced technologies believed to become available to an engine design initiative in 1985 (Table 1). Commercial production is anticipated in the early 1990's. The engines were evaluated on the basis of weight, single and twin airframe installation, fuel usage and performance at varying loads, speeds and ranges.

Due to its small size and low weight, the highly advanced rotary engine offers a high specific power density. The multi-fuel capability of this engine is particularly advantageous in areas which have limited availability of aviation fuel. The engine is also designed to satisfy emissions levels that meet the EPA 1979 piston aircraft standards and a brake specific fuel consumption under 0.38 lb/hp-hr at 75 percent cruise power.

CHAPTER 2.0 THE DIRECT-INJECTION STRATIFIED CHARGE (DISC) ENGINE

2.1 DISC ENGINE OPERATION

During DISC engine operation, a full charge of air is inducted through the inlet port or valving. A circular swirl is imparted to the air by inlet port design or a shroulded inlet valve and continues during the compression process. At roughly 30 degrees BTC fuel injection begins downstream and across stream of the swirling air. The length of injection and the quantity of fuel injected are determined by the load. In this manner, the pumping loss created by throttling to control output in the carbureted engine is eliminated.

The injection characteristics are such that a fuel-rich mixture is adjacent to the spark plug. The charge going away from the spark plug is composed of zones which are progressively leaner, eventually becoming solely air. Following the start of injection, the spark plug fires, causing the ignition of the fuel rich zone and initiating flame propagation. The swirling air is continually added to the burning mixture. Overall, the DISC engine operates lean.

The advantages of the stratified charge engine include multi-fuel capability, low NO_x emissions and good fuel economy at part load. The latter advantage decreases with increased engine speed. At high loads and high engine speeds, all of the available air is not sufficiently mixed with the propagating burning mixture, causing the combustion efficiency to decrease. Therefore, in this operating regime, low equivalence ratios are employed.

The weakness of the DISC engine lies in the high level of unburned HC emissions and low fuel economy at light load. Giovanetti et. al. [4] noted that the HC emissions from direct-injection spark ignition engines operating at light load exceeded those from the diesel and premixed spark ignition by a factor of ten. Work done by Balles, Ekchian and Heywood [5] indicates poor combustion efficiency at light load operation. They found that the heat released on a cycle-by-cycle basis at light load operation does not agree with the amount of fuel injected. This indicates partial or complete misfire of individual cycles. Investigation into this phenomenon has focused upon fuel-air mixing, cycle-to-cycle variation of chamber air motion and the injection event.

2.2 WANKEL DISC ENGINE

The Wankel engine geometry makes it particularly applicable to stratified charge operation [1,6]. The "waist" of the rotor epitrochoidal housing shown in Figure 1 increases the air motion past a stationary injector promoting the necessary chamber fuel distribution.

As stated in the preceeding chapter, the disadvantage of the Wankel engine lies in the high level of unburned HC and specific fuel consumption. Improvement in Wankel engine design has significantly increased fuel economy. The nature of stratified charge operation also contributes to remedying the low fuel economy of the carbureted Wankel.

2.3 LOW FUEL ECONOMY MECHANISMS

2.3.1 LEAKAGE

Apex Seal Leakage

High combustion pressures and imperfect sealing to the rotor housing result in leakage of unburned charge past the apex seal to the trailing and leading chambers. Eberle and Klomp [7] estimated that apex seal leakage represents 66 to 75 percent of total leakage. They also found that this leakage mechanism increases as engine speed decreases. Knoll et. al. [8] found in their dynamic analysis of rotary engine seals that at high speeds; no apex seal separation from the rotary housing occurs.

Apex seal modifications by Yamamota and Muroki [9] reduced the apex seal leakage area by 90 percent (Figure 2). Crowning was introduced to decrease the separation between the center of the apex seal and the rotor housing. The split position of type apex seal was modified to provide better compatibility between the two pieces of the seal. The improvements in apex seal design by Burley, Meloeny and Stark [10] of General Motors during their study on the sources of unburned HC emissions of rotary engines netted a 12 percent reduction in brake specific fuel consumption.

Corner Seal Leakage

In an attempt to reduce the clearance between the corner seal and the seal bore while allowing for a wide production tolerance, Yamamoto and Muroki [9] changed the corner seal configuration to give elasticity in the radial direction. To prevent leakage from the combustion chamber into the increased area between the apex seal and corner seal due to the new configuration, the corner seal hole is filled with a heat-resisting elastic material (Figure 2).

Side Seal Leakage

Unburned charge which leaks through the side seal passes through the internals of the rotor to the inlet manifold. Eberle and Klomp [7] estimated side seal leakage to be 25 to 33 percent of the total leakage.

Eberle and Klomp [7] predicted that a reduction in leakage area of five percent at 2000 RPM will reduce indicated specific fuel consumption by 6.5 percent. At an engine speed of 4000 RPM, the indicated specific fuel consumption will be reduced by 4.5 percent. The effect of sealing modifications made by Yamamoto and Muroki [9] including side seal spring modifications to reduce friction loss (Figure 2), on brake specific fuel consumption is shown in Figure 3.

2.3.2 CREVICE VOLUMES

The high surface area to volume ratio near the apex seals will cause quenching of the propagating flame. The high pressures during the early stages of expansion drive unburned HC into the leading apex seal crevice volumes. These gases return to the chamber and are exhausted through the exhaust manifold.

Norman [11] took crevice volume measurements of a cold Mazda 12B Wankel engine (Table 2). Under firing conditions, the values found in the table are lower due to expansion of metallic surfaces. The apex seal crevice volume is roughly 50 percent of the total measured crevice volumes.

2.3.3 ROTOR AND CHAMBER SURFACE QUENCH

Flames adjacent to relatively cool rotor and chamber surfaces are extinguished, resulting in a thin layer of unburned HC. Work done by Yamamoto and Muroki [9], Charles Jones [1] and Burley, Meloeny and Stark [10] showed that maintaining those surface temperatures adequately high reduces brake specific fuel consumption, especially at light loads. Burley, Meloeny and Stark [10] reported that an increase in rotor temperature by 200 ^{o}F at 2000 RPM descreases brake specific fuel consumption by 9.8 percent. However, NO_x increases by 20 percent due to higher combustion chamber temperatures (i.e. lower heat transfer rate through the rotor). Yamamoto and Muroki [9] found a decrease in brake specific fuel consumption of 3.5 percent if the surface temperature is increased by 20 ^{o}C.

2.3.4 TRAILING FLAME QUENCH

The rotor and housing are in close proximity at the trailing edge of the chamber during expansion. The small clearance, i.e. large surface area to volume ratio, and the high heat transfer rate reduce the temperature and pressure so that the flame is not able to propagate against gas motion. Also, the housing "waist" causes the flame to travel at high speeds in the direction of rotor motion and at lower speed in the opposite direction. To overcome these difficulties, Yamamoto and Muroki [9] suggested that two spark plugs be placed about the housing minor axis (Figure 4) at high speeds and loads.

Leakage, crevice volume and trailing flame quench are primarily localized phenomenon occuring near the apex seals. These zones, by the nature of stratified charge combustion are very lean or solely air. Therefore, these sources of unburned HC may not be as significant in a stratified charge rotary. Yamamoto and Muroki [9] discovered a nine percent decrease in brake specific fuel consumption at high loads and approximately a three percent decrease at light loads utilizing stratified charge combustion. The results of investigating various direct-injection spark ignition engines by Giovanetti et. al. [4] showed that the stratified charge rotary engine has the lowest indicated specific HC emissions (Figure 5). Table 3 contains the geometric specifications and operating conditions of those engines considered in the investigation.

CHAPTER 3.0 HEAT RELEASE ANALYSIS

Performance of a first law thermodynamic analysis on the engine combustion chamber utilizing measured pressure data is an analytical procedure termed heat release. The analysis begins by modeling one of the three Wankel engine combustion chambers as an open thermodynamic system and accounting for all modes of energy transfer (Figure 6). The energy mechanisms considered are the internal energy of the chamber contents, heat transfer to the walls, work transfer to the rotor, enthalpy loss due to crevice flows across the system boundary and enthalpy gain due to fuel injection. This allows calculation of the energy released due to combustion of the chamber contents. Normalization of the resulting energy released due to combustion (Q_{gross}) with the fuel lower heating value provides an estimate of the rate of fuel burning.

3.1 THERMODYNAMIC EQUATIONS

The first law written for the combustion chamber after accounting for all possible energy transfer mechanisms takes the form:

$$dU = h_{inj} dm_{inj} - h'_{cr} dm_{cr} - \delta W - \delta Q_{ht} \qquad (3.1)$$

where,

dU is the change in internal energy

$h_{inj} dm_{inj}$ is the enthalpy gain due to fuel injection

$h'_{cr} dm_{cr}$ is the enthalpy loss due to leakage flows across the system boundary

δW is the work done by the system

δQ_{ht} is the heat transfer from the system.

The sign convention is chosen such that work done by the system and heat transfer from the system is positive.

In performing the analysis, several simplifying assumptions have been made. First of all, the perfect gas law is obeyed throughout the cycle. Secondly, the chamber contents are modeled as a homogeneous mixture of fuel vapor and products of reaction. Thirdly, the volume occupied by liquid fuel within the combustion chamber is assumed negligible.

3.1.1 INTERNAL ENERGY AND WORK TERMS

The total internal energy can be expressed as the product of the chamber mass and the specific internal energy. Therefore, the internal energy term of Eqn. 3.1 is rewritten as:

$$dU = d(m_f u_f + m_p u_p) = m_f du_f + m_p du_p + u_f dm_f + u_p dm_p \qquad (3.2)$$

The subscript f refers to fuel vapor and the subscript p refers to the products of reaction. As in the analysis by Gatowski et. al. [12], only the change in sensible internal energy is considered. This allows the first two terms on the right hand side of Eqn. 3.2 to be expressed as:

$$m_f du_f + m_p du_p = mc_v dT \qquad (3.3)$$

where c_v is the specific heat at constant volume. The boundary work term is given by the expression pdV, where p is the chamber pressure and dV is the derivative of the chamber volume with respect to degrees.

3.1.2 MASS BALANCE

Three mass balances are considered. They are an overall chamber mass balance

$$dm = dm_{inj} - dm_{cr} \tag{3.4}$$

and component mass balances for fuel vapor and products respectively

$$dm_f = dm_{inj} - dm_{cr(f)} + dm_{R(f)} \tag{3.4a}$$

$$dm_p = dm_{cr(p)} + dm_{R(p)} \tag{3.4b}$$

Also note that the change in the reactive fuel vapor mass is equal to and of opposite sign to the change of the reactive product mass

$$dm_{R(p)} = -dm_{R(f)} \tag{3.5}$$

After substituting Eqns. 3.2 thru 3.5 and combining like terms, Eqn. 3.1 becomes:

$$mc_v dT - (h_f - u_f)dm_{inj} + (h' - u_p)dm_{cr} - (u_p - u_f)dm_{R(f)} +$$

$$pdV + \delta Q_{ht} = 0 \tag{3.6}$$

It was proposed [12] that $u_p - u_f$ be written as:

$$u_p - u_f = (u_p - u^o_p) + (u^o_p - u^o_f) - (u_f - u^o_f) \quad (3.7)$$

where the superscript ^{o} refers to the reference state. For this analysis that corresponds to 298 K at atmospheric pressure.

Furthermore, the energy released due to combustion, δQ_{gross}, is defined as:

$$\delta Q_{gross} = (u_p^o - u_f^o)dm_{R(f)} \quad (3.8)$$

After application of the ideal gas law, the relationships $\gamma = c_p/c_v$ and $c_p - c_v = R$, Eqn 3.6 becomes Eqn. 27 of [12].

$$\delta Q_{gross} = [(\frac{\gamma}{\gamma-1})pdV + (\frac{1}{\gamma-1})Vdp - (h^* - u_f + c_vT)dm_{inj} + (h' - u_p + c_vT)dm_{cr} + \delta Q_{ht}]/[1 + \Psi(T)] \quad (3.9)$$

where,

$$\Psi(T) = [(u_p - u_p^o) - (u_f - u_f^o)]/[u_p^o - u_f^o]$$

and

$$u_p^o - u_f^o = -LHV_f$$

3.1.3 FUEL INJECTION MODEL

Using the definition of enthalpy for an ideal gas

$$h = u + pv,$$

the fuel injection term becomes:

$$(u^*_{f(l)} + pv_{f(l)} - u_f + c_v T)dm_{inj}$$

The superscript * indicates injection system conditions and the subscript f(l) denotes liquid fuel. The specific volume of fuel at any instance is very small. Hence, $pv_{f(l)}$ can be neglected. Also, the internal energy of liquid fuel can be expressed as $u^*_f - u^*_{lf}$; u_{lf} is the internal energy of vaporization.

Since the internal energy is solely a function of temperature for an ideal gas, $u^*_f - u_f$ becomes

$$\int_T^{T^*} c_{vf}(T)dT$$

The specific heat at constant volume is not a strong function of temperature. Therefore, for this analysis, c_{vf} is taken as a constant. So, $u^*_f - u_f$ equals:

$$c_{vf}(T^* - T)$$

where T^* is the injection temperature. After expressing c_v as:

$$c_v = \frac{R}{\gamma-1}$$

the injection term takes the form:

$$(c_{vf}(T^* - T) - u^*_{lf} + \frac{R}{\gamma-1})dm_{inj}$$

Vaporization of the fuel as it is injected causes a decrease in chamber pressure. This fuel-injection model attempts to account for that effect by adding the energy which is liberated due to vaporization of fuel. Similarly,

$u_f - u^o_f$ in the denominator of $\Psi(T)$ may be expressed as $c_{vf}(T - T^o)$.

3.1.4 CREVICE FLOW MODEL

Proceeding in the same manner as the fuel injection term

$$h' - u_p = u' - u_p + pv_p = u' - u + RT'$$

for an ideal gas. The crevice volume term in Eqn. 3.9 now becomes:

$$\left(\int_T^{T'} \frac{R}{\gamma - 1} dT + RT' + \frac{R}{\gamma - 1} T\right) dm_{cr}$$

In calculating dm_{cr}, the crevice volume model of the spark ignition Wankel code developed by Norman [11] is used. Because the apex crevice volume accounted for more than 50 percent of the total measured crevice volume, all of the crevice volumes are taken as being lumped at the apex seal location. The lumped crevice volume has a constant value throughout the cycle and is associated with the chamber with the highest of the two pressures across the apex seal. Due to the large surface area to volume ratio of the apex seal crevice volume, the gases are assumed to be cooled to the crevice volume wall temperature.

The model assumes that once the gases enter the crevice volume, there is direct leakage to the adjacent chamber. The temperature of the leakage gases is equal to that of the gases within the crevice volume prior to leakage, i.e. the crevice volume wall temperature. The leakage area is constant throughout the cycle and quasi one-dimensional isentropic leakage flow is assumed.

Referring to Figure 7, which is a schematic of the leakage flow, a conservation of mass analysis determines dm_{cr}. If dm_{cr} is negative, T' is equal to the crevice volume wall temperature. A postive dm_{cr} means mass flow is out of the chamber and T' is equal to the mass average chamber temperature which is calculated by use of the ideal gas law.

3.1.5 THERMODYNAMIC PROPERTIES

Aside from the evaluation of the heat transfer term, Eqn. 3.9 has been reduced to one unknown, γ (the ratio of specific heats). Gatowski et. al. [12] proposed taking a linear fit of γ with chamber temperature

$$\gamma(T) = A + BT$$

The heat release analysis equation in its final form is:

$$\delta Q_{gross} = \Big\{ \frac{\gamma}{\gamma-1} pdV + \frac{1}{\gamma-1} Vdp - \Big[c_{vf}(T^* - T) - u^*_{lg} + \frac{R}{\gamma-1} T \Big] dm_{inj}$$

$$+ R \Big[\frac{1}{B} \ln\Big(\frac{A + BT' - 1}{A + BT - 1}\Big) + T' + \frac{T}{\gamma-1} \Big] dm_{cr} + \delta Q_{ht} \Big\} \Big/$$

$$\Big\{ 1 + \Big[\frac{R}{B} \ln\Big(\frac{A + BT^{o} - 1}{A + BT - 1}\Big) + c_{vf}(T - T^{o}) \Big] / LHV_f \Big\} \tag{3.10}$$

3.1.6 HEAT TRANSFER MODEL

The heat transfer model is one of forced convection over a flat plate. The empirical Nusselt-Reynolds number correlation [13] is applicable.

$$Nu = \frac{h_c L}{k} = C \, Re^{a} \, Pr^{0.3}$$

where a = 0.8

C = 0.037

Re is the Reynolds number

Pr is the Prandtl number, assumed at unity.

The heat transfer coefficient is determined by the method proposed by Woshni [14]. The ideal gas equation is used to substitute for density. The thermal conductivity and dynamic viscosity are scaled for temperature. During intake and compression, Woshni [14] proposed that the characteristic velocity be directly proportional to the piston (rotor) speed, V_r. The Wankel analysis employs a mean rotor tip speed V_r

$$V_r = \frac{\pi}{3} R_r N$$

where, N is the crank rotational speed and R_r is the rotary radius. During combustion and expansion, Woshni [14] suggested an additional velocity term, W_c due to the increased charge velocity resulting from combustion.

$$W_c = C_c \frac{V_D}{V_1} \frac{T_1}{P_1} (P_{fir} - P_{mot})$$

V_D is the displacement volume

T_1, P_1 and V_1 are conditions at start of combustion

P_{fir} is the firing pressure

P_{mot} is the motoring pressure

The rationale for the form of this term is that W_c increases rapidly from zero at the start of combustion, reaches a maximum then decays during expansion. The differences between P_{fir} and P_{mot} as well as T_{fir} and T_{mot} follow this trend. Heat transfer coefficients determined from measured surface temperature experiments performed by Woshni indicate rapid decline in the value at the completion of combustion. In that analysis, the measured surface temperature became the boundary condition for the solution of the Fourier heat transfer equation. The temperature gradient at the surface was calculated and related to the heat transfer coefficient. Therefore, Woshni [14] related W_c with ΔP because its decay with time is more rapid than ΔT. Comparing results with measured data, Woshni [14] found

$$C_c = 3.24(10)^{-3}$$

During the intake and compression strokes, the heat transfeer coefficient is given by:

$$h = C_1 \; 131 \; R_r^{0.8} \; p^{0.8} \; T^{-0.53} \; (2.28 \; V_r)^{0.8}$$

The heat transfer coefficient during combustion and expansion is given by:

$$h = C_1\ 131\ R_r^{0.8}\ p^{0.8}\ T^{-0.53}\ (2.28V_r + C_2W_c)^{0.8}$$

C_1 and C_2 were added to determine the sensitivity of the results to variations in the overall heat transfer coefficient and charge velocity.

The heat transfer rate to the walls is calculated by

$$\delta Q_{ht} = h\ A_s\ (T - T_{wall})$$

where A_s is the total surface area.

3.2 FUEL VAPORIZATION

Two limiting cases of fuel vaporization are considered. If the fuel injection rate is known, the vaporization rate can be assumed equal to the injection rate. Alternatively, the mass rate of injected fuel may be approximated by the rate of fuel burning given by $\delta Q_{gross}/LHV_f$ and Eqn. 3.10 is solved replacing dm_{inj} with this approximation. The real fuel vaporization rate will be between these two limits.

3.3 RESULTS AND CONCLUSIONS

Due to the unavailability of Wankel DISC engine data, the fuel-injection model was tested with direct-injection diesel engine pressure data supplied by Caterpillar. The geometrical and operating parameters of the tested engine are in table 4. The chamber and injection system pressure traces are shown in Figure 8. The start and completion of injection were determined by observing the injection system pressure.

In performing the analysis, several sensitivity studies were completed. The assumptions for the base case calculation were: C_1 = 2.0, C_2 = 2.0, a crevice volume of two percent of the clearance volume and a linear fit to $\gamma(T)$ appropriate to the equivalence ratio increasing during combustion from zero to

$$\gamma(T) = 1.4266 - 8.867(10)^{-5}T$$

were selected. Figures 9 and 10 respectively contain the rate and integrated heat release plots for the base case.

The sensitivity to heat transfer was studied by varying C_1 and C_2. Two cases were studied in which C_1 was set to 1.0 and 3.0 respectively. All other parameters remained unchanged. The integrated heat release for each of these cases was calculated and then normalized by the introduced chemical energy, which is defined by the product of the mass of fuel injected and the lower heating value. The percentage of introduced chemical energy for each of these cases was compared to that of the base case (Table 5). The identical procedure was repeated for C_2 and for crevice volumes of zero and four percent of the clearance volume. Figures 11 thru 13 contain the integrated heat release plots for each of these sensitivity studies. The largest effect was observed in the sensitivity to the overall heat transfer coefficient (varying C_1). Variation of the crevice volume was observed to net the least effect to the percentage of introduced chemical energy.

The sensitivity to $\gamma(T)$ was examined by selecting a second linear fit with temperature

$$\gamma(T) = 1.4284 - 9.467(10)^{-5}T.$$

Figure 14 contains a plot of the ratio of specific heats of the chamber contents as well as the two proposed linear fits with temperature. The results indicate that the heat released is not sensitive to changes in $\gamma(T)$ which give a reasonable match to the basic thermodynamic data. The difference in percent of introduced chemical energy was found to be less than one percent (Figure 15).

Lastly, a comparison was made between fuel vaporization at the injection rate, vaporization at the fuel burning rate and premixed charge combustion. The integrated heat release results are plotted in Figure 16. For the injection rate case, a "top hat" injection profile was assumed, i.e a constant injection rate for a specified injection duration. The step which occurs at 6 degrees BTC results from too high a vaporization rate. To verify this, a longer injection duration was selected. The rate of heat release plot for both the short and long injection duration is shown in Figure 17.

CHAPTER 4.0 CYCLE SIMULATION

4.1 BACKGROUND

In order to predict theoretically the performance of a Wankel engine, a model is needed for each of the four-stroke cycle processes as well as heat transfer, work transfer and leakage flows across the boundary of the chamber. Several cycle simulations and a variety of modeling theories have been developed for the spark ignition Wankel engine. Danieli, Keck and Heywood [15] proposed a quasi-dimensional, three-zone combustion model. The three combustion zones identified were a burnt products zone, an unburned mixture zone and a quench layer. Sierens et. al. [16] also proposed a quasi-dimensional, three-zone combustion model. It was assumed that once the propagating flame reached the chamber sides, the leading unburned mixture zone was separated from the trailing unburned mixture zone by a burnt mixture zone. Norman [11] developed a zero-dimensional, two-zone combustion model. The chamber contents consisted of burnt products of combustion and unburned mixture. The principal difference between the zero-dimensional Norman code and the quasi-dimensional performance models is that the latter includes a turbulent submodel to predict the rate of fuel burning. This approach requires that an assumption be made about the propagating flame geometry. The zero-dimensional Norman [11] model predicts the rate of burning by an appropriate algebraic expression as a function of crankangle. In this thesis, the Norman code has been modified for stratified-charge application.

4.2 CODE OUTLINE

Although several modeling and algorithm modifications were necessary, the basic underlying structure of the Norman code remained unchanged (Figure 18). The Main Program reads the necessary input data, initializes the thermodynamic state of the chamber contents, determines which process (intake, compression, combustion and exhaust) is called, predicts the cycle performance by calculating the mean effective pressure, volumetric efficiency, etc. and writes to the output files. The Main Program interacts with the subroutine ODERT [17], used for numerical integration. ODERT calls the appropriate process routine, which in turn calls the volume, thermodynamic, mass flow rate, heat transfer and crevice and leakage subroutines. During the call to the process routine, the rate of change in pressure, temperature, work, heat transfer, chamber composition, and mass flow are calculated. ODERT integrates these variables and returns the integrated values to the Main Program. At the completion of the cycle, a comparison is made between the final exhaust state and the initial intake state of the chamber contents. If the difference in these states is within a specified error criteria, computation ceases. However, if the error tolerance is not satisfied, the final exhaust state becomes the initialized intake state and another iteration begins.

4.3 PERFORMANCE MODEL MODIFICATIONS

4.3.1 COMBUSTION MODEL

Stratified-charge combustion can be characterized by three distinct phases. By utilizing the films taken of stratified-charge combustion by use of the rapid compression machine, Wong, Rife and Martin [18] noted an initial delay period between the initiation of injection to the start of combustion. During this period, fuel is transported to the spark plug and vaporized. Fuel-air mixing also commences and a flame kernel is established. Following the delay is a period of rapid combustion, during which, any unburned fuel-air mixture that contacts the developing flame burns rapidly. The rapid combustion period ends when all of the unburned fuel-air mixture has been entrained by the propagating flame. The combustion rate then decays during the mixing period. Burning during this period is controlled by the rate at which remaining fuel and partially burned products mix with air.

The premixed spark ignition Wankel combustion model was modified in two ways. First of all, the two-zone combustion model--unburned and a burnt zone--was converted to an one-zone model which describes the chamber contents by an average overall equivalence ratio and temperature. Secondly, the mass burning-rate equation used in the premixed spark ignition code was replaced by a heat release-rate equation. An algebraic expression defining the heat release rate for stratified-charge engines was substituted for the Weibe function used by Norman. Balles et. al. [19] formulated this expression by analyzing experimental pressure data from the rapid compression machine at the MIT Sloan Automotive Laboratory. In this analysis, the rate of heat release was calculated from the average pressure of 43 consecutive cycles of experimental data at operating conditions of 1000 RPM and 2000 RPM over a range of loads. The rate of heat release normalized by the introduced fuel energy was plotted for both of the engine speeds at equivalence ratios of 0.3 and 0.6 (Figure 19). The following trends were observed: 1) The start of positive heat release occurred at the same crankangle position and increased linearly, at approximately the same slope, to a peak value; 2) The peak heat release rate for all of the curves occurred at roughly the same crankangle location; 3) There is an exponential decay in heat release after the peak rate. Because of the similarity between the heat release curves, a single heat release rate curve (Figure 20) was plotted by averaging the rates in Figure 19. After application of the observed trends, an empirical model for stratified charge engines was developed. The model defines the rate of heat release by specifying four parameters:

Θ_s	start of combustion
Θ_m	crankangle position at peak rate of heat release
$dQ/d\Theta_m$	peak rate of heat release
τ	time constant of decay

An integral constraint defines the sum of the integrated rates between the interval of Θ_s to Θ_m and the interval of Θ_m to exhaust valve opening as the combustion efficiency. Therefore, three of the four model parameters need be specified. The fourth parameter may be calculated by direct application of the integral constraint. Between Θ_s and Θ_m the rate of heat release is given by:

$$\frac{dQ}{d\Theta} = \frac{dQ}{d\Theta_m} [(\Theta - \Theta_s) / (\Theta_m - \Theta_s)] \qquad (4.1)$$

For Θ greater than Θ_m, the rate of fuel burning is given by:

$$\frac{dQ}{d\Theta} = \frac{dQ}{d\Theta_m} \exp [- (\Theta - \Theta_m) / \tau] \tag{4.2}$$

The empirical model was a good fit to the actual normalized heat release curve versus crankangle for the conditions studied.

4.3.2 THERMODYNAMIC PROPERTIES

The thermodynamic routines required special attention. Due to fuel injection, the chamber overall equivalence ratio is no longer constant throughout the cycle as in the carbureted engine. The value rises from zero at start of injection to a final overall equivalence ratio at the end of injection. Therefore, the average chamber equivalence ratio at each crank position was determined as a function of instantaneous chamber fuel fraction and the stoichiometric fuel-air ratio. Thus allowing calculation of the thermodynamic properties of enthalpy and density as functions of pressure, temperature and equivalence ratio.

4.4 THERMODYNAMIC EQUATIONS

The analysis begins by treating the combustion chamber as an open thermodynamic system. The general conservation of energy equation is:

$$\dot{E} = \sum \dot{m}_j h_j - \dot{Q} - \dot{W} \tag{4.3}$$

where,

$\sum \dot{m}_j h_j$ is the net enthalpy flux across the system boundary

$\dot{Q}$ is the heat transfer to the walls

$\dot{W}$ is the work transfer to the rotor

The total energy of the system, neglecting kinetic and potential energy, may be expressed as:

$$E = H - pV \tag{4.4}$$

H is the total enthalpy of the system, V is the chamber volume and p is the chamber pressure which is assumed uniform throughout the chamber. In terms of specific enthalpy, $\dot{E}$ of Eqn 4.3 becomes:

$$\frac{d(mh)}{dt} - \frac{d(pV)}{dt} = \dot{m}h + m\dot{h} - \dot{p}V - p\dot{V} \tag{4.5}$$

Substituting Eqn 4.5 and the boundary work given by $p\dot{V}$ into Eqn 4.3 yields:

$$m\dot{h} = \sum \dot{m}_j h_j - \dot{Q} + \dot{p}V - \dot{m}h \tag{4.6}$$

It is assumed that the ideal gas law is obeyed throughout the cycle. Therefore, the rate of change of pressure is given by:

$$\dot{p} = p\left(\frac{\dot{R}}{R} + \frac{\dot{m}}{m} + \frac{\dot{T}}{T} - \frac{\dot{V}}{V}\right) \tag{4.7}$$

Similarly, the rate of change of the gas constant, R can be written as:

$$\dot{R} = \frac{1}{\rho T}\dot{p} - \frac{p}{\rho^2 T}\dot{\rho} - \frac{p}{\rho T^2}\dot{T} \tag{4.8}$$

The derivatives of the thermodynamic properties of enthalpy and density in terms of the temperature, pressure and equivalence ratio are:

$$\dot{h} = c_p \dot{T} + c_T \dot{p} + c_\phi \dot{\phi} \tag{4.9a}$$

and

$$\dot{\rho} = \left(\frac{\partial \rho}{\partial T}\right)_{p,\phi} \dot{T} + \left(\frac{\partial \rho}{\partial p}\right)_{T,\phi} \dot{p} + \left(\frac{\partial \rho}{\partial \phi}\right)_{T,p} \dot{\phi} \tag{4.9b}$$

$$c_p = \left(\frac{\partial h}{\partial T}\right)_{p,\phi} , \quad c_T = \left(\frac{\partial h}{\partial p}\right)_{T,\phi} , \quad c_\phi = \left(\frac{\partial h}{\partial \phi}\right)_{T,p}$$

After substituting Eqns. 4.7 thru 4.9 into Eqn. 4.6, an expression for $\dot{T}$ in terms of the thermodynamic properties, chamber mass and chamber volume is obtained:

$$\dot{T} = \frac{B}{A} \left[\frac{\dot{m}}{m} \left(1 - \frac{h}{B} \right) - \frac{\dot{V}}{V} - \frac{C}{B}\dot{\phi} + \frac{1}{Bm} \left(\sum \dot{m}_j h_j - \dot{Q} \right) \right] \tag{4.10}$$

where,

$$A = c_p + \frac{(\partial \rho / \partial T)}{(\partial \rho / \partial p)} \left(\frac{1}{\rho} - c_T \right)$$

$$B = \frac{1}{(\partial \rho / \partial p)} (1 - \rho c_T)$$

$$C = c_\phi + \frac{(\partial \rho / \partial \phi)}{(\partial \rho / \partial p)} \left(\frac{1}{\rho} - c_T \right)$$

The rate of change in pressure as a function of the rate of change of chamber temperature, mass, volume and thermodynamic properties is:

$$\dot{p} = \frac{\rho}{\partial\rho / \partial p} \left(-\frac{\dot{V}}{V} - \frac{1}{\rho}\frac{\partial\rho}{\partial T}\dot{T} - \frac{1}{\rho}\frac{\partial\rho}{\partial\phi}\dot{\phi} + \frac{\dot{m}}{m} \right) \tag{4.11}$$

The above analysis followed the procedure developed by Assanis et. al. [20] for the turbo-compounded diesel simulation due to the similarity of the combustion model. In the diesel simulation, combustion also was modeled as an one-zone heat release process. The thermodynamic state of the diesel engine combustion chamber contents also is defined as a function of temperature, pressure and equivalence ratio.

4.4.1 AVERAGE OVERALL EQUIVALENCE RATIO

In order to perform the analysis, the average overall chamber equivalence ratio must be known at each crank position. The equivalence ratio evaluated as a function of the chamber fuel fraction, F is:

$$\phi = \frac{F}{F/A_{sto}(1 - F)} \tag{4.12}$$

where F/A_{sto} is the stoichiometric fuel-air ratio. F is defined as the ratio of the mass of fuel to the total chamber mass. The time rate of change of the equivalence ratio is found by differentiating Eqn. 4.10

$$\dot{\phi} = \frac{\dot{F}}{F/A_{sto}(1 - F)^2} \tag{4.13}$$

where $\dot{F}$ is evaluated by:

$$\dot{F} = (\sum \dot{m}_j / m) (F_j - F) \tag{4.14}$$

F_j is the fuel fraction of the mass flow across the system boundary. Figure 21 contains a plot of the average overall chamber equivalence ratio. At the start of combustion, its value is very small, it steadily rises due to injection of fuel to a final overall value.

4.4.2 HEAT TRANSFER MODEL

As in the heat release analysis, the heat transfer model is one of turbulent convection over a flat plate. Therefore, the empirical Nusselt-Reynolds number corelation is applicable. The characteristic velocity of the chamber gases is calculated as per Woshni [14]. The transport properties, viscosity, thermal conductivity and Prandtl number, are calculated by the method proposed by Mansouri and Heywood [21]. The viscosity, Prandtl number and thermal conductivity are calculated as functions of temperature, pressure and equivalence ratio using the NASA program, "Thermodynamic and Transport Properties of Complex Chemical Systems." Approximate correlations were then developed to fit the calculated data.

4.4.3 CREVICE AND LEAKAGE MODEL

As in the heat release anaylsis (Section 3.1.4), the crevice volume and leakage model lumps all of the Wankel engine crevice volumes (Table 2) at the apex seal location. The lumped crevice volume has a constant volume throughout the cycle and is connected to the chamber with the highest of the two pressures across the apex seal. The crevice volume pressure is equal to that of the chamber to which it is connected. Due to the high surface area to volume ratio of the crevice volume, the model assumes that the gases which have flowed into the crevice volume are cooled to the crevice volume wall temperature. After the gases have entered the crevice volume, there is direct leakage to the adjacent chamber. The leakage area is constant throughout the cycle and quasi one-dimensional isentropic leakage flow is assumed (Figure 7).

In addition to the pressure and the temperature, the crevice volume average overall equivalence ratio is required in order to determine the thermodynamic state of the gases which have flowed into the crevice volume. The model assumes that if the crevice volume is connected to the leading or trailing chamber, the crevice volume composition is set equal to the composition of the leading or trailing chamber from the previous iteration. The composition and pressure of the chamber of interest are stored during each iteration; the composition and pressure of the leading and trailing chambers from the previous iteration are determined by applying the appropriate angle phasing at each crankangle. The following example illustrates this point. If the simulation has reached -300 degrees BTC--intake process for the chamber of interest--during the third iteration, the leading chamber is now in the compression process and its pressure is higher. Therefore, the crevice volume is connected to the leading chamber. The leading chamber is 360 degrees in phase ahead of the chamber of interest. The leading crevice volume composition is set equal to the stored composition of the chamber of interest at 60 ATC.

At some point during the simulation the pressure of the chamber of interest will be larger than that of the leading chamber. The crevice volume now is assumed to have switched to the chamber of interest. At this point the crevice volume model begins calculating the rate of change in crevice volume composition in a manner identical to that of the chamber of interest as shown Eqns. 4.12 thru 4.14. The effect of the crevice volume and leakage flows are included in the net enthalpy flux term, $\sum \dot{m}_j h_j$, of Eqn. 4.10. If $\dot{m}_{cr}$ is negative, flow is from the crevice volume to the chamber and h_{cr} is the enthalpy of the crevice volume contents. However, if $\dot{m}_{cr}$ is positive, flow is from the chamber to the crevice volume and h_{cr} is equal to that of the chamber.

4.5 RESULTS AND DISCUSSION

After completion of the modifications necessary to convert the Norman premixed spark-ignition Wankel engine simulation code to stratified-charge application, the performance model must be calibrated and tested against experimental data. Unavailability of experimental stratified-charge Wankel engine data prevented the accomplishment of this task. However, a parametric study investigating the effects of heat transfer, crevice volumes and leakage on the performance of the DISC Wankel engine was performed. In conducting the study, a baseline case consisting of no loss mechanisms was selected. The cycle simulation was then ran for four additional test cases and these results were compared to those of the baseline case (Table 6). The four cases selected were the addition of: 2) heat transfer; 3) heat transfer and crevice volumes; 4) heat transfer and leakage; 5) heat transfer, crevice volumes and leakage. Figure 22 contains the calculated chamber pressure and temperature curves for case number five. The effects of the various parametric studies on volumetric efficiency, gross indicated mean effective pressure and residual fraction are noted.

4.5.1 VOLUMETRIC EFFICIENCY

As shown in Table 6, heat transfer and crevice volumes have little effect on the volumetric efficiency. However, leakage without crevice volumes significantly reduces the volumetric efficiency. While the chamber of interest is undergoing the intake process, the trailing and leading chambers are undergoing respectively the exhaust and the compression processes. The pressures of the trailing and leading chambers are higher than the pressure of the chamber of interest. This results in direct leakage from the leading and trailing chambers to the chamber of interest reducing the quantity of induced mass from the inlet manifold.

4.5.2 GROSS INDICATED MEAN EFFECTIVE PRESSURE (IMEP)

The gross IMEP is defined as the combined work of the compression and expansion processes, i.e. the net work per cycle, divided by the displaced volume. The IMEP can be thought of as the constant pressure exerted against the rotor during the expansion process necessary to produce work equal to the indicated work. The IMEP is related to the chamber pressure and the engine volumetric efficiency for the following reasons. The indicated work of an engine is directly proportional to the mass of mixture inducted. Table 6 shows that the mass of air inducted decreases substantially with the addition of leakage as explained in Section 4.5.1. Also, the peak pressures during the combustion and expansion process are lower in the studies containing leakage. Lower pressures during the expansion stroke decrease the indicated work.

4.5.3 RESIDUAL FRACTION

The results in Table 6 show that crevice volumes have little effect on residual fraction. However, heat transfer and leakage have a significant effect on the residual fraction. Both of these energy loss mechanisms result in lower exhaust temperatures, hence, lower residual gas temperatures. These lower temperatures cause an increase in the density of the residual gas.

4.6 SUMMARY

A complete cycle performance model has been developed for the DISC Wankel engine. A parametric study investigating the effects of the loss mechanisms of heat transfer, crevice volumes and leakage on overall engine performance was completed. Although the performance model has not been calibrated, the resultant trends in performance due to the inclusion of these energy loss mechanisms was observed. Addition of convective heat transfer significantly reduced the gross IMEP and the thermal efficiency. The additional heat loss due to crevice volumes lowers the gross IMEP and the thermal efficiency. The heat loss effects due to leakage are similar to and greater than those due to crevice volumes. The mass of injected fuel decreases due to the decrease in volumetric efficiency, i.e. decrease in induced air. Although all three energy loss mechanisms applied together result in additional heat transfer, the net effect on performance is small.

LIST OF REFERENCES

1. Jones, Charles. "An Update of Applicable Automotive Engine Stratified Charge Developments." SAE Paper 820347, 1982.

2. Zmcroczek, Leon A. Advanced General Aviation Comparitive Engine/ Airframe Integration Study. NASA Contractor Report 165565, 1982

3. Badgley, P.; Berkowitz, M.; Jones, C.; Myers, D.; Norwood, E.; Pratt, W.B.; Ellis, D.R.; Huggins, G.; Mueller, A.; and Hembrey, J.H. Advanced Stratified Charge Rotary Aircraft Engine Designs Study. NASA Contractor Report 165398, 1982.

4. Giovanetti, Anthony J.; Ekchian, Jack A.; and Heywood, John B. "Analysis of Hydrocarbon Emissions Mechanisms in a Direct Injection Spark-Ignition Engine." SAE Paper 830587, 1983.

5. Balles, E.N.; Ekchian, J.A.; and Heywood, J.B. "Fuel Injection Characteristics and Combustion Behavior of a Direct-Injection Stratified-Charge Engine." SAE Paper 841379, 1984

6. Obert, Edward F. Internal Combustion Engines and Air Pollution. Harper & Row, Publishers, New York, 1973.

7. Eberle, Meinrad K. and Klomp, Edward D. "An Evaluation of the Potential Performance Gain for Leakage Reduction in Rotary Engines." SAE Paper 730117, 1973.

8. Knoll, J.; Vilmann, C.R.; Schock, H.J.; and Stumpf, R.P. "A Dynamic Analysis of Rotary Combustion Engine Seals." SAE Paper 840035, 1984.

9. Yamamoto, Kenichi and Muroki, Takumi. "Development of Exhaust Emissions and Fuel Economy of the Rotary Engine at Toyo Kogyo." SAE Paper 780417, 1978.

10. Burley, Harvey A.; Meloeny, Michael R.; and Stark, Terrence L. "Sources of Hydrocarbon Emissions in Rotary Engines." SAE Paper 780419, 1978.

11. Norman, Timothy John. "A Performance Model of a Spark Ignition Wankel Engine: Including the Effects of Crevice volumes, Gas Leakage, and Heat Transfer." S.M. Thesis, Massachusetts Institute of Technology, 1983.

12. Gatowski, J.A.; Balles, E.N.; Chun, K.M.; Nelson, F.E.; Ekchian, J.A.; and Heywood, J.B. "Heat Release Analysis of Engine Pressure Data." SAE Paper 841359, 1984

13. Rohsenow, W.M. and Choi, H.Y. Heat, Mass and Momentum Transfer. Prentice-Hall, New Jersey, 1961.

14. Woshni, G. "A Universally Applicable Equation for the Instantaneous Heat Transfer Coefficient in the Internal Combustion Engine." SAE Transactions, vol. 76, Paper 670931, 1968.

15. Danieli, Guido A.; Keck, James C.; and Heywood, John B. "Experimental and Theoretical Analysis of Wankel Engine Performance." SAE Paper 780416, 1978.

16. Sierens, R.; Baert, R.; Winterbone, D.E.; and Baruah, P.C. " A Comprehensive Study of Wankel Engine Performance." SAE paper 830332, 1983.

17. Shampine, L.F. and Gordon, M.K. Computer Solution of Ordinary Differential Equations: The Initial Value Problem. W.H. Freeman and Company, San Francisco, 1975.

18. Wong, V.W.; Rife, J. M.; and Martin, M.K. "Experiments in Stratified Combustion with a Rapid Compresion Machine." SAE Paper 780638, 1978.

19. Heywood, J.B.; Balles, Eric N.; and Ekchian, Jack A. "Generalized Internal Combustion Engine Cycle Simulations: Direct-Injection Stratified-Charge Rotary Engines for Aircraft Applications." Progress Report for period July 1983 - February 1984, March, 1984.

20. Assanis, Dennis A.; Ekchian, Jack A.; Heywood, John B.; and Reploge, Kriss K. "Computer Simulation of the Turbocompounded Diesel Engine System." Proceedings of the Twenty-Second Automotive Technology Development Contractors Coordination Meeting. Dearborn, MI, 1984; reprint, SAE paper, 1985.

21. Mansouri, S.H. and Heywood, J.B. "Correlations for the Viscosity and Prandtl Number for hydrocarbon-Air Combustion Products." Combustion Science and Technology, vol. 23: pp. 251-256, 1980.

TABLE 1

ADVANCED ROTARY ENGINE TECHNOLOGIES

Solid-State Ignition Trigger Vs. Mechanical Trigger

Plasma Jet Ignition System

Eliminating Pilot Injector

High Temperature Aluminum Castings

Turbocharger

Thin Wall (Iron) Rotor

Exhaust Port Thermal Liner (Metallic)

Improved Lubricants

Multiple Power Sources for Ignition

Induction Air Intercooler

Variable Displacement Pressure Oil Pump

Provision for Counter-Rotating Propellers

Total Diagnostics

Electronic Ignition Schedule

Computer vs. Mechanical Timing

Fiber Optics Data Bus

Low Pressure Drop Heat Exchangers

NASVYTIS Traction Speed Reducer (Prop)

Alternate Cooling Fluid

Composite Rotor Housing (Wear Resistant Liner)

Wing Leading Edge with Integral Coolant Cooler

Alternate Materials Seals

Retracting Apex Seals

Thermostatically Controlled Rotor Oil Cooling

Turbocharging with Variable Area Turbine

Spark Ignition Start/Auto-Ignition Run

Aluminum Rotor (Reinforced Lands)

Insulated Rotor - Thermal Barrier Coating

Independent Dual Ignition

Variable Compression Ratio

Insulated Rotor - Inserts on Metallic Pad Insulator

Adiabatic Engine Ceramic End Walls

Composite Rotor (Reinforced Apex Seal Land)

Electronic Injection (Fuel)

Adiabatic Engine Ceramic Rotor Inserts

Turbocompound

Adiabatic Engine - Ceramic Rotor Housing Liner

Pilot Nozzle Trigger for Ignition System

High Speed Propeller (No Reduction Gear)

NASVYTIS Traction Speed Reducer (Turbocompound Drive - If Used)

Adiabatic Engine - Ceramic Rolling Element Bearings

TABLE 2

MAZDA 12B WANKEL ENGINE CREVICE VOLUME SIZES AND LOCATIONS*.

LOCATION	SIZE
behind apex seal	0.746 cm^3
beneath corner seal	0.093 cm^3
side seal land	0.285 cm^3
beneath side seal	0.225 cm^3
spark plug recesses	0.142 cm^3
spark plug threads	?

* Measurements are taken from a cold engine.

TABLE 3

GEOMETRICAL SPECIFICATIONS AND OPERATING CONDITIONS OF STRATIFIED-CHARGE ENGINES.

Engine	Fuel	Eng.Speed (rev/min)	Geometry					Injector Type	Timing	
			No. of cyl.	Bore (cm)	Stroke (cm)	Displ. Vol. per cyl. (cc)	Comp. Ratio		Approx. Injection Timing	Approx. Ignition Timing
Texaco TCP L-141	CITE* Heptane C7H16	2000 1000	1	9.84	7.62	580	10.2	Roosa-Master XNM-54 single-hole pencil, orifice dia. 0.635 mm, crack pressure 13.79 MPa	15° BTC Start	20° BTC
Texaco TCCS LIS-183 (MIT-TCP)	Iso-octane 310-590 K D 100-600 F D Methanol	2000	1	9.84	9.84	748	11.0	Roosa-Master XNM-1029 flat seat, single-hole pencil, orifice dia. 0.58 mm, crack pressure 13.79 MPa	18-35° BTC Start	2° prior to injection start 20° duration
Internatl Harvester Engine (IH)	Indolene	1000 2000 3000	1	10.48	10.62	915	12.6	Pencil (Conical Seat)	Late	
White L-163-S	Gasoline	1200 2400 3600	4	10.16	8.26	670	12.0	Pencil nozzle, twin orifice	28° BTC Start	Concurrent with injection at all loads and speeds
Ford PROCO	unknown	1500	1	10.16	8.89	721	11.0	Ford experimental outwardly-opening poppet valve, crack pressure 1.72-2.41 MPa	50° BTC @ full load 5° BTC @ light load	CA° between injection start and spark increases with load
Mitsubishi MCP-352-A	Gasoline Kerosene	2000	1	8.00	7.00	352	8.0	Pintle nozzle, inwardly-opening	48-64° BTC spill timing	CA° between injection end and spark constant with load
MAN-FM	unknown	1500 3200	1	unknown	unknown	850	16.0	unknown	unknown	unknown
Curtiss-Wright SCRC	Gasoline	2000	1	N/A	N/A	983	8.5	Pilot nozzle, main nozzle inwardly opening	unknown	CA° between injection start and spark constant with load
Oldsmobile Prechamber Diesel (MIT-IDI)	No. 2 diesel	1500	1	10.31	8.60	717	22.5	unknown	1-7° BTC	N/A
Cummins 855-TC	Diesel fuel?	610-2100	6	unknown	unknown	2335	14.0	unknown	Fixed Stnd.	N/A
Premixed Spark-Ignition Engine	Gasoline	1000 3000	8	unknown	unknown	562	9.0	N/A	N/A	unknown

* Compression Ignition Turbine Engine Fuel

TABLE 4

GEOMETRICAL AND OPERATING PARAMETERS OF CATERPILLAR DIRECT-INJECTION DIESEL ENGINE.

Bore	12.065 cm
Stroke	16.510 cm
Connecting Rod Length	26.160 cm
Compression Ratio	15.5:1
Engine Speed	1300 RPM
Wall Temperature	450 K
Fuel Rate	130 g/min
A/F Ratio	23.20

TABLE 5

RESULTS OF SENSITIVITY ANALYSIS
(Expressed as percent of introduced chemical energy).

Heat Transfer:

Sensitivity to C_1		Sensitivity to C_2	
C_1	% Chemical Energy	C_2	% Chemical Energy
1.0	89.9	1.0	94.7
2.0	99.0	2.0	99.0
3.0	108.1	3.0	103.0

Crevice Volume:

%	% Chemical Energy
0	97.1
2	99.0
4	101.0

$\gamma(T)$ Fit:

1st Fit	99.0
2nd Fit	99.3

Fuel Vaporization:

Injection Rate	99.0
Burn Rate	96.4
Premixed	95.8

Except where indicated, all heat release analyses are performed with the following conditions: $C_1 = 2.0$, $C_2 = 2.0$. Crevice volume = 2% of the clearance volume; Best fit for $\gamma(T)$. Vaporization at the rate of injection.

TABLE 6

RESULTS OF THE STRATIFIED-CHARGE CYCLE SIMULATION FOR ALL CASES STUDIES.

Case	Heat Transfer	Crevice Volume	Leakage	Volumetric Efficiency	
				Inlet Conditions	Atmospheric Conditions
1	NO	NO	NO	87.3	85.6
2	YES	NO	NO	88.7	86.9
3	YES	YES	NO	89.7	87.9
4	YES	NO	YES	83.2	81.5
5	YES	YES	YES	81.2	79.6

Case	Gross IMEP (KPa)	Thermal Efficiency		T_{max}	$\theta\ T_{max}$	P_{max}	$\theta\ P_{max}$
		Gross	Net				
1	1133	45.7	45.3	2435.53	27.0	62.35	14.0
2	981	39.0	38.6	2271.64	23.0	61.11	13.0
3	911	36.2	35.8	2346.77	22.0	55.39	14.0
4	736	32.6	32.1	2140.85	23.0	54.54	12.0
5	740	32.8	32.4	2237.39	24.0	49.57	13.0

Case	Residual Fraction	Mass of Injected Fuel (g)	Inducted Mass (g)	Heat Transfer (KJ)	
				Walls	Crevice
1	0.0567	0.0320	0.60445	0.0	0.0
2	0.0771	0.0325	0.61367	0.32687	0.0
3	0.0792	0.0325	0.61386	0.31181	0.09040
4	0.1580	0.0292	0.55129	0.25560	0.18791
5	0.1527	0.0291	0.55011	0.26611	0.24439

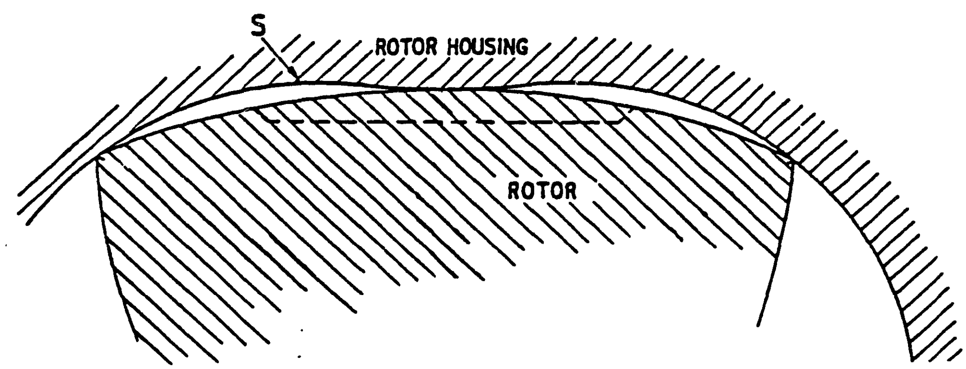


Figure 1. The Wankel engine rotor and epithrochoidal housing.

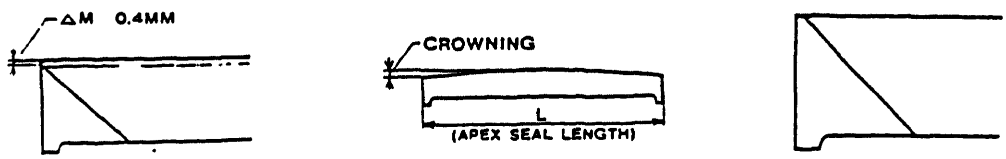


Figure 2a. Apex seal modifications.

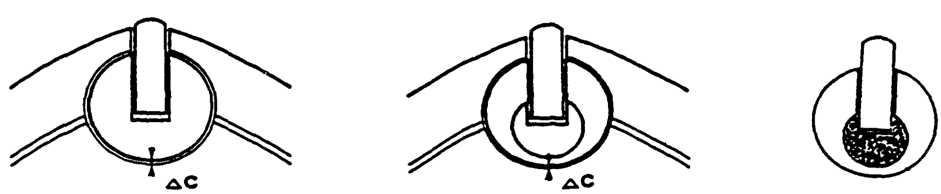


Figure 2b. Corner seal modifications.

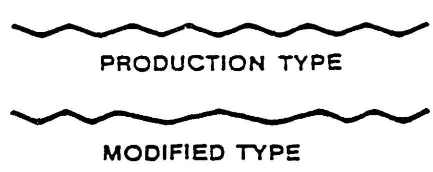


Figure 2c. Side seal spring modification.

Figure 2. Toyo Kogyo Wankel engine sealing modifications.

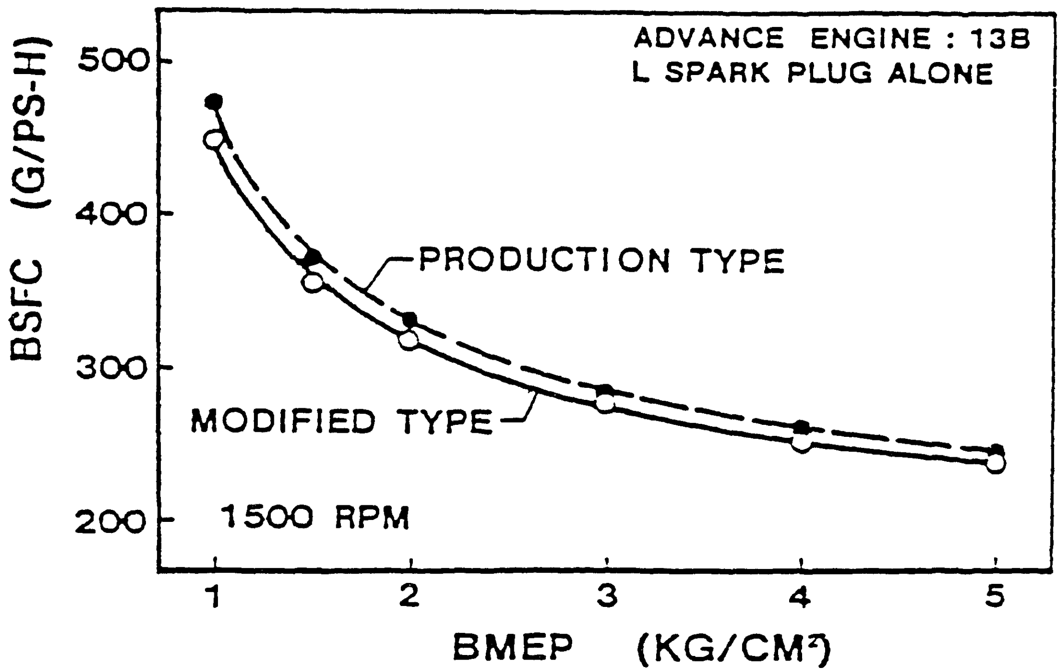


Figure 3. The affect of Toyo Kogyo sealing modifications on brake specific fuel consumption.

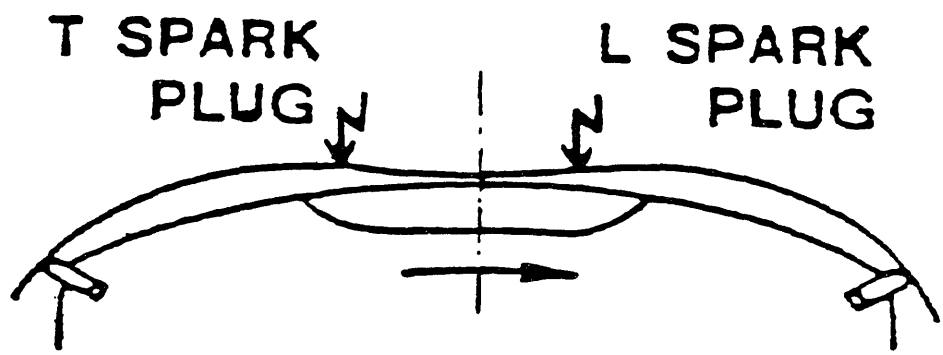


Figure 4. Leading and trailing spark plug placement about minor axis during high load and speed operation.

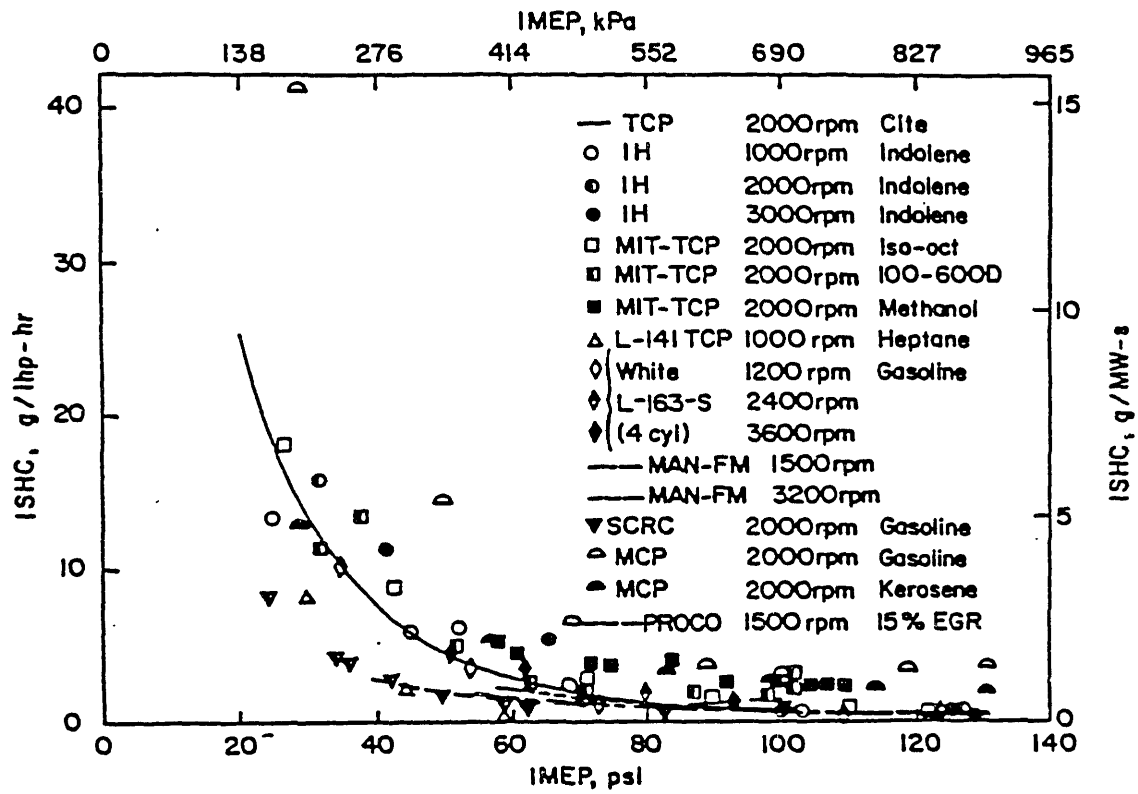


Figure 5. Indicated specific HC emissions versus load for stratified-charge engines.

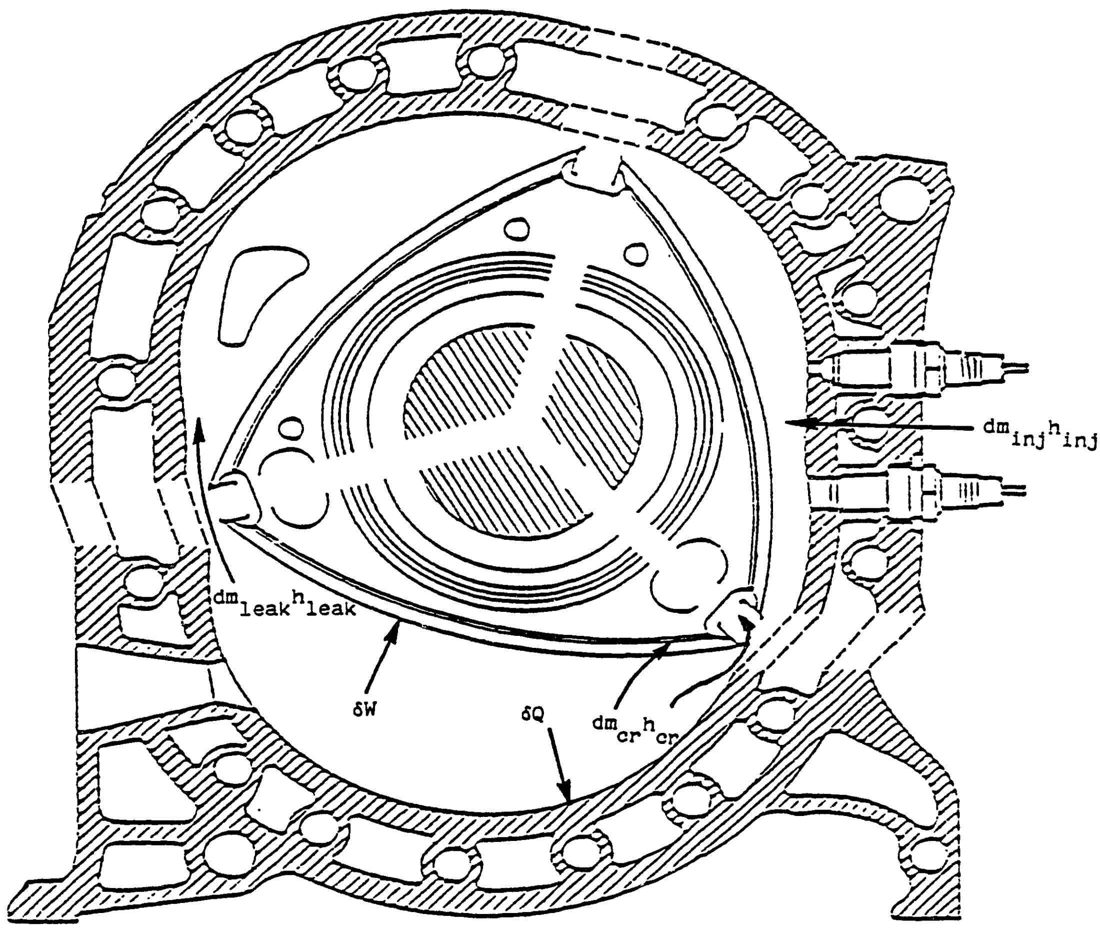
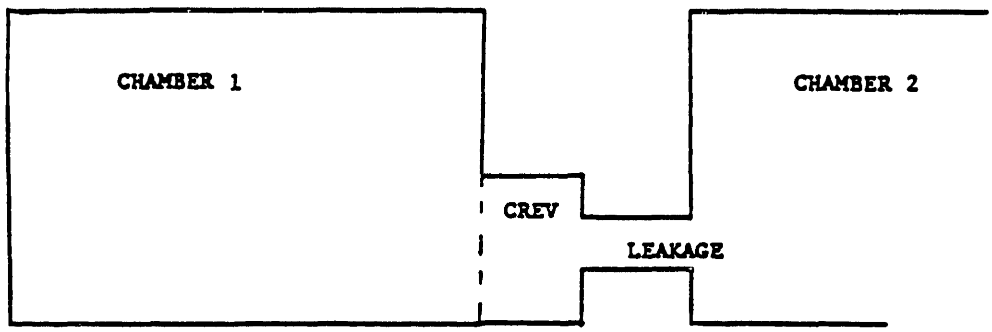


Figure 6. Energy transfer mechanisms across the Wankel engine combustion chamber boundary.



APPLY CONSERVATION OF MASS TO CREVICE VOLUME

$$\dot{m}_{1,crev} = \frac{dm_{crev}}{dt} + \dot{m}_{crev,2}$$

Figure 7. Schematic representation of crevice and leakage flows calculation.

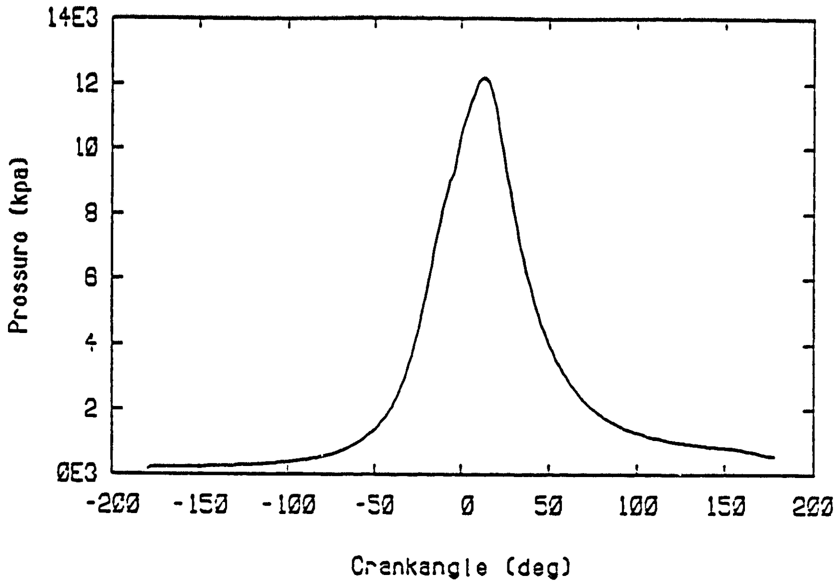


Figure 8a. Cylinder pressure.

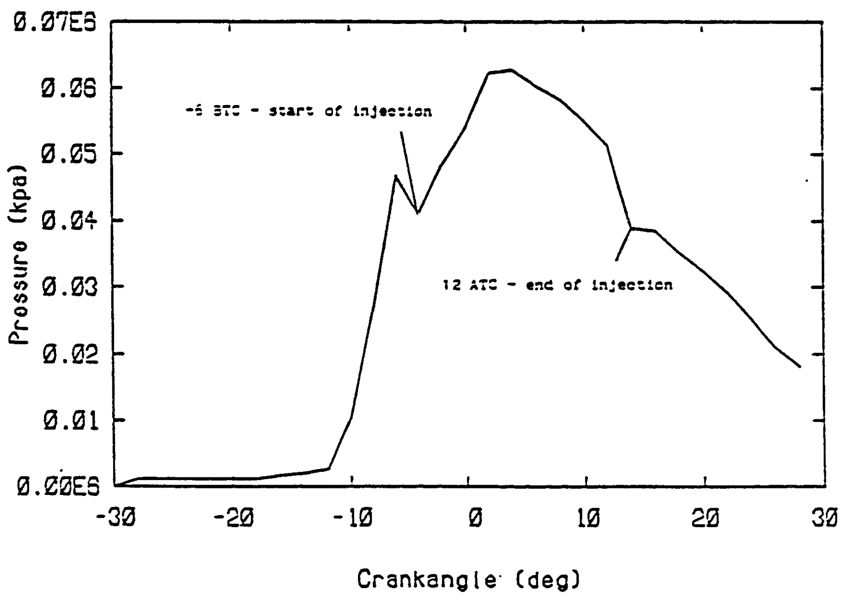


Figure 8b. Injection system pressure.

Figure 8. Caterpillar dircet-injection diesel engine cylinder and injection system pressure.

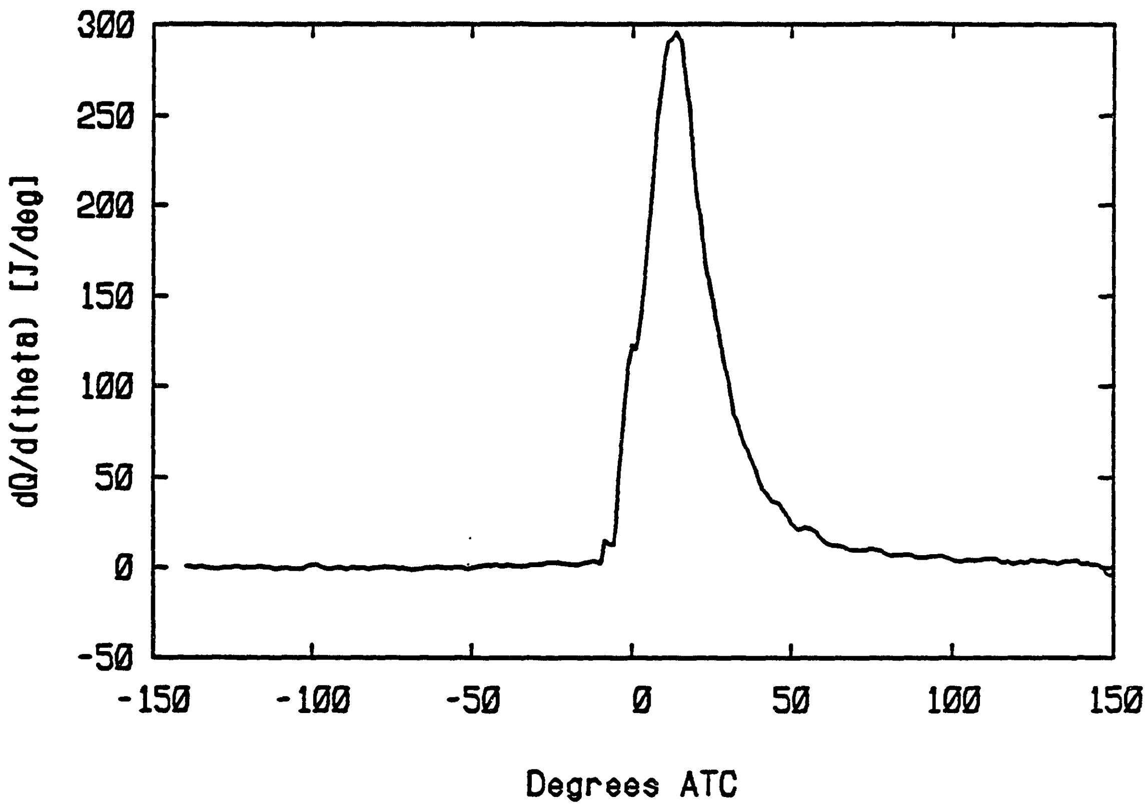


Figure 9. Rate of heat release for base case.

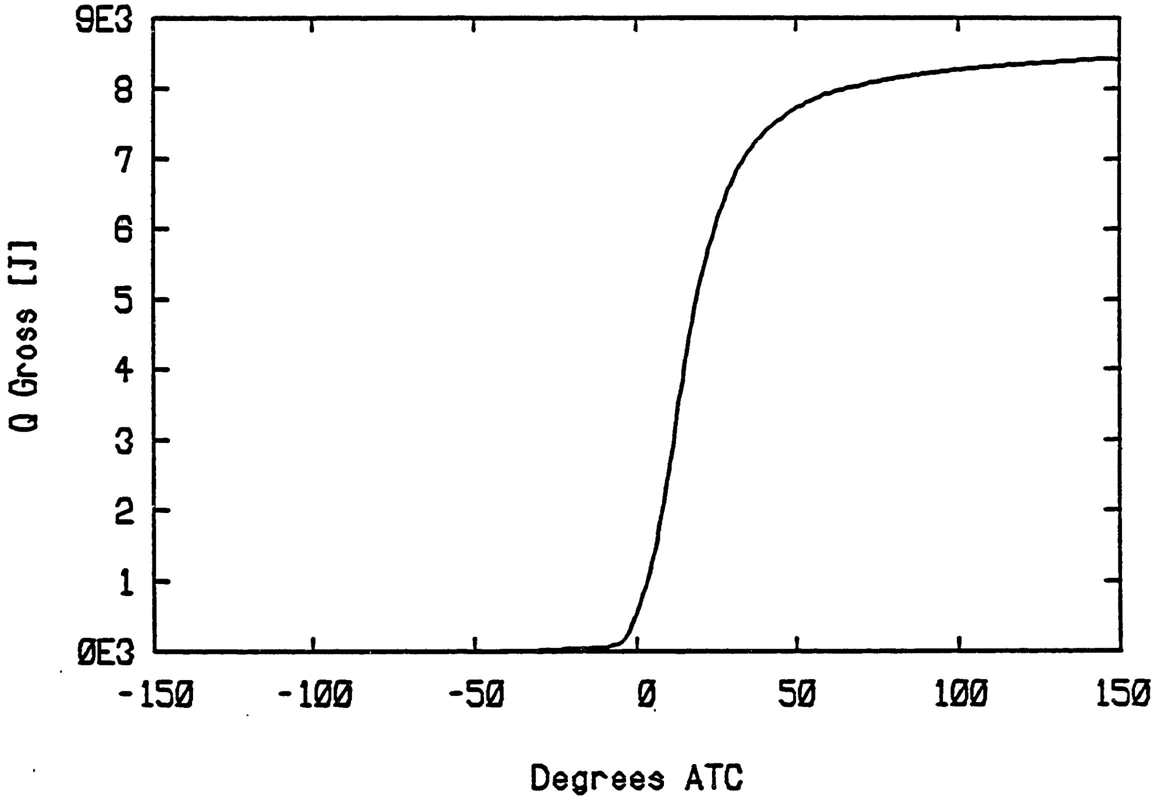


Figure 10. Integrated heat release for base case.

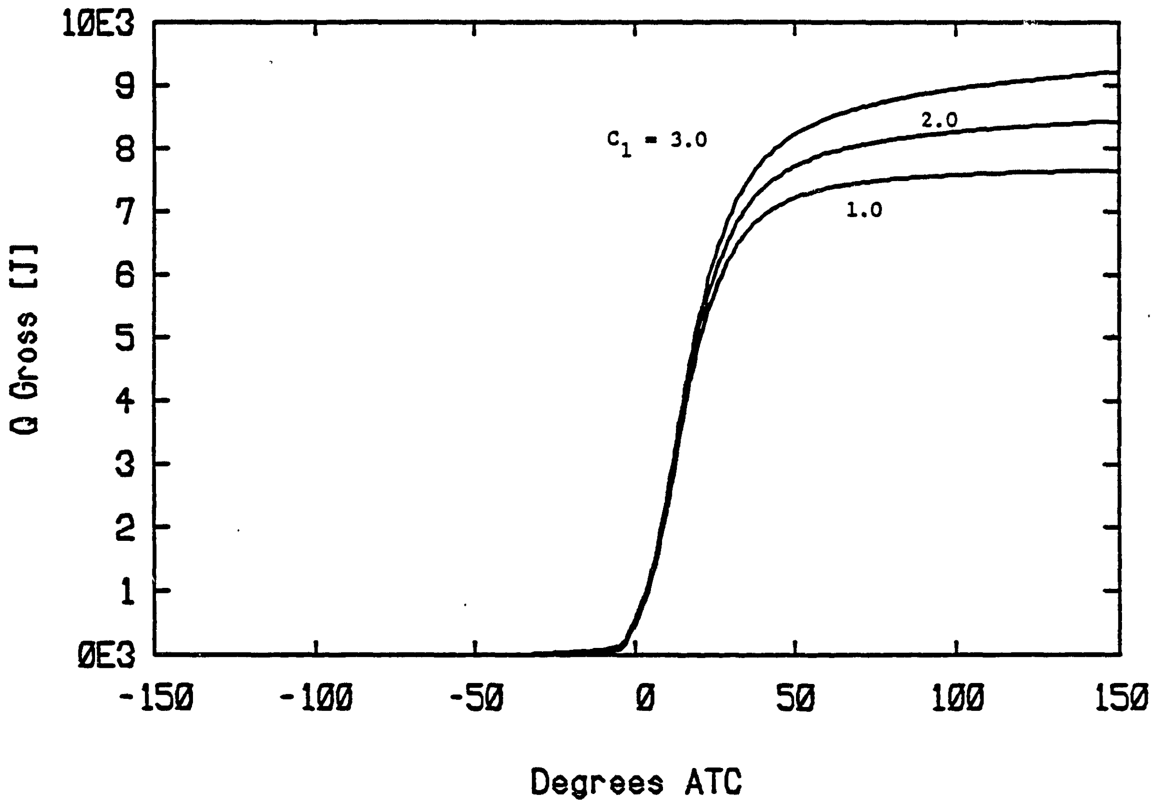


Figure 11. Integrated heat release curves illustrating sensitivity to C_1.

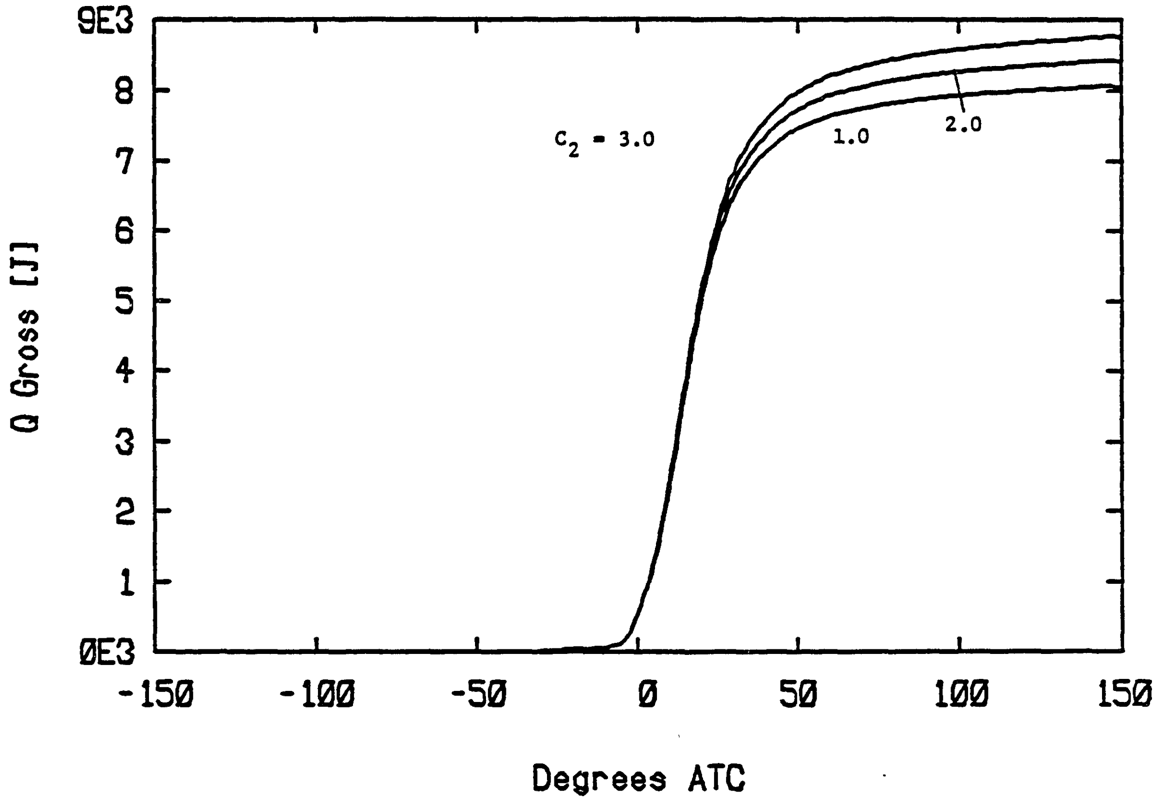


Figure 12. Integrated heat release curves illustrating sensitivity to C_2.

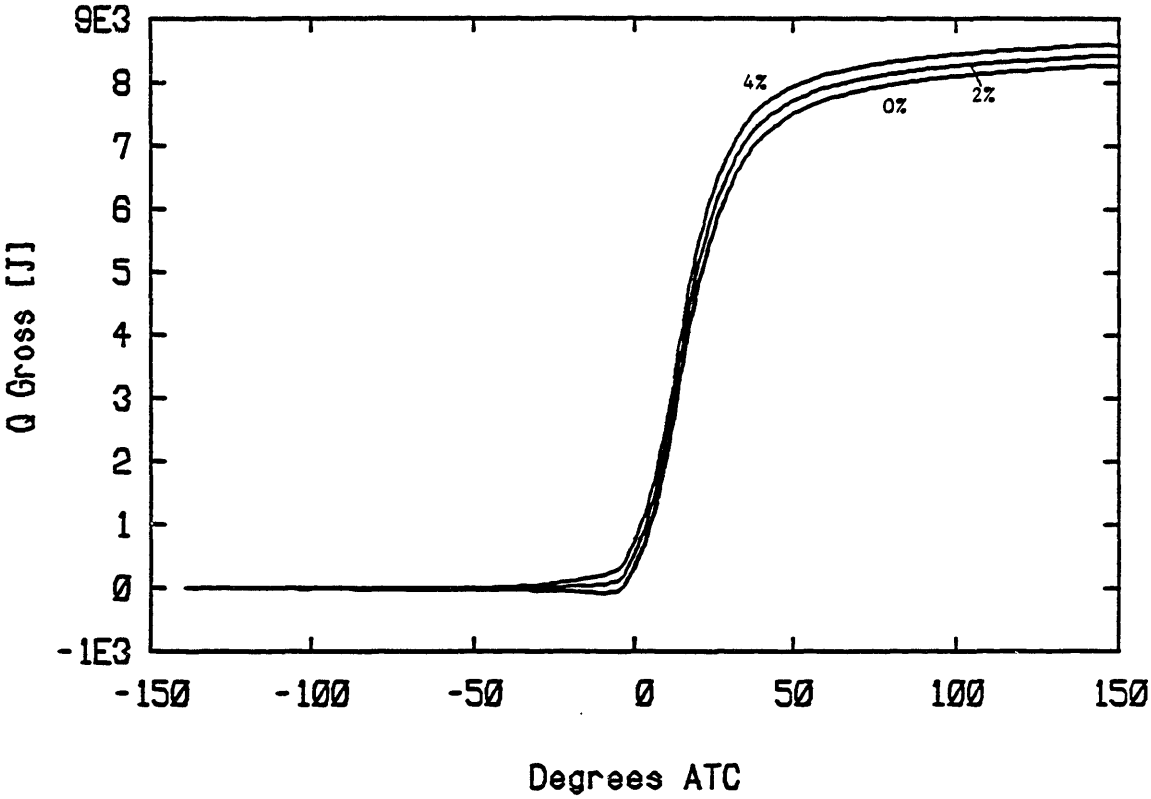


Figure 13. Integrated heat release curves illustrating sensitivity to crevice volume (expressed as percent of clearance volume).

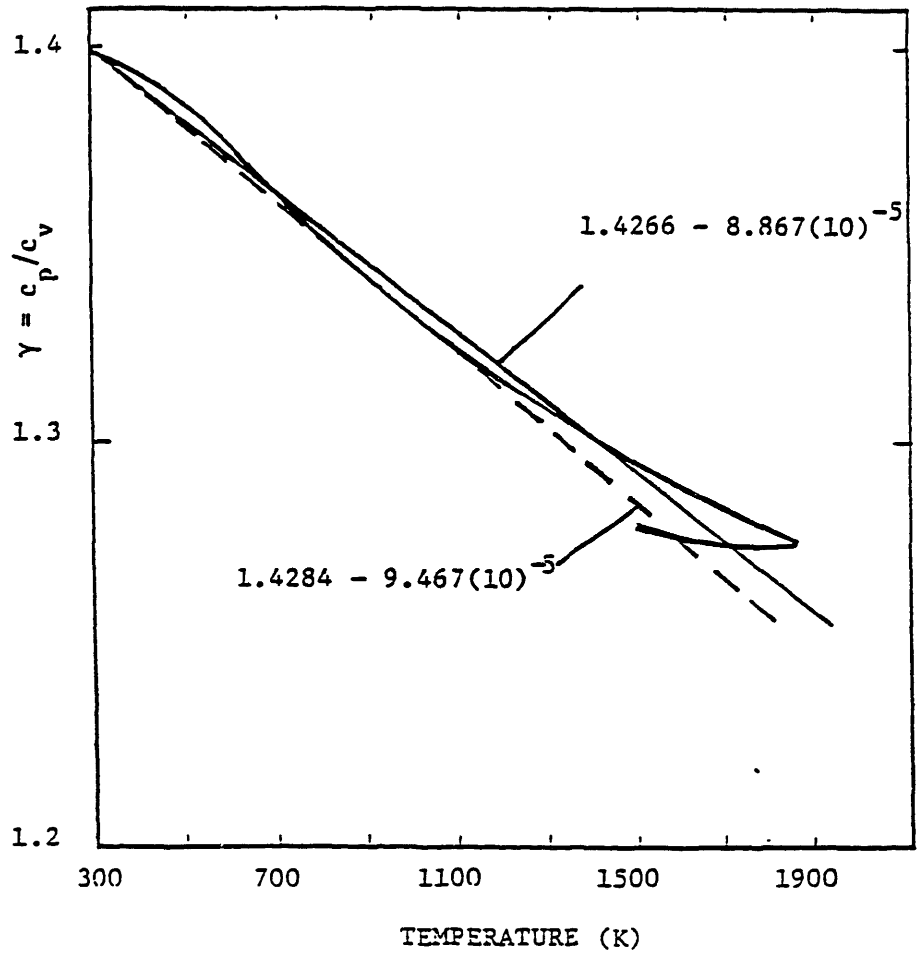


Figure 14. Selected linear functions of temperature for $\gamma(T)$.

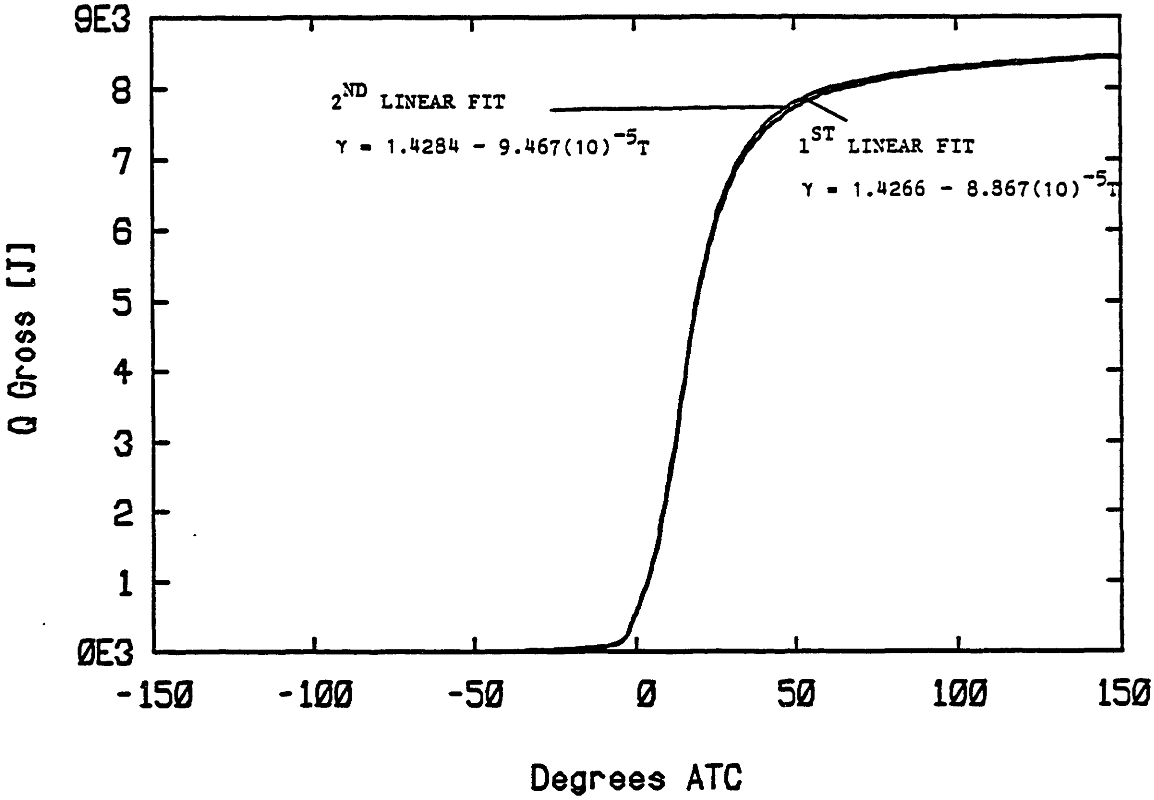


Figure 15. Integrated heat release curves for the two selected linear functions of $\gamma(T)$.

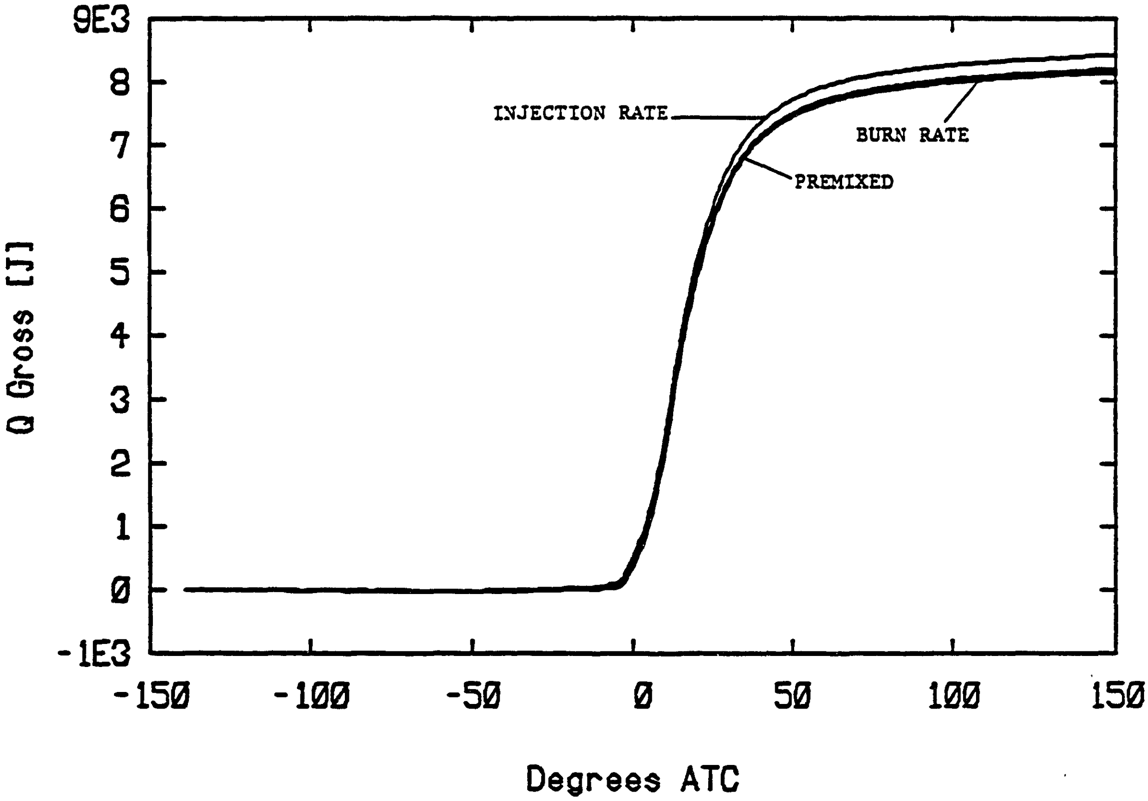


Figure 16. Integrated heat release curves for the two limiting vaporization rates and premixed charge combustion.

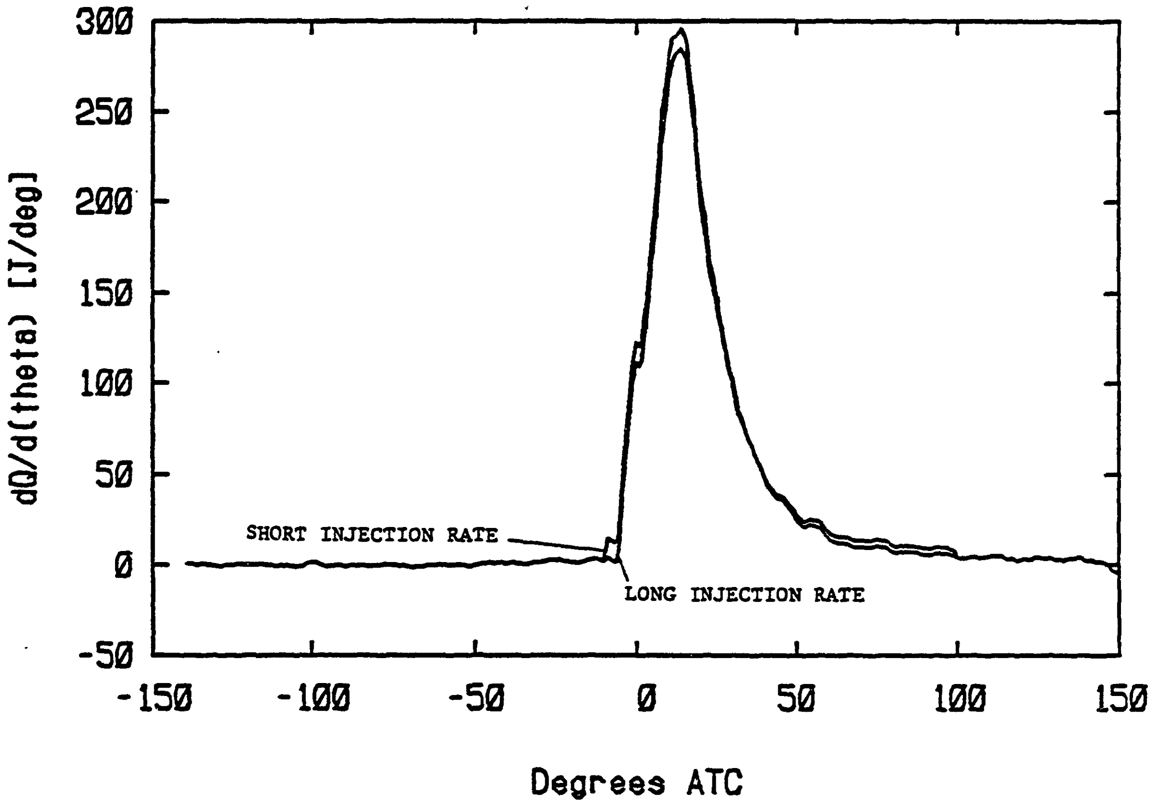


Figure 17. Rate of heat release curves comparing long and short injection duration rates.

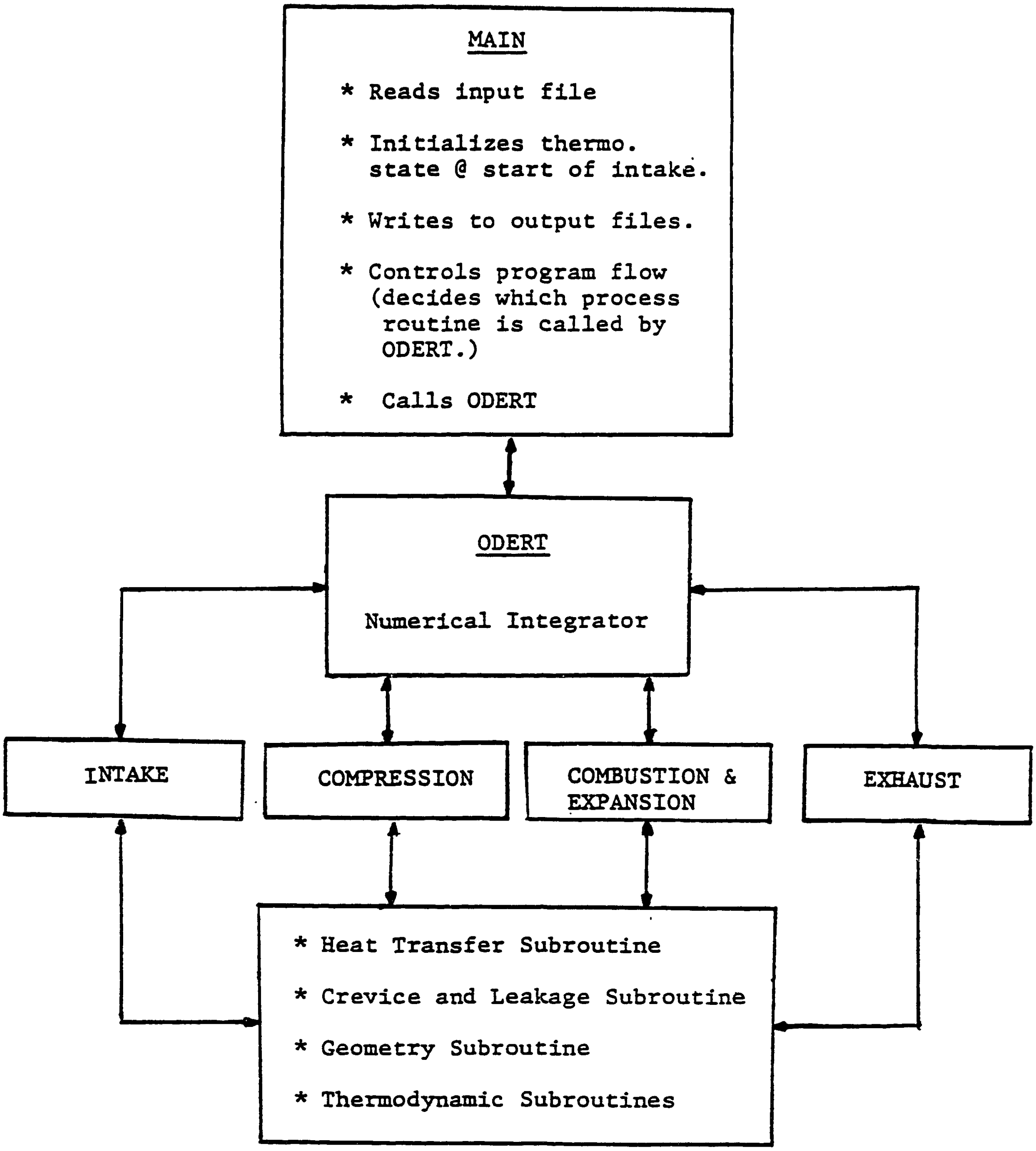


Figure 18. Flow chart of Wankel stratified-charge engine cycle simulation.

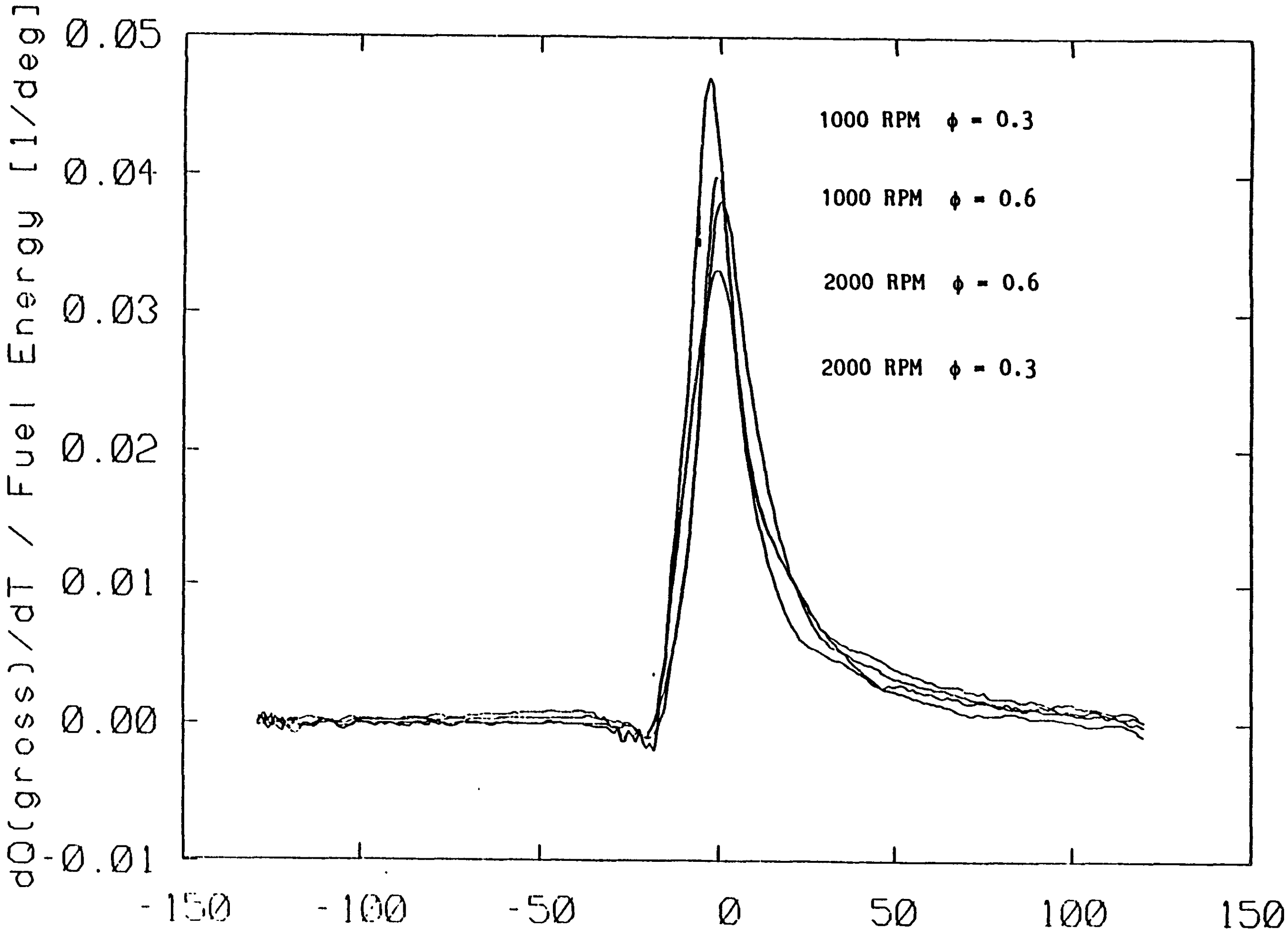


Figure 19. Normalized heat release rate curves for engine speeds of 1000 and 2000 RPM at $\phi = 0.3$ and $\phi = 0.6$.

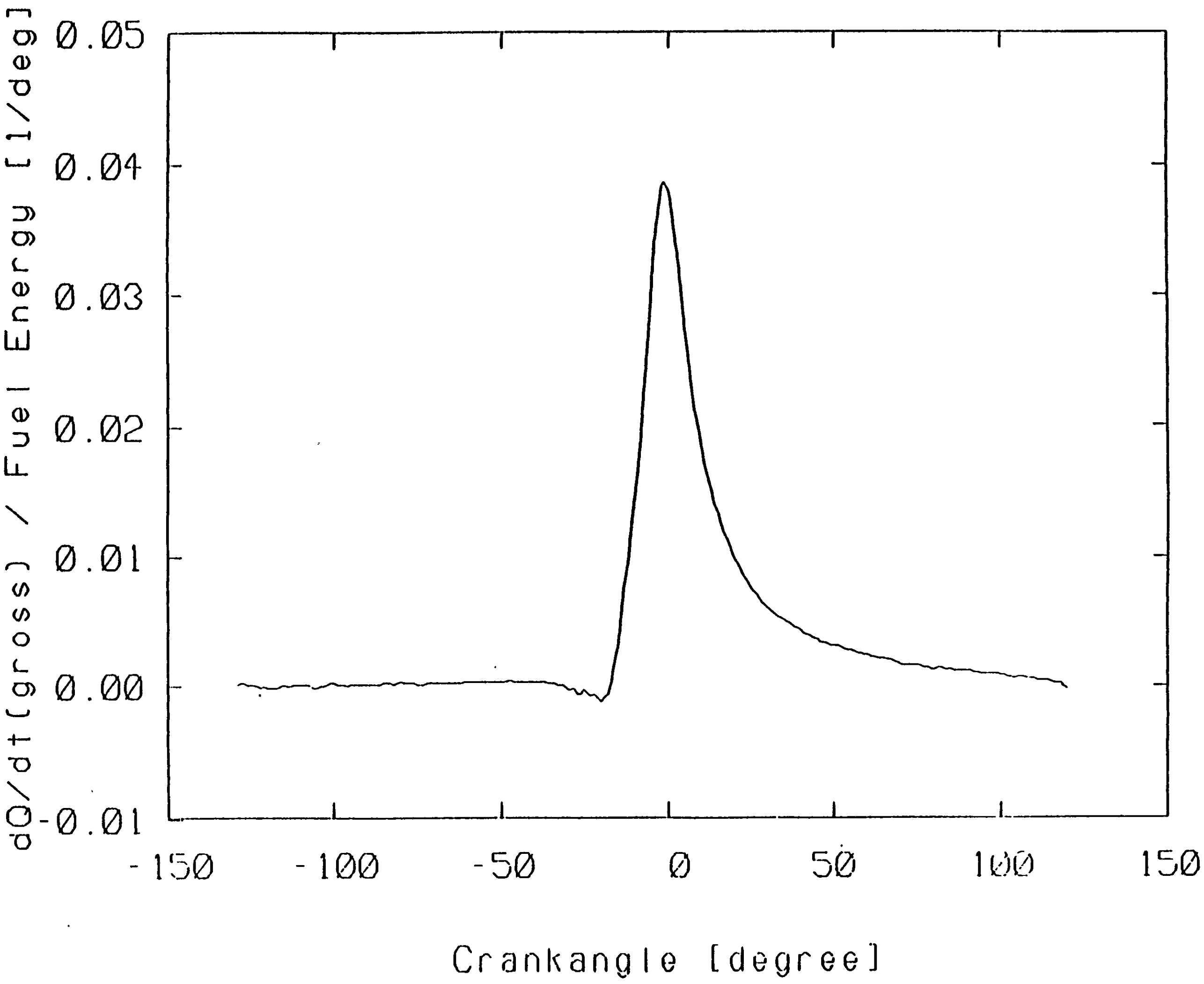


Figure 20. Average normalized heat release rate curve.

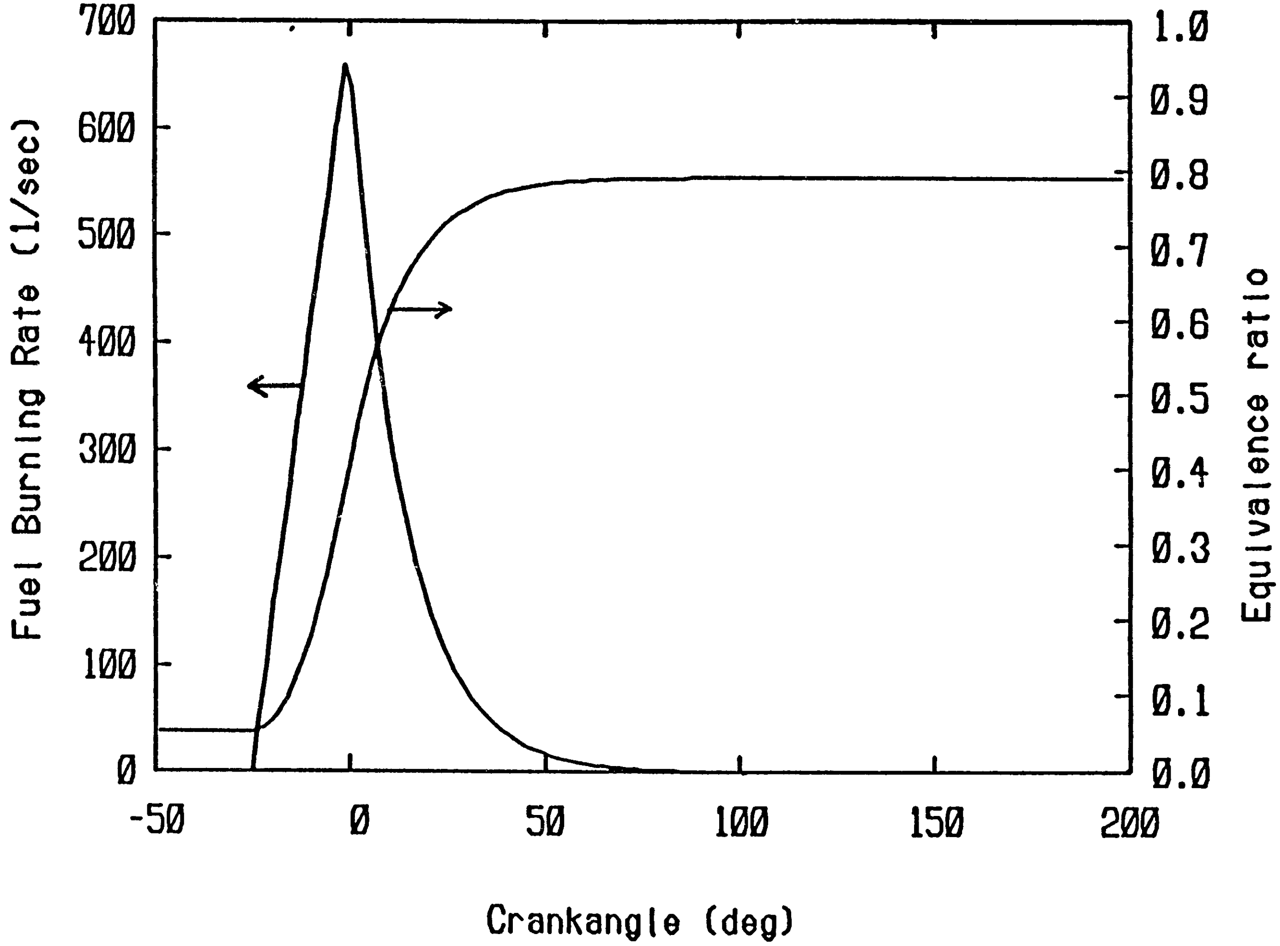


Figure 21. Chamber fuel mass burning rate and instantaneous average overall equivalence ratio.

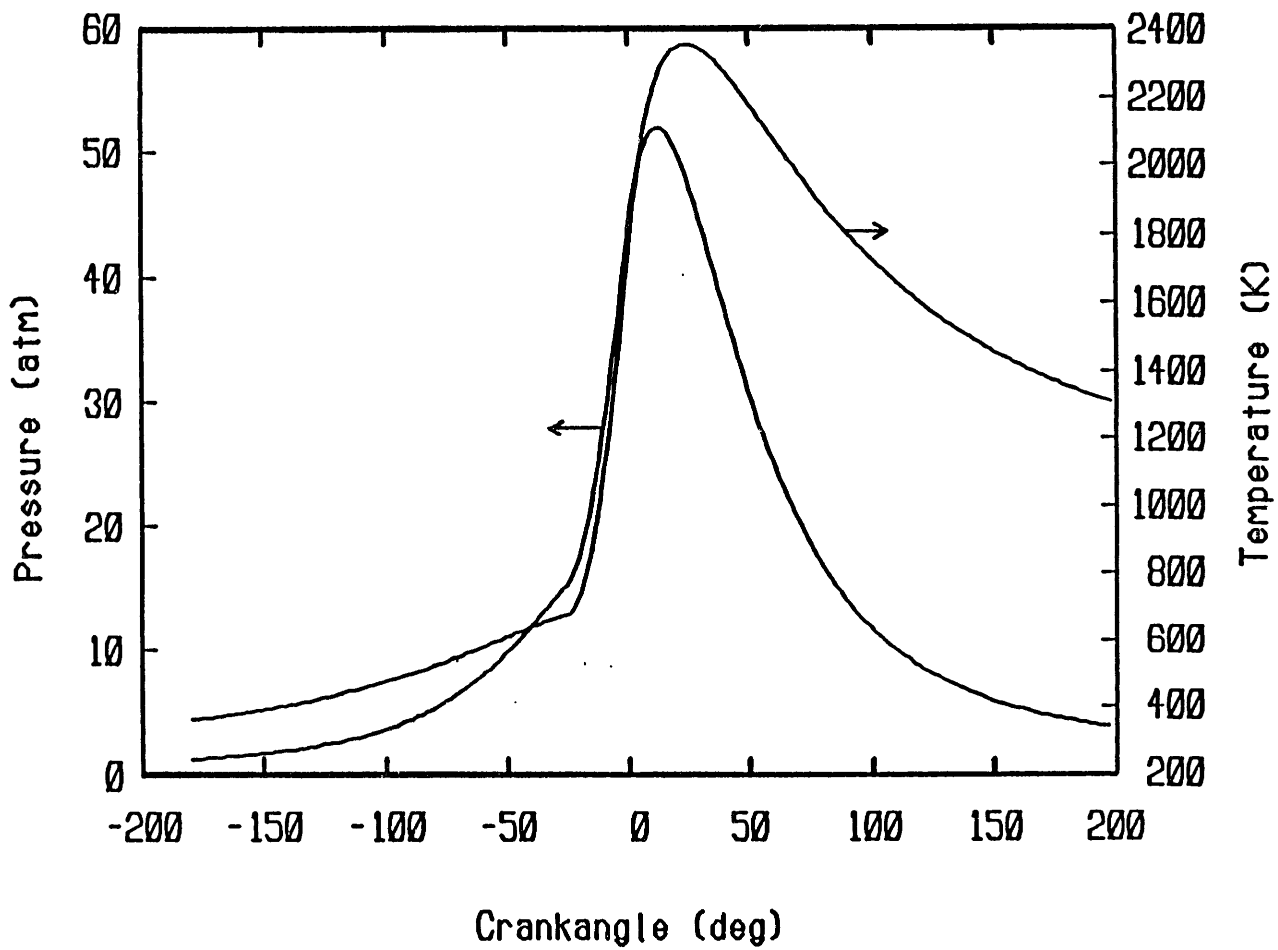


Figure 22. Chamber pressure and temperature for firing run at engine speed of 3000 RPM and equivalence ratio of 0.8 (includes all energy loss mechanisms).

HEAT RELEASE ESTIMATION AND PREDICTION OF WANKEL STRATIFIED-CHARGE COMBUSTION ENGINE

by

JANET MARIE ROBERTS

B.S.M.E. University of Pittsburgh
(1983)

Submitted to the Department of
Mechanical Engineering
in Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

September 1985

Volume 2

VOLUME 2 CONTENTS

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C
C
C
C                ZERO-DIMENSIONAL SIMULATION OF THE
C
C
C          DIRECT-INJECTION STRATIFIED-CHARGE WANKEL ENGINE:
C
C
C                   A PERFORMANCE PREDICTIVE MODEL
C
C
C
C
C
C
C                              BY
C
C
C
C
C                       TIMOTHY J. NORMAN
C
C                       JOHN B. HEYWOOD
C
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C                       S. HOSSEIN MANSOURI
C
C          MODIFIED BY  JANET M. ROBERTS
C                             AUGUST 1985
C
C                  SLOAN AUTOMOTIVE LABORATORY
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C                        FEBRUARY 1983
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C
C
C
C
C
C     PURPOSE
C
C        THE PROGRAM IS A ZERO-DIMENSIONAL SIMULATION OF THE
C
C        DIRECT-INJECTION STRATIFIED-CHARGE WANKEL ENGINE OPERATING CYCLE.
C
C        THE PROGRAM CALCULATES TEMPERATURE AND PRESSURE IN THE
C
C        CHAMBER AND PREDICTS ENGINE PERFORMANCE AS A FUNCTION
C
C        OF ENGINE DESIGN AND OPERATING CONDITIONS.
C
C
C     DESCRIPTION OF PARAMETERS:
C
C        PARAMETER  INPUT  OUTPUT   DESCRIPTION
C
C
C     1  GEOMETRICAL AND DESIGN PARAMETERS
C
C        ECCEN      YES    NO       ECCENTRICITY OF ROTOR (CM)
C        ROTRAD     YES    NO       RADIUS OF ROTOR (CM)
C        DEPTH      YES    NO       HEIGHT OF CHAMBER (CM)
C        VFLANK     YES    NO       VOLUME OF ROTOR POCKET (CM**3)
C        TIPO       YES    NO       INTAKE PORT OPENS (DEG)
C        TIPC       YES    NO       INTAKE PORT CLOSES (DEG)
C        TEPO       YES    NO       EXHAUST PORT OPENS (DEG)
C        TEPC       YES    NO       EXHAUST PORT CLOSES (DEG)
C        THIPO      YES    NO       INTAKE PORT OPENING TIME (DEG)
C        THEPO      YES    NO       EXHAUST PORT OPENING TIME (DEG)
C        IPA        YES    NO       INTAKE PORT OPEN AREA (CM**2)
C        EPA        YES    NO       EXHAUST PORT OPEN AREA (CM**2)
C
C
C     2  OPERATING PARAMETERS
C
C        PATM       YES    NO       ATMOSPHERIC PRESSURE (ATM)
C        TATM       YES    NO       ATMOSPHERIC TEMPERATURE (K)
C        PIM        YES    NO       INTAKE PRESSURE (ATM)
C        PEM        YES    NO       EXHAUST PRESSURE (ATM)
C        TFRESH     YES    NO       FRESH CHARGE TEMPERATURE (K)
C        TEGR       YES    NO       EGR TEMPERATURE (K)
C        EGR        YES    NO       EXHAUST GAS RECIRCULATION (%)
C        TSPARK     YES    NO       IGNITION TIMING (DEG)
C        RPM        YES    NO       ENGINE SPEED (RPM)
C
C
C     3  LEAKAGE AND CREVICE VOLUME SUB-MODEL CONSTANTS
C
```

```
C        AREALK     YES    NO       LEAK AREA PER APEX SEAL (CM**2)
C        CREVOL     YES    NO       CREVICE VOLUME PER APEX SEAL (CM**2)
C        TCREV      YES    NO       CREVICE VOLUME GAS TEMPERATURE (K)
C
C
C     4  HEAT TRANSFER CONSTANTS: NU = CONS'T * (REYNOLDS NO.)**EXP'NT
C
C        CONHT      YES    NO       CONS'T
C        EXPHT      YES    NO       EXP'NT
C        CON1       YES    NO       CONSTANT FOR NON-FIRE CHARACTERISTIC
C                   ---    --       VELOCITY
C        CON2       YES    NO       CONSTANT FOR COMBUSTION
C                   ---    --       CHARACTERISTIC VELOCITY
C        TROTOR     YES    NO       ROTOR SURFACE TEMPERATURE (K)
C        TSIDE      YES    NO       SIDE PLATE SURFACE TEMPERATURE (K)
C        THOUS      YES    NO       HOUSING SURFACE TEMPERATURE (K)
C
C
C
C     5  FUEL AND AIR SPECIFICATIONS
C
C        FUELTP     YES    NO       = 1  :   ISOOCTANE
C        ------     ---    --       = 2  :   PROPANE
C        ------     ---    --                (SEE SUBROUTINE FUELDT)
C        PHI        NO     NO       EQUIVALENCE RATIO
C        CX         NO     NO       NUMBER OF CARBON ATOMS IN THE
C        -----      --     --       FUEL (8.0 FOR C8H18)
C        DEL        NO     NO       MOLAR C:H RATIO OF THE FUEL
C        PSI        NO     NO       MOLAR N:O RATIO OF AIR
C        QLOWER     NO     NO       LOWER HEATING VALUE OF FUEL (MJ/KG)
C        HFORM      NO     NO       ENTHALPY OF INJECTED FUEL (J/G)
C
C
C     6  ERROR TOLERANCES
C
C        AREROT     YES    NO       ERROR TOLERANCE FOR CALCULATING
C        ------     ---    --       ROOTS (SEE SUBROUTINE ODERT).
C        CIINTG     YES    NO       ERROR TOLERANCE FOR INTEGRATION
C        ------     ---    --       DURING INTAKE PROCESS (SEE
C        ------     ---    --       SUBROUTINE ODERT).
C        CCINTG     YES    NO       SAME, DURING COMPRESSION PROCESS
C        CBINTG     YES    NO       SAME, DURING COMBUSTION PROCESS
C        CEINTG     YES    NO       SAME, DURING EXHAUST PROCESS
C        REL        YES    NO       RELATIVE ERROR TOLERANCE FOR
C        ---        ---    --       CONTINUING INTEGRATION TO TOUT
C        ---        ---    --       (SEE MAIN PROGRAM).
C        MAXITS     YES    NO       MAXIMUM NUMBER OF ITERATIONS TO
C        ------     ---    --       COMPLETE CYCLE SIMULATION
C
C
C     7  INITIAL GUESSES AT THE START OF INTAKE PROCESS
C
C        PSTART     NO     NO       INITIAL PRESSURE IN CYLINDER (ATM)
C        TSTART     NO     NO       INITIAL TEMPERATURE IN CYLINDER (K)
```

```
C        PHISTA       YES    NO        INITIAL AVERAGE CHAMBER EQUIVALENCE
C                                      RATIO
C
C
C     8  TIME INCREMENTS
C
C        TPRINT      YES    NO        PRINTING INTERVAL DURING INTAKE,
C        -----       ---    --        COMPRESSION, AND EXHAUST (DEG)
C        TPRINX      YES    NO        PRINTING INTERVAL DURING COMBUSTION
C        -----       ---    --        AND EXPANSION(DEG)
C
C
C     9  OPERATING CASE
C
C        FIRE        YES    NO        = .TRUE.  FOR FIRING CASE
C        ----        ---    --        = .FALSE. FOR MOTORING CASE
C        SPBURN      YES    NO        = .TRUE.  FOR SPECIFIED BURN RATE
C        ----        ---    --        = .FALSE. NOT USED IN THIS PROGRAM
C
C
C    10  COMBUSTION MODEL INPUTS
C
C        XBZERO      YES    NO        INITIAL MASS FRACTION BURNED
C        ------      ---    --        (INITIALIZES COMBUSTION MODEL)
C        XBSTOP      YES    NO        MASS FRACTION BURNED AT END OF
C        ------      ---    --        COMBUSTION.
C        TMAX        YES    NO        ANGLE OF MAX HEAT RELEASE
C        DQDTMAX     YES    NO        MAX RATE OF HEAT RELEASE
C
C
C
C     REMARKS
C        NONE
C
C
C     SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED:
C
C     1  WORKING SUBROUTINES
C
C        INTAKE     CMPRES     CMBSTN     EXAUST    CREVIC
C        GINT1      GINT2      GCMP       GEXH
C
C
C     2  SPECIAL UTILITY SUBROUTINES
C
C        IPACD      EPACD      CSAVDV     TABLE     BUILD
C
C
C     3  GENERAL UTILITY SUBROUTINES
C
C        HPROD      CLDPRD     HELPHT
C        UTRANS     BTRANS     MFLRT      THERMO
C        FUELDT     WRITE      ERRCHK     INTRP     ITRATE
C        ODERT      DERT1      ROOT       STEP1
```

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C
C
C     METHOD
C        SEE REPORT
C
C     WRITTEN BY  S. G. POULOS, S. H. MANSOURI, AND T. J. NORMAN
C     EDITED BY T. J. NORMAN
C     EDITED BY J. M. ROBERTS
C
C
      LOGICAL FIRE, SPBURN
      INTEGER FUELTP
      REAL*8 DT, DY(30), TOUT, RELERR, ABSERR, WORK, REROOT, AEROOT
      REAL MW, MWIM, MSTART, MASS, MAXERR, IPA, MFUEL
      DIMENSION Y(30), YP(30), WORK(730), IWORK(5)
      COMMON/EPARAM/ ECCEN, ROTRAD, DEPTH, VFLANK
      COMMON/TEMPS/TROTOR,TSIDE,THOUS
      COMMON/MANFP/ PIM, TIM, EGR, PEM, MSTART
      COMMON/BURN/ SPBURN, FIRE, FIREFL
      COMMON/DTDTH/ ESPDI, RPM
      COMMON/TIMES/ TIPO, TIPC, TEPO, TEPC, THIPO, THEPO, TSPARK
      COMMON/PORTS/ IPA, EPA
      COMMON/IMTHP/ HIM, MWIM, GIM, RHOIM
      COMMON/FUEL/ FUELTP, ENW, CX, HY, OZ, DEL, PSI, PHICON, PHI,
     &             QLOWER, FASTO, HFORM
      COMMON/FIXX/ INFLAG
      COMMON/HEATS/VELHTX, HTRCOE, HTPARO, HTPASI, HTPAHO, HTXRO,
     &             HTXSI, HTXHO, QFRRO, QFRSI, QFRHO
      COMMON/HTRAN/THTRAN
      COMMON/YYYY1/ VIP, VEP
      COMMON/ITRLIM/ MAXTRY, MAXERR
      COMMON/RHMAS/ RHO, MASS, VOLUME, H, GAMMA
      COMMON/SPECB/ TMAX, TAU, DQDTMAX
      COMMON/XSTOP/ XBSTOP
C
C
      COMMON/CREV/DRHODP,CSUBT,MW,ITERAS,DVDT,CSUBP,DRHODT,HIMM,RESIDL,
     &           RESFIM,CSUBF,DRHODF
      COMMON/CREVIN/AREALK,CREVOL,TCREV,X1LDIN,X1LGIN,FRLDIN,FRLGIN
      COMMON/CREVQ/CRMASD,CRMASG,X1LDC,X1LAGC,ZMAST,ZMASS,ZLEAKD,ZLEAKG,
     &             ZCRCOD,ZCRCOG,FRZCRCOD,FRZCRCOG
      COMMON/TABLES/ PRES(0:1080), X1(0:1080), FUELFR(0:1080)
      COMMON/HEATXG/AROTOR,ASIDE,AHOUS,ROTVEL,DCHAR
      COMMON/HTTXIN/CONHT,EXPHT,CON1,CON2
      COMMON/FLFR/FSTART
      COMMON/FLOW/FMIN,MFUEL
C
      NAMELIST/INPUT/ FIRE, SPBURN, FUELTP, PHISTA, ECCEN, ROTRAD,
     &  DEPTH, VFLANK, RPM, TIPO, TIPC, TEPO, TEPC, TSPARK, THIPO,
     & THEPO, IPA, EPA, XBZERO, XBSTOP, TMAX,
     & DQDTMAX, PATM, TATM, PIM, TFRESH, TEGR, EGR, PEM, TROTOR,
     & TSIDE, THOUS, CONHT, EXPHT, TPRINT, TPRINX, AREROT, CIINTG,
     & CCINTG, CBINTG, CEINTG, MXTRY, REL, MAXITS, MAXERR,
     & MAXTRY, AREALK, CREVOL, TCREV,  CON1, CON2
```

```
C
      EXTERNAL INTAKE, CMPRES, CMBSTN, EXAUST, GINT1, GINT2, GCMP,
     &         GCMB, GEXH
C
C@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
C
C        STANDARD DATA SET -- OVERRIDE BY USING NAMELIST INPUT
C
C--------------------
      FIRE   = .TRUE.
      SPBURN = .TRUE.
      FUELTP =  1
      PHISTA =  1.00
C--------------------
      ECCEN  =  1.50
      ROTRAD = 10.5
      DEPTH  =  7.00
      VFLANK = 35.00
      RPM    = 3000.
C--------------------
      TIPO   = -530.0
      TIPC   = -180.0
      TEPO   = 199.0
      TEPC   = 588.5
      TSPARK = - 30.0
      THIPO  = 120.0
      THEPO  = 40.0
      IPA    = 13.8
      EPA    = 6.5
C--------------------
      XBZERO = 0.0003
      XBSTOP = 0.995
      TMAX   = 0.0
      DQDTMAX= 0.04
C--------------------
      PATM   = 1.0
      TATM   = 300.0
      PIM    = 0.98
      TFRESH = 300.0
      TEGR   = 300.0
      EGR    = 0.0
      PEM    = 1.02
C--------------------
      TROTOR = 370.0
      TSIDE  = 370.0
      THOUS  = 370.0
      CONHT  = 0.0377
      EXPHT  = 0.8
C--------------------
      TPRINT = 10.0
      TPRINX = 1.0
C--------------------
      AREROT = .0002
      CIINTG = 0.0001
```

```
      CCINTG = 0.0001
      CBINTG = 0.00005
      CEINTG = 0.0001
      MXTRY  = 1
      REL    = .0002
      MAXITS = 3
      MAXERR = 0.03
      MAXTRY = 2
C-------------------
      AREALK = 0.01
      CREVOL = 0.875
      TCREV  = 370
C-------------------
      CON1   = 0.75
      CON2   = 0.324
C-------------------
C
C
C        READ NAMELIST INPUT
C
      READ (8,INPUT)
C
      ESPDI  = 1./(6. * RPM)
C
C
C         TO ALLOW A NORMALIZED OUTPUT INTO DUMMY1 DATA FILE GIVE
C         ZMAST (MASS AT TIPC) A VALUE OF UNITY UNTIL INTAKE PORT CLOSES
C
      ZMAST = 1.
C
C         CALCULATE COMPRESSION RATIO
C
      PI=3.1415926539
      ROOT3 = SQRT(3.0)
      DVOLUM = 3. * ROOT3 * ECCEN * ROTRAD * DEPTH
      ALEAN  = ASIN( 3.*ECCEN/ROTRAD)
      FH     = 1.5 * ROOT3 * ECCEN * ROTRAD
      FC     = 2. * ECCEN * ROTRAD * COS( ALEAN ) +
     &         ( 2/9.*ROTRAD*ROTRAD + 4.*ECCEN*ECCEN ) * ALEAN +
     &         PI/3. * ECCEN*ECCEN
      CMRTIO = (( FH + FC )*DEPTH + VFLANK)/(( FC- FH )*DEPTH + VFLANK)
C
C        CALCULATE ALL FUEL-RELATED PARAMETERS
C
C
C
      CALL FUELDT
C
C        MAKE INITIAL GUESSES FOR FIRST CYCLE ITERATION
C
      PSTART = 1.1
      TSTART = 330.
C
C         CALCULATE INITIAL CHAMBER FUEL FRACTION
```

```
C
      FSTART = PHISTA / ( PHISTA + 1./FASTO )
C
      IF (FIRE) PSTART = 1.015
      IF (FIRE) TSTART =  900.
      IF (.NOT.FIRE) FSTART = 0.0
      FMIN = 0.0
C
C        FIND THERMODYNAMIC STATE OF INTAKE CHARGE
C
      CALL THERMO (TIPO, TFRESH, PIM, 0.0, HFRESH, XXA, XXB, XXC,
     &              XXD, XXE, XXF, XXG, XXH, XXI, XXJ, XXK, XXL, XXM)
      CALL THERMO (TIPO, TEGR, PIM, FSTART, HEGR, XXA, XXB, XXC,
     &              XXD, XXE, XXF, XXG, XXH, XXI, XXJ, XXK, XXL, XXM)
      HIM = (1. - EGR/100.)*HFRESH + (EGR/100.)*HEGR
      RESFIM = EGR/100.
      TGUESS = (1. - EGR/100.)*TFRESH + (EGR/100.)*TEGR
      CALL ITRATE (TIPO, TGUESS, PIM, RESFIM, HIM,
     &              CSUBPI, CSUBTI, CSUBFI,
     &              RHOIM, DRODTI, DRODPI, DRODFI,
     &              GIM, MWIM)
      TIM = TGUESS
C
C
C***********************************************************************
C
C        START OF CURRENT CYCLE ITERATION
C
C***********************************************************************
C
      DO 470 ITERAS = 1, MAXITS
C
      WRITE (7,449) ITERAS, MAXITS
C
C        CALCULATE MASS IN CYLINDER
C
      RESFRK = 0.0
      IF (FIRE) RESFRK = 1.0
      IF (.NOT. FIRE) EGR = 0.0
      CALL THERMO (TIPO, TSTART, PSTART, FSTART, ENTHLP,
     &       CSUBP, CSUBT, CSUBF, RHO, DRHODT, DRHODP, DRHODF,
     &       GAMMA, MW, XXA, XXB, XXC, XXD)
      CALL CSAVDV (TIPO, VOLUME, DVDT)
      MSTART = RHO * VOLUME/1000.
C
C
C        WRITE MAIN HEADINGS AND ECHO INPUT PARAMETERS
C
    5 WRITE  (16,3333)
      WRITE  (16,3333)
      WRITE  (16,2901)
      WRITE  (16,3333)
      WRITE  (16,3333)
      WRITE  (16,77)
```

```
      WRITE  (16,3333)
      WRITE  (16,2902)
      IF (FIRE) WRITE (16,2903)
      IF (.NOT. FIRE) WRITE (16,2904)
      IF (SPBURN .AND. FIRE) WRITE (16,2905)
      IF (SPBURN .AND. FIRE) WRITE (16,2906) DQDTMAX, TMAX
      IF (.NOT. SPBURN .AND. FIRE) WRITE (16,2907)
      WRITE  (16,3333)
      WRITE  (16,2908)
      IF (FIRE .AND. FUELTP .EQ. 1) WRITE (16,2909)
      IF (FIRE .AND. FUELTP .EQ. 2) WRITE (16,2910)
      IF (FIRE) WRITE (16,2911) PHISTA
      IF (FIRE .AND. ((PHISTA .GT. 1.3) .OR. (PHISTA .LT. 0.7)))THEN
           WRITE (16,999)
      ENDIF
      IF (FIRE .AND. ((PHISTA .GT. 1.3) .OR. (PHISTA .LT. 0.7)))THEN
           WRITE (7,999)
      ENDIF
      IF (FIRE) WRITE  (16,2912) TSPARK
      WRITE (16,2913) RPM
      WRITE  (16,3333)
      WRITE  (16,2914)
      WRITE  (16,2915) PIM, PEM, TFRESH, EGR, TEGR, TIM, PATM, TATM
      WRITE  (16,3333)
      WRITE  (16,2916)
      WRITE  (16,2917) CONHT, EXPHT, TROTOR, TSIDE, THOUS
      WRITE  (16,3333)
      WRITE  (16,2918)
      WRITE  (16,2919) ECCEN, ROTRAD, DEPTH, CMRTIO, DVOLUM,
     &                VFLANK, TIPO, TIPC, TEPO, TEPC
      WRITE  (16,3333)
      WRITE  (16,2940)
      WRITE  (16,2941) AREALK, CREVOL, TCREV
      WRITE  (16,3333)
      WRITE  (16,2920)
      WRITE  (16,2921) MAXITS, ITERAS, TPRINT, TPRINX, XBZERO, XESTOP,
     &                XBSTOP, CIINTG, CCINTG, CBINTG, CEINTG, AREROT,
     &                REL, ERMAX, MAXERR, MAXTRY
      WRITE  (16,3333)
      WRITE  (16,3333)
      WRITE  (16,2225)
      WRITE (10,2225)
      WRITE (13,2225)
C
      WRITE  (16,4595)
      WRITE  (16,4596)
      WRITE  (16,3333)
      WRITE (10,8111)
      WRITE (10,9900)
      WRITE (10,3333)
      WRITE (13,7111)
      WRITE (13,4592)
      WRITE (13,3333)
C
```

```
C        INITIALIZE PARAMETERS FOR CALL TO SUBROUTINE ODERT
C
      Y(1)  = 0.0
      Y(2)  = 0.0
      Y(3)  = 0.0
      Y(4)  = 0.0
      Y(5)  = 1.0
      IF (FIRE) Y(5) = 0.0
CJ    Y(6) REMOVED
CJ    Y(7) REMOVED
      Y(8)  = 0.0
      Y(9)  = 0.0
      Y(10) = 0.0
      Y(11) = TSTART
      Y(12) = PSTART
      Y(13) = 0.0
      Y(14) = 0.0
      Y(15) = 0.0
      Y(16) = 0.0
      Y(17) = 0.0
      Y(18) = 0.0
      Y(19) = 0.0
      Y(20) = 0.0
      Y(21) = X1LDIN
      Y(22) = X1LGIN
      Y(23) = MSTART
      Y(24) = 0.0
      Y(25) = 0.0
      Y(26) = FSTART
      Y(27) = RESFIM
      Y(28) = FSTART
      Y(29) = FRLDIN
      Y(30) = FRLGIN
C
      HEATI = 0.0
      WORKI =.0.0
      VIP = 0.0
C
      DO 10 I = 1, 30
           DY(I) = Y(I)
   10 CONTINUE
      WRITE (16,1277) TIPO, DY(12), DY(11), DY(1), DY(2), VIP,
     &                 DY(5), DY(16)
      AEROOT = ARerot
      REROOT = AREROT
C
C###########################################################################
C
C        START OF INTAKE PROCESS (TIPO - TIPC)
C
C###########################################################################
C
   20 I = 0
      MFUEL = 0.0
```

```
      NEQN = 30
      IFLAG = 1
      T = TIPO
      TEND = -270.
      DT = T
C
C        CHECK WHICH WAY INTAKE FLOWS AT CYCLE START
C
   30 I = I + 1
      IFLAG = 1
      IF (DY(12) .GT. PIM) GO TO 90
C
C        INTAKE FLOW INTO CHAMBER OF NEW CHARGE
C        ( FRESH AIR + EGR ); SET INFLAG = 1
C
   40 INFLAG = 1
C
C
      NCALL = IFIX( ABS(TEND - T) )
      IF (NCALL .LE. 0) GO TO 70
C
C        NCALL:  NO. OF TIMES INTEGRATING SUBROUTINE IS CALLED
C
      DO 60 NC = 1, NCALL
           TOUT = INT (T + 1.)
   50      ABSERR = CIINTG
           RELERR = CIINTG
C
           CALL ODERT (INTAKE, NEQN, DY, DT, TOUT, RELERR, ABSERR,
     &                  IFLAG, WORK, IWORK, GINT1, REROOT, AEROOT)
           CALL HELPHT (DT, DY, 1)
C
           T = DT
C
C          SUBROUTINE BUILD CONSTRUCTS THE PRESSURE HISTORY OF
C          THE CHAMBER AND STORES THE CREVICE GAS COMPOSITIONS
C          WHEN AVAILABLE.
C
           CALL BUILD (DT,DY)
C
       TWRITE = T/TPRINT
C
C           IFLAG IS THE RETURN CODE FROM ODERT. IFLAG NOT EQUAL
C           TO 2 OR 8 IS ABNORMAL AND SHOULD BE CHECKED (REFER
C           TO SUBROUTINE ODERT).
C
       IF ( IFLAG .NE. 2 ) GO TO 55
       IF ( TWRITE .NE. INT(TWRITE) ) GO TO 56
C
   55  WRITE  (7,881) DT, DY(12), INFLAG, IFLAG
       WRITE  (16,1210) DT, DY(12), DY(11), DY(1), DY(2), VIP,
     &                     VEP, DY(5), THTRAN, DY(16), INFLAG, IFLAG
       WRITE (10,9210) DT,DY(23),CRMASD,CRMASG,DY(18),DY(19),
     &                     FRZCRCOD,FRZCRCOG
```

```
      WRITE (13,4210) DT, VELHTX, HTPARO, HTPASI, HTPAHO,
     &                    QFRRO, QFRSI, QFRHO
C
   56 CONTINUE
          IF (ABS(T/TEND - 1.0) .LE. REL) GO TO 190
          IF (IFLAG .EQ. 8) GO TO 90
C
C            I.E. REVERSE FLOW ACROSS INTAKE PORT.
C
          IF (IFLAG .NE. 2) GO TO 50
   60 CONTINUE
C
C        NO ROOT FOR GINT1; COMPLETE INTAKE PROCESS.
C
   70 TOUT = TEND
   80 ABSERR = CIINTG
      RELERR = CIINTG
C
      CALL ODERT (INTAKE, NEQN, DY, DT, TOUT, RELERR, ABSERR,
     &            IFLAG, WORK, IWORK, GINT1, REROOT, AEROOT)
      CALL HELPHT (DT, DY, 1)
C
          T = DT
          CALL BUILD (DT,DY)
C
       TWRITE = T/TPRINT
       IF ( IFLAG .NE. 2 ) GO TO 85
       IF ( TWRITE .NE. INT(TWRITE) ) GO TO 86
C
   85 WRITE  (7,881)  DT, DY(12), INFLAG, IFLAG
      WRITE  (16,1210) DT, DY(12), DY(11), DY(1), DY(2), VIP,
     &                 VEP, DY(5), THTRAN, DY(16), INFLAG, IFLAG
      WRITE (10,9210) DT,DY(23),CRMASD,CRMASG,DY(18),DY(19),
     &                FRZCRCOD,FRZCRCOG
      WRITE (13,4210) DT, VELHTX, HTPARO, HTPASI, HTPAHO,
     &                QFRRO, QFRSI, QFRHO
C
   86 CONTINUE
      IF (ABS(T/TEND - 1.0) .LE. REL) GO TO 190
      IF (IFLAG .EQ. 8) GO TO 90
      IF (IFLAG .NE. 2) GO TO 80
C
C        ROOT FOUND FOR GINT1; FLOW ACROSS INTAKE PORT
C        REVERSES AND FLOWS INTO INTAKE MANIFOLD.  FIND
C        ROOT WHEN FLOW ONCE AGAIN REVERSES DIRECTION.
C
   90 INFLAG = 0
      NCALL = IFIX( ABS(TEND - T) )
      IF (NCALL .LE. 0) GO TO 120
      DO 110 NC = 1, NCALL
          TOUT = INT(T + 1.)
  100     ABSERR = CIINTG
          RELERR = CIINTG
C
```

```
          CALL ODERT (INTAKE, NEQN, DY, DT, TOUT, RELERR, ABSERR,
     &               IFLAG, WORK, IWORK, GINT1, REROOT, AEROOT)
          CALL HELPHT (DT, DY, 1)
C
          T = DT
          CALL BUILD (DT,DY)
C
      TWRITE = T/TPRINT
      IF ( IFLAG .NE. 2 ) GO TO 105
      IF ( TWRITE .NE. INT(TWRITE) ) GO TO 106
  105 WRITE  (7,881)  DT, DY(12), INFLAG, IFLAG
      WRITE  (16,1210) DT, DY(12), DY(11), DY(1), DY(2), VIP,
     &                    VEP, DY(5), THTRAN, DY(16), INFLAG, IFLAG
      WRITE (10,9210) DT,DY(23),CRMASD,CRMASG,DY(18),DY(19),
     &                FRZCRCOD,FRZCRCOG
      WRITE (13,4210) DT, VELHTX, HTPARO, HTPASI, HTPAHO,
     &                    QFRRO, QFRSI, QFRHO
C
  106  CONTINUE
          IF (ABS(T/TEND - 1.0) .LE. REL) GO TO 190
          IF (IFLAG .EQ. 8) GO TO 140
          IF (IFLAG .NE. 2) GO TO 100
  110 CONTINUE
  120 TOUT = TEND
  130 ABSERR = CIINTG
      RELERR = CIINTG
C
      CALL ODERT (INTAKE, NEQN, DY, DT, TOUT, RELERR, ABSERR,
     &            IFLAG, WORK, IWORK, GINT1, REROOT, AEROOT)
      CALL HELPHT (DT, DY, 1)
C
          T = DT
          CALL BUILD (DT,DY)
C
      TWRITE = T/TPRINT
      IF ( IFLAG .NE. 2 ) GO TO 135
      IF ( TWRITE .NE. INT(TWRITE) ) GO TO 136
  135 WRITE  (7,881)  DT, DY(12), INFLAG, IFLAG
      WRITE  (16,1210) DT, DY(12), DY(11), DY(1), DY(2), VIP,
     &                    VEP, DY(5), THTRAN, DY(16), INFLAG, IFLAG
      WRITE (10,9210) DT,DY(23),CRMASD,CRMASG,DY(18),DY(19),
     &                    FRZCRCOD,FRZCRCOG
      WRITE (13,4210) DT, VELHTX, HTPARO, HTPASI, HTPAHO,
     &                QFRRO, QFRSI, QFRHO
C
  136 IF (ABS(T/TEND - 1.0) .LE. REL) GO TO 190
      IF (IFLAG .EQ. 8) GO TO 140
      IF (IFLAG .NE. 2) GO TO 130
C
C       ROOT FOUND FOR GINT1; FLOW ACROSS INTAKE PORT HAS
C       REVERSED DIRECTION.  FIND ROOT WHEN ALL MASS THAT HAS
C       FLOWN INTO INTAKE MANIFOLD FLOWS BACK INTO CYLINDER.
C
  140 INFLAG = 0
```

```
      NCALL = IFIX( ABS(TEND - T) )
      IF (NCALL .LE. 0) GO TO 170
      DO 160 NC = 1, NCALL
           TOUT = INT( T + 1.)
  150      ABSERR = CIINTG
           RELERR = CIINTG
C
           CALL ODERT (INTAKE, NEQN, DY, DT, TOUT, RELERR, ABSERR,
     &                 IFLAG, WORK, IWORK, GINT2, REROOT, AEROOT)
           CALL HELPHT (DT, DY, 1)
C
           CALL BUILD (DT, DY)
           T = DT
C
       TWRITE = T/TPRINT
       IF ( IFLAG .NE. 2 ) GO TO 155
       IF ( TWRITE .NE. INT(TWRITE) ) GO TO 156
  155 WRITE  (7,881)  DT, DY(12), INFLAG, IFLAG
      WRITE  (16,1210) DT, DY(12), DY(11), DY(1), DY(2), VIP,
     &                    VEP, DY(5), THTRAN, DY(16), INFLAG, IFLAG
      WRITE (10,9210) DT,DY(23),CRMASD,CRMASG,DY(18),DY(19),
     &                FRZCRCOD,FRZCRCOG
      WRITE (13,4210) DT, VELHTX, HTPARO, HTPASI, HTPAHO,
     &                    QFRRO, QFRSI, QFRHO
C
  156      IF (ABS(T/TEND - 1.0) .LE. REL) GO TO 190
           IF (IFLAG .EQ. 8) GO TO 40
           IF (IFLAG .NE. 2) GO TO 150
  160 CONTINUE
  170 TOUT = TEND
  180 ABSERR = CIINTG
      RELERR = CIINTG
C
      CALL ODERT (INTAKE, NEQN, DY, DT, TOUT, RELERR, ABSERR,
     &            IFLAG, WORK, IWORK, GINT2, REROOT, AEROOT)
      CALL HELPHT (DT, DY, 1)
C
      CALL BUILD (DT, DY)
      T = DT
C
       TWRITE = T/TPRINT
       IF ( IFLAG .NE. 2 ) GO TO 185
       IF ( TWRITE .NE. INT(TWRITE) ) GO TO 186
  185 WRITE  (7,881)  DT, DY(12), INFLAG, IFLAG
      WRITE  (16,1210) DT, DY(12), DY(11), DY(1), DY(2), VIP,
     &                    VEP, DY(5), THTRAN, DY(16), INFLAG, IFLAG
      WRITE (10,9210) DT,DY(23),CRMASD,CRMASG,DY(18),DY(19),
     &                    FRZCRCOD,FRZCRCOG
      WRITE (13,4210) DT, VELHTX, HTPARO, HTPASI, HTPAHO,
     &                QFRRO, QFRSI, QFRHO
C
  186 IF (ABS(T/TEND - 1.0) .LE. REL) GO TO 190
      IF (IFLAG .EQ. 8) GO TO 40
      IF (IFLAG .NE. 2) GO TO 180
```

```
C
C#########################################################################
C
C        END OF INTAKE PROCESS
C
C#########################################################################
C
  190 IF (I .EQ. 2) GO TO 200
      HEATI = DY(8) + DY(9) + DY(10)

      WORKI = DY(16)
      TEND = TIPC
      GO TO 30
C
C        CALCULATE VOLUMETRIC EFFICIENCY (VOLEFI)
C
  200 VOLEFI = 100. * DY(1)*1000./( DVOLUM * RHOIM * (1. + PHI*FASTO) )
      VOLEFA = VOLEFI * (PIM/PATM) * (TATM/TIM)
      WRITE (7,1281) VOLEFI
      WRITE  (16,1210) TIPC, DY(12), DY(11), DY(1), DY(2), VIP,
     &                    VEP, DY(5), THTRAN, DY(16), INFLAG, IFLAG
      WRITE (16,3333)
      WRITE (16,2225)
      WRITE (16,1110)
      WRITE (16,4597)
      WRITE (16,3333)
      WRITE (16,1211) TIPC, DY(12), DY(11), THTRAN,
     &                DY(16), IFLAG
C
C        CALCULATE TOTAL MASS OF FUEL INDUCTED IN THIS CYCLE (FMIN)
C
      ZMAST = DY(23)
      FMIN = DY(1)*PHISTA*FASTO
      IF (.NOT. FIRE) FMIN = 0.0
C
C        CALCULATE RESIDUAL FRACTION AT TIPC
C
      RESIDL = 1. - DY(5)
C
C#########################################################################
C
C        START OF COMPRESSION PROCESS (FIRING CASE) (TIPC - TSPARK)
C        START OF COMPRESSION AND EXPANSION PROCESSES
C        (MOTORING CASE) (TIPC - TEPO)
C
C#########################################################################
C
      MFUEL = 0.0
      TID = TSPARK
      TBD = TSPARK
      NEQN = 30
      IFLAG = 1
      T = TIPC
      TEND = TEPO
```

```
      IF (FIRE) TEND = TSPARK
      DT = T
      NCALL = IFIX( ABS(TEND - T) )
      IF (NCALL .LE. 0) GO TO 230
      DO 220 NC = 1, NCALL
           TOUT = INT( T + 1.)
  210      ABSERR = CCINTG
           RELERR = CCINTG
C
           CALL ODERT (CMPRES, NEQN, DY, DT, TOUT, RELERR, ABSERR,
     &                  IFLAG, WORK, IWORK, GCMP, REROOT, AEROOT)
           CALL HELPHT (DT, DY, 2)
C
           CALL BUILD (DT, DY)
           T = DT
C
       TWRITE = T/TPRINT
       IF ( IFLAG .NE. 2 ) GO TO 215
       IF ( TWRITE .NE. INT(TWRITE) ) GO TO 216
  215  WRITE  (7,882)  DT, DY(12), IFLAG
       WRITE  (16,1211) DT, DY(12), DY(11), THTRAN,
     &                    DY(16), IFLAG
       WRITE (10,9210) DT,DY(23),CRMASD,CRMASG,DY(18),DY(19),
     &                    FRZCRCOD,FRZCRCOG
       WRITE (13,4210) DT, VELHTX, HTPARO, HTPASI, HTPAHO,
     &                    QFRRO, QFRSI, QFRHO
C
  216      IF (ABS( T - TEND ) .LE. REL) GO TO 250
           IF (IFLAG .EQ. 8) GO TO 220
           IF (IFLAG .NE. 2) GO TO 210
  220 CONTINUE
  230 TOUT = TEND
  240 ABSERR = CCINTG
      RELERR = CCINTG
C
      CALL ODERT (CMPRES, NEQN, DY, DT, TOUT, RELERR, ABSERR,
     &             IFLAG, WORK, IWORK, GCMP, REROOT, AEROOT)
      CALL HELPHT (DT, DY, 2)
C
      CALL BUILD (DT, DY)
      T = DT
C
       TWRITE = T/TPRINT
       IF ( IFLAG .NE. 2 ) GO TO 245
  245 WRITE  (7,882)  DT, DY(12), IFLAG
      WRITE  (16,1211) DT, DY(12), DY(11), THTRAN,
     &                 DY(16), IFLAG
      WRITE (10,9210) DT,DY(23),CRMASD,CRMASG,DY(18),DY(19),
     &                     ZCRCOD,ZCRCOG
      WRITE (13,4210) DT, VELHTX, HTPARO, HTPASI, HTPAHO,
     &                 QFRRO, QFRSI, QFRHO
C
  246 IF (ABS( T - TEND ) .LE. REL) GO TO 250
      IF (IFLAG .NE. 2) GO TO 240
```

```
C
C###########################################################################
C
C        IF FIRING CASE, GO TO START OF COMBUSTION
C        IF MOTORING CASE, BEGIN EXHAUST PROCESS (TEPO - TIPO)
C
C###########################################################################
C
 250  WRITE (16,3333)
      IF (FIRE) GO TO 330
      WRITE (16,2225)
      WRITE (16,1111)
      WRITE (16,4599)
      WRITE (16,3333)
      VEP = 0.0
      WRITE (16,1213) TEPO, DY(12), DY(11), DY(2), VEP,
     &                THTRAN, DY(16), IFLAG
C
      I = 0
      NEQN = 30
      IFLAG = 1
      T = TEPO
      TEND = 270.
      DT = T
  260 I = I + 1
      IFLAG = 1
      NCALL = IFIX( ABS(TEND - T) )
      IF (NCALL .LE. 0) GO TO 290
      DO 280 NC = 1, NCALL
           TOUT = INT( T + 1.)
  270      ABSERR = CEINTG
           RELERR = CEINTG
C
           CALL ODERT (EXAUST, NEQN, DY, DT, TOUT, RELERR, ABSERR,
     &                 IFLAG, WORK, IWORK, GEXH, REROOT, AEROOT)
           CALL HELPHT (DT, DY, 4)
C
           CALL BUILD (DT, DY)
           T = DT
C
       TWRITE = T/TPRINT
       IF ( IFLAG .NE. 2 ) GO TO 275
       IF ( TWRITE .NE. INT(TWRITE) ) GO TO 276
  275  WRITE  (7,882)  DT, DY(12), IFLAG
       WRITE  (16,1213) DT, DY(12), DY(11), DY(2), VEP,
     &                   THTRAN, DY(16), IFLAG
       WRITE (10,9210) DT,DY(23),CRMASD,CRMASG,DY(18),DY(19),
     &                   FRZCRCOD,FRZCRCOG
       WRITE (13,4210) DT, VELHTX, HTPARO, HTPASI, HTPAHO,
     &                   QFRRO, QFRSI, QFRHO
C
  276      IF (ABS(T/TEND - 1.0) .LE. REL) GO TO 310
           IF (IFLAG .NE. 2) GO TO 270
  280 CONTINUE
```

```
  290 TOUT = TEND
  300 ABSERR = CEINTG
      RELERR = CEINTG
C
      CALL ODERT (EXAUST,NEQN,DY,DT,TOUT,RELERR,ABSERR,IFLAG,
     &            WORK,IWORK,GEXH,REROOT,AEROOT)
      CALL HELPHT (DT, DY, 4)
C
      CALL BUILD (DT, DY)
      T = DT
       TWRITE = T/TPRINT
       IF ( IFLAG .NE. 2 ) GO TO 305
       IF ( I .EQ. 2  .AND.  ABS(T/TEND - 1.) .LE. REL ) GO TO 305
       IF ( TWRITE .NE. INT(TWRITE) ) GO TO 306
  305 WRITE  (7,882)  DT, DY(12), IFLAG
      WRITE  (16,1213) DT, DY(12), DY(11), DY(2), VEP,
     &                 THTRAN, DY(16), IFLAG
      WRITE (10,9210) DT,DY(23),CRMASD,CRMASG,DY(18),DY(19),
     &                     FRZCRCOD,FRZCRCOG
      WRITE (13,4210) DT, VELHTX, HTPARO, HTPASI, HTPAHO,
     &                QFRRO, QFRSI, QFRHO
C
  306 IF (ABS(T/TEND - 1.0) .LE. REL) GO TO 310
      IF (IFLAG .NE. 2) GO TO 300
  310 IF (I .EQ. 2) GO TO 320
C
      HEATCE = DY(8) + DY(9) + DY(10) - HEATI
      WORKCE = DY(16) - WORKI
      TEND = TIPO + 1080.
      GO TO 260
C
  320 HEATE = DY(8) + DY(9) + DY(10) - HEATCE - HEATI
      WORKE = DY(16) - WORKCE - WORKI
      WRITE (16,3333)
C
C#######################################################################
C
C        END OF EXHAUST PROCESS (MOTORING CASE)
C
C#######################################################################
C
      GO TO 455
  330 CONTINUE
C
      HEATC = DY(8) + DY(9) + DY(10) - HEATI
      WORKC = DY(16) - WORKI
      WRITE (16,2225)
      WRITE (16,1112)
      WRITE (16,4598)
      WRITE (16,3333)
C
C        REINITIALIZE 'ODERT' FOR START OF COMBUSTION
C
C        CALCULATE PRESSURE RISE DUE TO INITIAL HEAT RELEASE
```

```
C
      MASS = DY(23)
      PZERO = DY(12) + 9.8692326 * MASS * XBZERO * QLOWER *
     &        (GAMMA - 1.)/VOLUME
C
      TAU = XBSTOP / DQDTMAX - 0.5 * ( TMAX - TSPARK )
C
C        CALCULATE INITIAL BURNED ZONE TEMPERATURE
C
      HGUESS = H
      TGUESS = DY(11)
      CALL ITRATE (TSPARK,TGUESS,PZERO,DY(26),HGUESS,XXA,XXB,
     &             XXC,XXD,XXE,XXF,XXG,XXH,XXI)
C
C
      DY(4)  = XBZERO
      DY(12) = PZERO
C
      WRITE  (16,1212) TSPARK, DY(12), DY(11),
     &                 DY(4), THTRAN, DY(16), IFLAG
      DT = TSPARK
      CALL HELPHT (DT, DY, 3)
      WRITE (13,4210) TSPARK, VELHTX, HTPARO, HTPASI, HTPAHO,
     &                QFRRO, QFRSI, QFRHO
C
C#######################################################################
C
C        START OF COMBUSTION PROCESS (TSPARK - TEPO)
C
C#######################################################################
C
      IDCNT = 0
      IBCNT = 0
      NEQN = 30
      IFLAG = 1
      T = TSPARK
      TEND = TEPO
      DT = T
      NCALL = IFIX( ABS(TEND - T) )
      IF (NCALL .LE. 0) GO TO 360
      DO 350 NC = 1, NCALL
          TOUT = INT( T + 1.)
  340     ABSERR = CBINTG
          RELERR = CBINTG
          TOLDXB = T
          XBOLD = DY(4)
C
          CALL ODERT (CMBSTN,NEQN,DY,DT,TOUT,RELERR,ABSERR,IFLAG,
     &                WORK,IWORK,GCMB,REROOT,AEROOT)
          CALL HELPHT (DT, DY, 3)
          IF (DY(4) .LE. 1.0) GO TO 344
          IF (DY(4) .GT. 1.0) XBSTOP = XBSTOP - 0.002
          GO TO 5
C
```

```
  344      CALL BUILD (DT, DY)
           T = DT
C
           IF ((IDCNT .GT. 0) .OR. (DY(4) .LT. 0.1)) GO TO 345
           TID = TOLDXB + (T - TOLDXB)*(0.1 - XBOLD)/(DY(4) - XBOLD)
           IDCNT = IDCNT + 1
  345      IF ((IBCNT .GT. 0) .OR. (DY(4) .LT. 0.9)) GO TO 347
           TBD = TOLDXB + (T - TOLDXB)*(0.9 - XBOLD)/(DY(4) - XBOLD)
           IBCNT = IBCNT + 1
  347      TWRITE = T/TPRINX
           IF (IFLAG .NE. 2 ) GO TO 348
           IF (TWRITE .NE. INT(TWRITE) ) GO TO 349
C
  348      WRITE  (7,883)  DT, DY(12), DY(4), IFLAG
           WRITE  (16,1212) DT, DY(12), DY(11),
     &                     DY(4), THTRAN, DY(16), IFLAG
           WRITE (10,9210) DT,DY(23),CRMASD,CRMASG,DY(18),DY(19),
     &                     FRZCRCOD,FRZCRCOG
           WRITE (13,4210) DT, VELHTX, HTPARO, HTPASI, HTPAHO,
     &                     QFRRO, QFRSI, QFRHO
C
  349      IF (ABS(T/TEND - 1.0) .LE. REL) GO TO 380
           IF (IFLAG .NE. 2) GO TO 340
  350 CONTINUE
  360 TOUT = TEND
  370 ABSERR = CBINTG
      RELERR = CBINTG
      TOLDXB = T
      XBOLD = DY(4)
C
      CALL ODERT (CMBSTN,NEQN,DY,DT,TOUT,RELERR,ABSERR,IFLAG,
     &            WORK,IWORK,GCMB,REROOT,AEROOT)
      CALL HELPHT (DT, DY, 3)
      IF (DY(4) .LE. 1.0) GO TO 374
      IF (DY(4) .GT. 1.0) XBSTOP = XBSTOP - 0.02
      GO TO 5
C
  374 CALL BUILD (DT, DY)
      T = DT
C
      IF ((IDCNT .GT. 0) .OR. (DY(4) .LT. 0.1)) GO TO 375
      TID = TOLDXB + (T - TOLDXB)*(0.1 - XBOLD)/(DY(4) - XBOLD)
      IDCNT = IDCNT + 1
  375 IF ((IBCNT .GT. 0) .OR. (DY(4) .LT. 0.9)) GO TO 377
      TBD = TOLDXB + (T - TOLDXB)*(0.9 - XBOLD)/(DY(4) - XBOLD)
      IBCNT = IBCNT + 1
C
  377 WRITE  (7,883)  DT, DY(12), DY(4), IFLAG
      WRITE  (16,1212) DT, DY(12), DY(11),
     &                DY(4), THTRAN, DY(16), IFLAG
      IF (ITERAS .EQ. 1)WRITE (19,*) DT,DY(26),PHI
        WRITE (10,9210) DT,DY(23),CRMASD,CRMASG,DY(18),DY(19),
     &                  FRZCRCOD,FRZCRCOG
        WRITE (13,4210) DT, VELHTX, HTPARO, HTPASI, HTPAHO,
```

```
     &                    QFRRO, QFRSI, QFRHO
C
      IF (ABS(T/TEND - 1.0) .LE. REL) GO TO 380
      IF (IFLAG .NE. 2) GO TO 370
C
C########################################################################
C
C         START OF EXHAUST PROCESS (FIRING CASE) (TEPO - TIPO)
C
C########################################################################
C
 380  WRITE (16,3333)
      WRITE (16,2225)
      WRITE (16,1111)
      WRITE (16,4599)
      WRITE (16,3333)
      VEP = 0.0
      WRITE (16,1213) TEPO, DY(12), DY(11), DY(2), VEP,
     &                THTRAN, DY(16), IFLAG
C
C         REINITIALIZE 'ODERT' FOR START OF EXHAUST
C
      DY(5) = RESIDL * (1.-DY(4))
      MFUEL = 0.0
C
      I = 0
      NEQN = 30
      IFLAG = 1
      T = TEPO
      TEND = 270.
      DT = T
  390 I = I + 1
      NCALL = IFIX( ABS(TEND - T) )
      IF (NCALL .LE. 0) GO TO 420
      DO 410 NC = 1, NCALL
           TOUT = INT( T + 1.)
  400      ABSERR = CEINTG
           RELERR = CEINTG
C
           CALL ODERT (EXAUST,NEQN,DY,DT,TOUT,RELERR,ABSERR,IFLAG,
     &                 WORK,IWORK,GEXH,REROOT,AEROOT)
           CALL HELPHT (DT, DY, 4)
C
           CALL BUILD (DT, DY)
           T = DT
       TWRITE = T/TPRINT
       IF ( IFLAG .NE. 2 ) GO TO 405
       IF ( I .EQ. 2   .AND.  ABS(T/TEND - 1.) .LE. REL )
     &   GO TO 435
       IF ( TWRITE .NE. INT(TWRITE) ) GO TO 406
  405      WRITE  (7,882)  DT, DY(12), IFLAG
           WRITE  (16,1213) DT, DY(12), DY(11), DY(2), VEP,
     &                      THTRAN, DY(16), IFLAG
           WRITE (10,9210) DT,DY(23),CRMASD,CRMASG,DY(18),DY(19),
```

```
     &                         FRZCRCOD,FRZCRCOG
           WRITE (13,4210) DT, VELHTX, HTPARO, HTPASI, HTPAHO,
     &                         QFRRO, QFRSI, QFRHO
C
  406      IF (ABS(T/TEND - 1.0) .LE. REL) GO TO 440
           IF (IFLAG .NE. 2) GO TO 400
  410 CONTINUE
  420 TOUT = TEND
  430 ABSERR = CEINTG
      RELERR = CEINTG
C
      CALL ODERT (EXAUST,NEQN,DY,DT,TOUT,RELERR,ABSERR,IFLAG,
     &            WORK,IWORK,GEXH,REROOT,AEROOT)
      CALL HELPHT (DT, DY, 4)
C
      CALL BUILD (DT, DY)
      T = DT
       TWRITE = T/TPRINT
       IF ( IFLAG .NE. 2 ) GO TO 435
       IF ( I .EQ. 2  .AND.  ABS(T/TEND - 1.) .LE. REL ) GO TO 435
       IF ( TWRITE .NE. INT(TWRITE) ) GO TO 436
C
  435 WRITE  (7,882)  DT, DY(12), IFLAG
      WRITE  (16,1213) DT, DY(12), DY(11), DY(2), VEP,
     &                 THTRAN, DY(16), IFLAG
      WRITE (10,9210) DT,DY(23),CRMASD,CRMASG,DY(18),DY(19),
     &                 FRZCRCOD,FRZCRCOG
      WRITE (13,4210) DT, VELHTX, HTPARO, HTPASI, HTPAHO,
     &                 QFRRO, QFRSI, QFRHO
C
  436 IF (ABS(T/TEND - 1.0) .LE. REL) GO TO 440
      IF (IFLAG .NE. 2) GO TO 430
  440 IF (I .EQ. 2) GO TO 450
C
      HEATCE = DY(8) + DY(9) + DY(10) - HEATI
      WORKCE = DY(16) - WORKI
      TEND = TIPO + 1080.
      GO TO 390
C
C########################################################################
C
C         END OF EXHAUST PROCESS (FIRING CASE)
C
C########################################################################
C
  450 HEATE = DY(8) + DY(9) + DY(10) - HEATCE - HEATI
      WORKE = DY(16) - WORKCE - WORKI
      WRITE (16,3333)
C
C         CONVERGENCE CHECK
C
  455 Y(12) = DY(12)
      Y(11) = DY(11)
      Y(1) = DY(1)
```

```
      Y(2) = DY(2)
      IF (ITERAS .EQ. 1) GO TO 460
      IF (ABS( (Y(12) - PSTART)/PSTART ) .GT. 0.02) GO TO 460
      IF (ABS( (Y(11) - TSTART)/TSTART ) .GT. 0.02) GO TO 460
      IF (ABS( (Y(1) - Y(2))/MSTART )    .GT. 0.02) GO TO 460
      GO TO 480
  460 PSTART = DY(12)
      TSTART = DY(11)
C
C       INITIALIZE THE CREVICE GAS COMPOSITIONS
C
      X1LDIN = DY(22)
      X1LGIN = DY(21)
      FRLDIN = DY(29)
      FRLGIN = DY(30)
CN
C
CN470 CONTINUE
C
C**********************************************************************
C
C        END OF CURRENT CYCLE ITERATION
C
C**********************************************************************
C
C        CALCULATION RESULTS FOR THIS CYCLE
C
  480 THREFN = 0.0
      THREFG = 0.0
      HEATX  = 0.0
      IF (.NOT. FIRE) GO TO 490
      THREFN = 100. * DY(16)/(FMIN * QLOWER)
      THREFG = 100. * WORKCE/(FMIN * QLOWER)
      HEATX  = 100. * (DY(8) + DY(9) + DY(10))/(FMIN * QLOWER)
  490 ZPMEP  = 1.0E+06 * (WORKI + WORKE)/DVOLUM
      ZIMEP  = 1.0E+06 *.WORKCE/DVOLUM
      ZISFC  = 3600. * FMIN/WORKCE
      RESFRK = 0.0
      IF (FIRE) RESFRK = 1.0
      AVREXH = DY(17)/DY(2)*1.0E+6
      TGUESS = 500.
      IF (FIRE) TGUESS = 1300.
      CALL ITRATE (T, TGUESS, PEM, DY(26), AVREXH, XXA, XXB, XXC,
     &             XXD, XXE, XXF, XXG, XXH, XXI, XXJ, XXK)
      AVREXT = TGUESS
      DTHIGD = TID - TSPARK
      DTIGD  = DTHIGD * ESPDI * 1.0E+3
      DTHBRN = TBD - TID
      DTBURN = DTHBRN * ESPDI * 1.0E+3
C
C        ENERGY BALANCE
C
      TOHIN = 1.0E-6 * HIM * DY(1)
      TOHEX =  DY(17)
```

```
      TOHEAT = HEATI + HEATCE + HEATE
      TOWORK = WORKI + WORKCE + WORKE
C
C
      DECYCL = -TOHIN + TOHEAT + TOWORK - FMIN*HFORM/1.E+3 + TOHEX +
     &            DY(20) + DY(3)
      DEONHI = 100.0 * DECYCL/TOHIN
      DEONQ = 0.0
      IF (FIRE) DEONQ = 100.0 * DECYCL/(FMIN * QLOWER)
      WRITE (16,2225)
      WRITE (16,5910)
      WRITE (16,3333)
      WRITE (16,5920) VOLEFI, VOLEFA, ZPMEP, ZIMEP, ZISFC, THREFG,
     &             THREFN, HEATX
      WRITE (16,5921) DTHIGD, DTIGD, DTHBRN,DTBURN, AVREXT
      WRITE (16,3333)
      WRITE (16,9876) MSTART, ZMAST, FMIN, RESIDL
      WRITE (16,3333)
      WRITE (16,1261) HEATI, WORKI
      IF (FIRE) WRITE (16,1264) HEATC, WORKC
      IF (FIRE) WRITE (16,1262) HEATCE, WORKCE
      IF (.NOT. FIRE) WRITE (16,1262) HEATCE, WORKCE
      WRITE (16,1263) HEATE, WORKE
      WRITE (16,3333)
      WRITE (16,1890) TOHIN, TOHEX, TOHEAT, TOWORK, DY(20), DY(3),
     &             DECYCL, DEONHI, DEONQ
      WRITE (16,3333)
C
C         NO CONVERGENCE CHECK IS PERFORMED AFTER THE FIRST ITERATION
C         BECAUSE THE CREVICE AND LEAKAGE MODEL IS NOT YET ACTIVATED
C
      IF (ITERAS .EQ. 1)  GO TO 470
      IF (ABS( (Y(12) - PSTART)/PSTART ) .GT. 0.02) GO TO 470
      IF (ABS( (Y(11) - TSTART)/TSTART ) .GT. 0.02) GO TO 470
      IF (ABS( (Y(1) - Y(2))/MSTART )    .GT. 0.02) GO TO 470
C
       GO TO 471
  470 CONTINUE
  471 CONTINUE
CJ
CJ    CALL WRITE
C
C@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
C
C       FORMAT STATEMENTS
C
 2225 FORMAT (1H1)
C
  881 FORMAT (1H ,2X,'CA = ',F8.2,10X,'P = ',F10.5,9X,'INFLAG = ',I2,
     &        8X,'IFG = ',I2)
C
  882 FORMAT (1H ,2X,'CA = ',F8.2,10X,'P = ',F10.5,28X,'IFG = ',I2)
C
  883 FORMAT (1H ,2X,'CA = ',F6.2,10X,'P = ',F10.5,9X,'XB = ',F9.6,
```

```
     &        5X,'IFG = ',I2)
C
  449 FORMAT (////,1H ,13X,'START OF ITERATION  #',I2,2X,'OF ',I2,
     &        ' ALLOWED',//)
   77 FORMAT (//(54X,' >>>>> INPUT DATA <<<<< ' )//)
C
 4595 FORMAT (/////(1X,' >>>>> START OF INTAKE PROCESS      ')//)
C
 4596 FORMAT ((4X,'CA',7X,'P',9X,'TEMP',7X,'MIN',6X,'MEX',9X,'VIV',7X,
     &        'VEV',9X,'X1',9X,'Q DOT',9X,'WORK',8X,'IMF   IFG')/
     &        (2X,'(DEG)',4X,'(ATM)',7X,'(K)',8X,'(G)',6X,'(G)',7X,
     &        ' (CM/SEC)',2X,' (CM/SEC)',6X,'(-)',7X,'(KJ/DEG)',7X,
     &        '(KJ)'))
C
 4597 FORMAT ((4X,'CA',7X,'P',9X,'TEMP',61X,
     &        'Q DOT',9X,'WORK',14X,'IFG')/
     &        (2X,'(DEG)',4X,'(ATM)',7X,'(K)',61X,
     &        '(KJ/DEG)',7X,
     &        '(KJ)'))
C
 4598 FORMAT ((4X,'CA',7X,'P',22X,'TEMP ',8X,4X,6X,4X,
     &        'XBURND',19X,'Q DOT',9X,'WORK',14X,'IFG')/
     &        (2X,'(DEG)',4X,'(ATM)',20X,'(K)',10X,5X,
     &        3X,7X,'(-)',20X,'(KJ/DEG)',7X,
     &        '(KJ)'))
C
 4599 FORMAT ((4X,'CA',7X,'P',9X,'TEMP',16X,'MEX',19X,
     &        'VEV',20X,'Q DOT',9X,'WORK',14X,'IFG')/
     &        (2X,'(DEG)',4X,'(ATM)',7X,'(K)',17X,'(G)',17X,
     &        ' (M/SEC)',16X,'(KJ/DEG)',7X,
     &        '(KJ)'))
C
 1110 FORMAT (///(1X,' >>>>> START OF COMPRESSION PROCESS      ')//)
C
 1111 FORMAT (///(1X,' >>>>> START OF EXHAUST PROCESS      ')//)
C
 1277 FORMAT (1F7.1,2X,F9.4,2X,F9.2,2X,2F10.5,2X,F8.1,2X,11X,
     &        F9.5,16X,1F10.6)
C
 1210 FORMAT (1F7.1,2X,F9.4,2X,F9.2,2X,2F10.5,2X,F8.1,2X,F8.1,3X,
     &        F9.5,3X,1F10.6,3X,1F10.6,3X,1I4,1I6)
C
 1211 FORMAT (1F7.1,2X,F9.4,2X,F9.2,57X,
     &        1F10.6,3X,1F10.6,9X,1I4)
C
 1212 FORMAT (1F7.1,2X,F9.4,13X,F10.2,12X,8X,2X,F8.5,15X,
     &        1F10.6,3X,1F10.6,9X,1I4)
C
 1213 FORMAT (1F7.1,2X,F9.4,2X,F9.2,12X,1F10.5,12X,F8.1,15X,
     &        1F10.6,3X,1F10.6,9X,1I4)
C
 9876 FORMAT ( /('      MASS IN CYLINDER AT TIVO = ',F8.5,' G')//
     &          ('      MASS IN CYLINDER AT TIVC = ',F8.5,' G')//
     &          ('      MASS OF FUEL INDUCTED    = ',F8.5,' G')//
```

```
     &           ('     RESIDUAL FRACTION         = ',F8.5)/)
C
 1890 FORMAT ( /('     TOTAL ENTHALPY IN / CYCLE    = ',F9.5,' KJ')//
     &           ('     TOTAL ENTHALPY OUT / CYCLE   = ',F9.5,' KJ')//
     &           ('     TOTAL HEAT LOSS / CYCLE      = ',F9.5,' KJ')//
     &           ('     TOTAL WORK OUTPUT / CYCLE    = ',F9.5,' KJ')//
     &           ('     HEAT LOSS TO CREVICE/CYCLE   = ',F9.5,' KJ')//
     &           ('     "LOST" FUEL ENERGY           = ',F9.5,' KJ')//
     &           ('     NET ENERGY GAIN / CYCLE      = ',F9.5,' KJ')//
     &           ('     (ENERGY GAIN)/(ENTHALPY IN) = ',F9.5,' %')//
     &           ('     (ENERGY GAIN)/(MFUEL*LHV)   = ',F9.5,' %')/)
C
 1261 FORMAT ( /('     HEATI   =  ',F10.6,' KJ',' (TIPO   -   -270)')/
     &            ('     WORKI   =  ',F10.6,' KJ')/ )
C
 1281 FORMAT (///('  VOLUMETRIC EFFICIENCY = ',1F5.1,' %')//)
C
 1262 FORMAT (  /('     HEATCE  =  ',F10.6,' KJ',' (TIPC   -    +270')/
     &            ('     WORKCE  =  ',F10.6,' KJ')/ )
C
 1263 FORMAT (  /('     HEATE   =  ',F10.6,' KJ',' (+270   -   TIPO)')/
     &            ('     WORKE   =  ',F10.6,' KJ')/ )
C
 1264 FORMAT (  /('     HEATC   =  ',F10.6,' KJ',' (-270   - TSPARK)')/
     &            ('     WORKC   =  ',F10.6,' KJ')/ )
C
 3210 FORMAT (5X,1F7.1,2X,2(1F12.1,2X),2(1F12.2,2X),
     &        2X,3(F10.5,4X),F9.4)
C
 4210 FORMAT (5X,1F7.1,2X,F10.1,3X,3(F13.1,3X),4X,3(F12.3,5X))
C
 9210 FORMAT (5X,1F7.1,6X,F8.4,4X,F10.6,1X,5(6X,F10.6))
 9211 FORMAT (5X,F7.1,6X,F8.4)
 1112 FORMAT (///(1X,' >>>>> START OF COMBUSTION AND EXPANSION PROCESSES
     &         ')///)
C
 4592 FORMAT (//(9X,'CA',7X,'VELHTX',7X,'HTPARO',7X,'HTPASI',7X,
     &         'HTPAHO',13X,'Q% ROTOR',10X,'Q% SIDE',8X,'Q% HOUSING')/
     &         (8X,'(DEG)',4X,'(CM/SEC)',5X,'(KW/M**2)',4X,'(KW/M**2)',
     &         4X,'(KW/M**2)',14X,'(%)',14X,'(%)',14X,'(%)'))
C
 4594 FORMAT (//(9X,'CA',7X,'MEANKE',8X,'TURBKE',8X,' VMKE ',8X,
     &         'UPRIME',10X,'MACRSC',8X,'MICRSC',9X,'SSUBL',8X,'BTIMSC')/
     &         (8X,'(DEG)',5X,'(ERG)',9X,'(ERG)',8X,'(CM/SEC)',6X,
     &        '(CM/SEC)',10X,'(CM)',10X,'(CM)',9X,'(CM/SEC)',7X,'(MS)'))
C
 9900 FORMAT (//(9X,'CA',9X,'CHAMBER',5X,'LEAD CREVICE',5X,
     &         'LAG CREVICE',5X,'LEAD LEAKAGE',4X,'LAG LEAKAGE',5X,
     &         'LEAD CREVICE',5X,'LAG CREVICE')/
     &         (20X,'MASS',8X,'MASS',13X,'MASS',12X,'MASS',12X,'MASS',
     &         12X,'COMPOSITION',6X,'COMPOSITION')/
     &         (7X,'(DEG)',10X,'(G)',12X,'(G)',13X,'(G)',14X,'(G)',
     &         13X,'(G)',12X,'(  )',12X,'(  )')//)
C
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C3111 FORMAT (///,1H ,59X,'NOX FORMATION')
C
C5111 FORMAT (///,1H ,48X,'ADIABATIC CORE / BOUNDARY LAYER DATA')
C
C4111 FORMAT (///,1H ,54X,'FLAME PROPAGATION DATA')
C
C6111 FORMAT (///,1H ,55X,'TURBULENT FLOW MODEL')
C
 7111 FORMAT (///,1H ,56X,'HEAT TRANSFER DATA')
C
C
 8111 FORMAT (///,1H ,40X,'LEAKAGE AND CREVICE VOLUME DATA')
C
C3222 FORMAT (//,1H ,6X,'CA',7X,'YAC',7X,'YBL',7X,'YNOAC',5X,'YNOBL',5X,
C    &        'YNO',6X,'XNOAC',6X,'XNOBL',5X,'XNO',8X,'PPMAC',6X,
C    &        'PPMBL',6X,'PPMNO')
C
C4222 FORMAT (//,1H ,6X,'CA',5X,'VENONV',5X,'VBRONV',5X,'DFLONB',5X,
C    &        'AFLONB',5X,'AHUONB',5X,'AHBONB',5X,'APUONB',5X,'APBONB',
C    &        5X,'ACUONB',5X,'ACBONB')
C
C5222 FORMAT (//,1H ,6X,'CA',8X,'YAC',8X,'YBL',8X,'VACONV',6X,'VBLONV',
C    &        6X,'DBLONB',10X,'TWALLB',7X,'TB',9X,'TAC',8X,'TBLAYR')
C
 3333 FORMAT (1H ,1X,'______________________________________________',
     &        '_______________________________________________________',
     &        '_________________________',/)
C
C3444 FORMAT (1H ,3X,F8.1,8(2X,F8.6),3(2X,F9.2))
C
C5444 FORMAT (1H ,2X,F8.1,5(4X,F8.6),2X,4(3X,F9.1))
C
C6444 FORMAT (1H ,2X,F8.1,10(3X,F8.5))
C
 5910 FORMAT (///(46X,'>--------------+--------------<')/
     &           (46X,'>                             <')/
     &           (46X,'>     CALCULATION RESULTS     <')/
     &           (46X,'>                             <')/
     &           (46X,'>--------------+--------------<')///)
C
 5920 FORMAT (/(33X,' -->  VOLUMETRIC EFFICIENCY; (%) ')/
     & (33X,'      BASED ON: INTAKE / ATM           ----> ',2(F8.1))///
     & (33X,' -->  PUMPING MEAN EFFECTIVE  ')/
     & (33X,'      PRESSURE; (KPA) : PEMP           ---->  ',1F6.0)///
     & (33X,' -->  GROSS INDICATED MEAN EFFECTIVE ')/
     & (33X,'      PRESSURE; (KPA) : IMEP           ---->  ',1F6.0)///
     & (33X,' -->  GROSS INDICATED SPECIFIC FUEL  ')/
     & (33X,'      CONSUMPTION; (G/IKW-HR) : ISFC   ---->  ',1F6.0)///
     & (33X,' -->  GROSS INDICATED THERMAL       ')/
     & (33X,'      EFFICIENCY; (%)                  ---->  ',1F7.1)///
     & (33X,' -->  NET INDICATED THERMAL         ')/
     & (33X,'      EFFICIENCY; (%)                  ---->  ',1F7.1)///
     & (33X,' -->  (HEAT TRANSFER PER CYCLE)/    ')/
     & (33X,'      (MASS OF FUEL TIMES LHV); (%)    ---->  ',1F7.1)//)
```

```
5921 FORMAT ((33X,' -->  IGNITION DELAY (0 - 10%)      ')/
    & (33X,'      (CRANK ANGLE) / (MS)              ---->  ',2(F8.2))///
    & (33X,' -->  BURN DURATION (10 - 90%)     ')/
    & (33X,'      (CRANK ANGLE) / (MS)              ---->  ',2(F8.2))///
    & (33X,' -->  MEAN EXHAUST                   ')/
    & (33X,'      TEMPERATURE; (K)        .         ---->  ',1F7.1)/)
2901 FORMAT (/////,1H ,39X,'M.I.T. ZERO-DIMENSIONAL WANKEL ENGINE',
    &        ' CYCLE SIMULATION',/////)
2902 FORMAT (/,1H ,10X,'>>>>> OPERATING MODE',/)
2903 FORMAT (/,1H ,25X,'FIRING CYCLE')
2904 FORMAT (/,1H ,25X,'MOTORED CYCLE',/)
2905 FORMAT (/,1H ,25X,'SPECIFIED BURN RATE')
2906 FORMAT (/,1H ,30X,'MAXIMUM NORMALIZED HEAT RELEASE RATE  = ',F8.3,
    &        /,1H ,30X,'ANGLE OF DQMAX                        = ',F8.3)
2907 FORMAT (/,1H ,25X,'PREDICTED BURN RATE',/)
2908 FORMAT (/,1H ,10X,'>>>>> OPERATING CONDITIONS',/)
2909 FORMAT (/,1H ,25X,'FUEL USED IS ISOOCTANE')
2910 FORMAT (/,1H ,25X,'FUEL USED IS PROPANE')
2911 FORMAT (/,1H ,25X,'F/A EQUIVALENCE RATIO = ',F9.3)
2912 FORMAT (/,1H ,25X,'SPARK TIMING          = ',F8.2,' DEG CA')
2913 FORMAT (/,1H ,25X,'ENGINE SPEED          = ',F7.1,' RPM',/)
2914 FORMAT (/,1H ,10X,'>>>>> MANIFOLD CONDITIONS',/)
2915 FORMAT (/,1H ,25X,'INTAKE MANIFOLD PRESSURE  = ',F10.4,' ATM',/
    &        /,1H ,25X,'EXHAUST MANIFOLD PRESSURE = ',F10.4,' ATM',/
    &        /,1H ,25X,'FRESH CHARGE TEMPERATURE  = ',F8.2,'   K',/
    &        /,1H ,25X,'EXHAUST GAS RECIRCULATION = ',F8.2,'   %',/
    &        /,1H ,25X,'EGR TEMPERATURE           = ',F8.2,'   K',/
    &        /,1H ,25X,'INTAKE CHARGE TEMPERATURE = ',F8.2,'   K',/
    &        /,1H ,25X,'ATMOSPHERIC PRESSURE      = ',F10.4,' ATM',/
    &        /,1H ,25X,'ATMOSPHERIC TEMPERATURE   = ',F8.2,'   K',/)
2916 FORMAT (/,1H ,10X,'>>>>> HEAT TRANSFER AND TURBULENCE',
    &                 ' PARAMETERS',/)
2917 FORMAT (/,1H ,25X,'HEAT TRANSFER CONSTANT          = ',F10.4,/
    &        /,1H ,25X,'HEAT TRANSFER EXPONENT          = ',F10.4,/
    &        /,1H ,25X,'ROTOR TEMPERATURE               =',F9.2,'   K',/
    &        /,1H ,25X,'SIDE WALL TEMPERATURE           =',F9.2,'   K',/
    &        /,1H ,25X,'HOUSING WALL TEMPERATURE        =',F9.2,'   K',/
    &        )
2918 FORMAT (/,1H ,10X,'>>>>> ENGINE DESIGN PARAMETERS',/)
2919 FORMAT (/,1H ,25X,'ECCENTRICITY OF ROTOR   = ',F9.3,' CM',/
    &        /,1H ,25X,'RADIUS OF ROTOR         = ',F9.3,' CM',/
    &        /,1H ,25X,'DEPTH OF CHAMBER        = ',F9.3,' CM',/
    &        /,1H ,25X,'COMPRESSION RATIO       = ',F9.3,/
    &        /,1H ,25X,'DISPLACED VOLUME        = ',F9.3,' CC',/
    &        /,1H ,25X,'VOLUME OF ROTOR POCKET  = ',F9.3,' CC',/
    &        /,1H ,25X,'INTAKE PORT OPENS      = ',F7.1,'   DEG CA',/
    &        /,1H ,25X,'INTAKE PORT CLOSES     = ',F7.1,'   DEG CA',/
    &        /,1H ,25X,'EXHAUST PORT OPENS     = ',F7.1,'   DEG CA',/
    &        /,1H ,25X,'EXHAUST PORT CLOSES    = ',F7.1,'   DEG CA',/)
2920 FORMAT (/,1H ,10X,'>>>>> COMPUTATIONAL PARAMETERS',/)
2921 FORMAT (/,1H ,25X,'MAXIMUM # OF ITERATIONS =   ',I4,/
    &        /,1H ,25X,'OUTPUT AT ITERATION #   =   ',I4,/
    &        /,1H ,25X,'TPRINT                  = ',F9.2,
    &        /,1H ,25X,'TPRINX                  = ',F9.2,
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     &        /,1H ,25X,'XBZERO                   = ',F12.5,
     &        /,1H ,25X,'XESTOP                   = ',F12.5,
     &        /,1H ,25X,'XBSTOP                   = ',F12.5,
     &        /,1H ,25X,'CIINTG                   = ',F13.6,
     &        /,1H ,25X,'CCINTG                   = ',F13.6,
     &        /,1H ,25X,'CBINTG                   = ',F13.6,
     &        /,1H ,25X,'CEINTG                   = ',F13.6,
     &        /,1H ,25X,'AREROT                   = ',F13.6,
     &        /,1H ,25X,'REL                      = ',F13.6,
     &        /,1H ,25X,'ERMAX                    = ',F13.6,
     &        /,1H ,25X,'MAXERR                   = ',F13.6,
     &        /,1H ,25X,'MAXTRY                   = ',I6,/)
 2940 FORMAT (/,1H , 10X,'>>>>> LEAKAGE AND CREVICE VOLUME PARAMETERS'/)
 2941 FORMAT (/,1H , 25X,'LEAK AREA PER APEX     = ',F12.6,'  CM*CM'
     &        //,1H , 25X,'CREVICE VOLUME PER APEX= ',F12.6,'  CC    '
     &        //,1H , 25X,'CREVICE GAS TEMPERATURE= ',F12.6,'  K'/)
  999 FORMAT (///,1H ,15X,
     &        'WARNING!!  RESULTS FROM THIS CYCLE SIMULATION',/,16X,
     &        'MAY NOT BE ACCURATE FOR PHI > 1.3 OR PHI < 0.7',///)
 9999 STOP
      END
```

```
C     SUBROUTINE INTAKE
C
C     PURPOSE
C        CALCULATES OR ASSISTS THE CREVICE AND HEAT TRANSFER SUBROUTINES
C        CALCULATE THE TIME RATE OF CHANGE OF PRESSURE, TEMPERATURE,
C        MASS, HEAT TRANSFER,AND WORK TRANSFER IN THE CHAMBER DURING
C        INTAKE.
C
C     USAGE
C        CALL INTAKE (DT, DY, DYP)
C
C     DESCRIPTION OF PARAMETERS
C
C        PARAMETER  INPUT  OUTPUT   DESCRIPTION
C
C        DT         YES    NO       TIME (DEG)
C        DY(1)      NO     NO       MASS INDUCTED INTO CHAMBER THROUGH
C        -----      --     --       INTAKE PORT (G)
C        DY(2)      NO     NO       MASS EXHAUSTED FROM CHAMBER THROUGH
C        -----      --     --       EXHAUST PORT (G)
C        DY(5)      YES    NO       MASS FRACTION OF FRESH CHARGE (-)
C        DY(8)      NO     NO       HEAT TRANSFER TO ROTOR (KJ)
C        DY(9)      NO     NO       HEAT TRANSFER TO SIDE PLATES (KJ)
C        DY(10)     NO     NO       HEAT TRANSFER TO HOUSING (KJ)
C        DY(11)     YES    NO       CHAMBER TEMPERATURE (K)
C        DY(12)     YES    NO       CHAMBER PRESSURE (ATM)
C        DY(16)     NO     NO       TOTAL WORK TRANSFER (KJ)
C        DY(17)     NO     NO       TOTAL ENTHALPY EXHAUSTED (KJ)
C        DY(18)     NO     NO       TOTAL MASS LEAKED PAST LEAD
C        ------     --     --       APEX SEAL  (G)
C        DY(19)     NO     NO       TOTAL MASS LEAKED PAST TRAILING
C        ------     --     --       APEX SEAL  (G)
C        DY(20)     NO     NO       TOTAL HEAT LOSS TO CREVICE VOLUME
C        ------     --     --       WALLS (KJ)
C        DY(21)     NO     NO       MASS FRACTION OF FRESH CHARGE
C        ------     --     --       IN LEAD CREVICE  (-)
C        DY(22)     NO     NO       MASS FRACTION OF FRESH CHARGE
C        ------     --     --       IN TRAILING CREVICE  (-)
C        DY(23)     YES    NO       TOTAL MASS IN CHAMBER  (G)
C        DY(24)     NO     NO       TOTAL MASS THAT HAS LEFT AND ENTERED
C        ------     --     --       LEADING CHAMBER OR CREVICE (G)
C        DY(25)     NO     NO       TOTAL MASS THAT HAS LEFT AND ENTERED
C        ------     --     --       TRAILING CHAMBER OR CREVICE (G)
C        DY(26)     YES    NO       CHAMBER FUEL FRACTION
C        DY(27)     YES    NO       INLET MANIFOLD FUEL FRACTION
C        DY(28)     YES    NO       EXHAUST MANIFOLD FUEL FRACTION
C        DY(29)     YES    NO       LEADING CREVICE FUEL MASS FRACTION
C        DY(30)     YES    NO       TRAILING CREVICE FUEL MASS FRACTION
C
C        --------------------------------------------------------------
C
C        DYP(1)     NO     YES      RATE AT WHICH MASS IS INDUCTED
C        ------     --     ---      THROUGH THE INTAKE PORT  (G/DEG)
C        DYP(2)     NO     YES      RATE AT WHICH MASS IS EXHAUSTED
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C        ------      --      ---       THROUGH THE EXHAUST PORT (G/DEG)
C        DYP(5)      NO      YES       RATE OF CHANGE OF MASS FRACTION OF
C        ------      --      ---       FRESH CHARGE (1/DEG)
C        DYP(8)      NO      YES       RATE OF HEAT TRANSFER THROUGH
C        -------     --      ---       ROTOR WALL  (KJ/DEG)
C        DYP(9)      NO      YES       RATE OF HEAT TRANSFER THROUGH
C        -------     --      ---       SIDE PLATES (KJ/DEG)
C        DYP(10)     NO      YES       RATE OF HEAT TRANSFER THROUGH
C        -------     --      ---       HOUSING  (KJ/DEG)
C        DYP(11)     NO      YES       RATE OF CHANGE OF CHAMBER
C        ------      --      ---       TEMPERATURE (K/DEG)
C        DYP(12)     NO      YES       RATE OF CHANGE OF CHAMBER
C        ------      --      ---       PRESSURE (ATM/DEG)
C        DYP(16)     NO      YES       RATE OF TOTAL WORK TRANSFER (KJ/DEG)
C        DYP(17)     NO      YES       RATE AT WHICH TOTAL ENTHALPY IS
C        -------     --      ---       EXHAUSTED (KJ/DEG)
C        DYP(18)     NO      YES       RATE OF CHANGE OF MASS LEAKED PAST
C        -------     --      ---       LEAD APEX SEAL (G/DEG)
C        DYP(19)     NO      YES       RATE OF CHANGE OF MASS LEAKED PAST
C        -------     --      ---       TRAILING APEX SEAL (G/DEG)
C        DYP(20)     NO      YES       RATE OF HEAT TRANSFER TO CREVICE
C        -------     --      ---       VOLUME WALLS (KJ/DEG)
C        DYP(21)     NO      YES       RATE OF CHANGE OF FRESH CHARGE MASS
C        -------     --      ---       FRACTION IN LEAD CREVICE  ( )
C        DYP(22)     NO      YES       RATE OF CHANGE OF FRESH CHARGE MASS
C        -------     --      ---       FRACTION IN TRAILING CREVICE ( )
C        DYP(23)     NO      YES       RATE OF CHANGE OF TOTAL CHAMBER
C        -------     --      ---       MASS (G/DEG)
C        DYP(24)     NO      YES       NET RATE OF CHANGE OF MASS LEAVING
C        -------     --      ---       CHAMBER TO ENTER LEAD CREVICE AND
C        -------     --      ---       LEAD CHAMBER (G/DEG)
C        DYP(25)     NO      YES       NET RATE OF CHANGE OF MASS LEAVING
C        -------     --      ---       CHAMBER TO ENTER TRAILING CREVICE
C        -------     --      ---       AND TRAILING CHAMBER (G/DEG)
C        DYP(26)     NO      NO        RATE OF CHANGE OF CHAMBER FUEL
C                                      FRACTION
C        DYP(27)     NO      NO        RATE OF CHANGE OF INLET MANIFOLD
C                                      FUEL FRACTION
C        DYP(28)     NO      NO        RATE OF CHANGE OF EXHAUST MANIFOLD
C                                      FUEL FRACTION
C        DYP(29)     NO      NO        RATE OF CHANGE OF LEADING CREVICE
C                                      FUEL MASS FRACTION
C        DYP(30)     NO      NO        RATE OF CHANGE OF TRAILING CREVICE
C                                      FUEL MASS FRACTION
C
C
C
C     REMARKS
C        NONE
C
C     SUBROUTINE AND FUNCTION SUBPROGRAMS REQUIRED
C        THERMO      IPACD       MFLRT       HEATTX
C        CSAVDV      EPACD       CREVIC
C
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C
C     METHOD
C        SEE REPORT
C
C     WRITTEN BY S. H. MANSOURI, S. G. POULOS, AND T. J. NORMAN
C     EDITED BY T. J. NORMAN
C     EDITED BY J. M. ROBERTS
C
      SUBROUTINE INTAKE (DT, DY, DYP)
C
      REAL*8 DT, DY(30), DYP(30)
      REAL MW, MWIM, MWIMM, MASS, MSTART,
     &     MAXERR, IPA, MFUEL
      DIMENSION Y(30), YP(30)
      COMMON/EPARAM/ ECCEN, ROTRAD, DEPTH, VFLANK
      COMMON/TEMPS/TROTOR,TSIDE,THOUS
      COMMON/DTDTH/ ESPDI, RPM
      COMMON/MANFP/ PIM, TIM, EGR, PEM, MSTART
      COMMON/TIMES/ TIPO, TIPC, TEPO, TEPC, THIPO, THEPO, TSPARK
      COMMON/IMTHP/ HIM, MWIM, GIM, RHOIM
      COMMON/FIXX/ INFLAG
      COMMON/HEATS/VELHTX, HTRCOE, HTPARO, HTPASI, HTPAHO, HTXRO,
     &             HTXSI, HTXHO, QFRRO, QFRSI, QFRHO
      COMMON/HTRAN/THTRAN
      COMMON/YYYY1/ VIP, VEP
      COMMON/RHMAS/ RHO, MASS, VOLUME, H, GAMMA
      COMMON/CREV/DRHODP,CSUBT,MW,ITERAS,DVDT,CSUBP,DRHODT,HIMM,RESIDL,
     &            RESFIM,CSUBF,DRHODF
      COMMON/BURN/SPBURN,FIRE,FIREFL
      COMMON/DUMMY/ADUMY,BDUMY,CDUMY
      COMMON/FLOW/FMIN,MFUEL
C
      VIP = 0.0
      VEP = 0.0
C
      DO 10  I = 1, 30
           Y(I) = DY(I)
   10 CONTINUE
      T = DT
      DO 20 I = 1, 30
           YP(I) = 0.0
   20 CONTINUE
C
C        FIND THERMODYNAMIC AND TRANSPORT PROPERTIES IN CHAMBER
C
      RESFRK = 1. - Y(5)
      FR = Y(26)
      CALL THERMO (T, Y(11), Y(12), FR, H, CSUBP, CSUBT, CSUBF,
     &            RHO, DRHODT, DRHODP, DRHODF, GAMMA, MW,
     &            ADUMY, BDUMY, CDUMY, HDUMY)
      MASS = Y(23)
C
C        FIND OUT IF INTAKE PORT IS OPEN.
C
      .
```

```
      IF (T .GE. TIPC) GO TO 50
C
C        YES IT IS.
C        FIND OUT IF ANY MASS FLOWS ACROSS INTAKE PORT.
C
      IF (PIM - Y(12)) 30, 50, 40
C
C        REVERSE FLOW PAST PORT.
C        CALCULATE CD AND EFFECTIVE AREA.
C
   30 PR = Y(12)/PIM
      CALL IPACD (T, AREA, CD)
C
C        CALCULATE MASS FLOW RATE FROM CHAMBER TO INTAKE MANIFOLD.
C
      CALL MFLRT (CD, AREA, Y(12), MW, Y(11), PIM, GAMMA, FRAIV)
C
C        CALCULATE RATES DUE TO THIS FLOW.
C
      YP(1) = -FRAIV
      IF (AREA .LE. 0.0) GO TO 35
      VIP = -FRAIV/(RHO * AREA)*1000.
C
   35 HIMM = H
      GO TO 50
C
C        FLOW INTO CHAMBER.
C        CALCULATE CD AND AREA.
C
   40 PR = PIM/Y(12)
      CALL IPACD (T, AREA, CD)
C
C        CALCULATE THERMODYNAMIC STATE OF MATERIAL FLOWING
C        INTO CHAMBER.
C        INFLAG = 0; CHAMBER GASES IN INTAKE MANIFOLD FLOWING BACK
C        INFLAG = 1; FRESH CHARGE (I.E. AIR, FUEL, AND EGR).
C
      TIMM = TIM * INFLAG + Y(11) * (1 - INFLAG)
      HIMM = HIM * INFLAG + H * (1 - INFLAG)
      MWIMM = MWIM * INFLAG + MW * (1 - INFLAG)
      GIMM = GIM * INFLAG + GAMMA * (1 - INFLAG)
      RHOIMM = RHOIM * INFLAG + RHO * (1 - INFLAG)
C
C        CALCULATE MASS FLOW RATE
C
      CALL MFLRT (CD, AREA, PIM, MWIMM, TIMM, Y(12), GIMM, FRAIV)
C
C        CALCULATE RATES DUE TO THIS FLOW
C
      YP(1) = FRAIV
      YP(26) = ( Y(27) - Y(26)) * YP(1)/MASS
      IF (AREA .LE. 0.0) GO TO 50
      VIP = FRAIV/(RHOIMM * AREA)*1000.
C
```

```
C       IS EXHAUST PORT STILL OPEN ?
C
   50 IF ((T + 1080.) .GE. TEPC) GO TO 80
C
C       YES IT IS.
C       ANY FLOW ACROSS IT ?
C
      IF (Y(12) - PEM) 60, 80, 70
C
C       YES, FLOW INTO CHAMBER.
C       FIND CD AND AREA FOR EXHAUST PORT.
C
   60 PR = PEM/Y(12)
CT
CT       FOR A CORRECT CALCULATION OF THE EXHAUST PORT OPEN
CT       AREA AN ADJUSTED TIME MUST BE USED.
      TEP = T + 1080.
CT
      CALL EPACD (TEP, AREA, CD)
C
C       FIND MASS FLOW RATE.
C
      CALL MFLRT (CD, AREA, PEM, MW, Y(11), Y(12), GAMMA, FRAEV)
C
C       CALCULATE RATES DUE TO THIS FLOW.
C
      YP(2) = -FRAEV
      YP(26) = YP(26) + ( Y(28) - Y(26)) * FRAEV/MASS
      IF (AREA .LE. 0.0) GO TO 80
      VEP = -FRAEV/(RHO * AREA)*1000.
      GO TO 80
C
C       FLOW FROM CHAMBER INTO EXHAUST MANIFOLD.
C       FIND AREA AND CD FOR EXHAUST PORT.
C
   70 PR = Y(12)/PEM
C
C        FOR A CORRECT CALCULATION OF THE EXHAUST PORT OPEN AREA
C        AN ADJUSTED TIME MUST BE USED.
C
      TEP = T + 1080.
      CALL EPACD (TEP, AREA, CD)
C
C       FIND MASS FLOW RATE.
C
      CALL MFLRT (CD, AREA, Y(12), MW, Y(11), PEM, GAMMA, FRAEV)
C
C       CALCULATE RATES DUE TO THIS FLOW.
C
      YP(2) = FRAEV
      IF (AREA .LE. 0.0) GO TO 75
      VEP = FRAEV/(RHO * AREA)*1000.
   75 CONTINUE
C
```

```
C         FIND SURFACE AREAS AND VOLUME OF CHAMBER
C
   80 CALL CSAVDV (T, VOLUME, DVDT)
      MDOT = YP(1) - YP(2)
      MDOTFR = YP(1) * (1. - EGR/100.) * INFLAG - YP(2) * Y(5)
     &          + YP(1) * Y(5) * (1 - INFLAG)
C
C                CALCULATE HEAT TRANSFER RATES
C
C
         CALL HEATTX (T,Y,YP,THTRAN)
C
C
C
C        CALCULATE RATES OF CHANGE OF TEMPERATURE AND PRESSURE IN
C        THE CHAMBER.  THEN CALCULATE RATE OF DOING WORK.
C
   90 CALL CRLVIC (T,Y,YP)
      YP(16) = Y(12) * DVDT * .101325E-3
C
C   CONVERT HEAT TRANSFER RATES TO KILOJOULES
C
      YP(8)  = YP(8) * 1.E-10
      YP(9)  = YP(9) * 1.E-10
      YP(10) = YP(10) * 1.E-10
      THTRAN = THTRAN * 1.E-10 * ESPDI
C
      YP(17) = YP(2) * H/1.0E+6
C
C        CONVERT ALL TIME DERIVATIVES TO RATE PER CRANK
C        ANGLE DEGREE.
C
      DO 100 I = 1, 30
         DYP(I) = YP(I) * ESPDI
  100 CONTINUE
C
      DO 110  I = 1, 30
         DY(I) = Y(I)
  110 CONTINUE
C
      RETURN
      END
```

```
C       SUBROUTINE CMPRES
C
C       PURPOSE
C          CALCULATES OR ASSISTS THE CREVICE AND HEAT TRANSFER SUBROUTINES
C          CALCULATE THE TIME RATE OF CHANGE OF PRESSURE, TEMPERATURE,
C          MASS, HEAT TRANSFER, AND WORK TRANSFER IN THE CHAMBER DURING
C          COMPRESSION.
C
C       USAGE
C          CALL CMPRES (DT, DY, DYP)
C
C       DESCRIPTION OF PARAMETERS
C
C          PARAMETER  INPUT  OUTPUT   DESCRIPTION
C
C          DT          YES    NO       TIME (DEG)
C          DY(5)       YES    NO       MASS FRACTION OF FRESH CHARGE (-)
C          DY(8)       NO     NO       HEAT TRANSFER TO ROTOR (KJ)
C          DY(9)       NO     NO       HEAT TRANSFER TO SIDE PLATES (KJ)
C          DY(10)      NO     NO       HEAT TRANSFER TO HOUSING (KJ)
C          DY(11)      YES    NO       CHAMBER TEMPERATURE (K)
C          DY(12)      YES    NO       CHAMBER PRESSURE (ATM)
C          DY(16)      NO     NO       TOTAL WORK TRANSFER (KJ)
C          DY(18)      NO     NO       TOTAL MASS LEAKED PAST LEAD
C          ------      --     --       APEX SEAL  (G)
C          DY(19)      NO     NO       TOTAL MASS LEAKED PAST TRAILING
C          ------      --     --       APEX SEAL  (G)
C          DY(20)      NO     NO       TOTAL HEAT LOSS TO CREVICE VOLUME
C          ------      --     --       WALLS (KJ)
C          DY(21)      NO     NO       MASS FRACTION OF FRESH CHARGE
C          ------      --     --       IN LEAD CREVICE  (-)
C          DY(22)      NO     NO       MASS FRACTION OF FRESH CHARGE
C          ------      --     --       IN TRAILING CREVICE  (-)
C          DY(23)      YES    NO       TOTAL MASS IN CHAMBER  (G)
C          DY(24)      NO     NO       TOTAL MASS THAT HAS LEFT AND ENTERED
C          ------      --     --       LEADING CHAMBER OR CREVICE (G)
C          DY(25)      NO     NO       TOTAL MASS THAT HAS LEFT AND ENTERED
C          ------      --     --       TRAILING CHAMBER OR CREVICE (G)
C          DY(26)      NO     NO       CHAMBER FUEL MASS FRACTION
C          DY(29)      YES    NO       LEADING CREVICE FUEL MASS FRACTION
C          DY(30)      YES    NO       TRAILING CHAMBER FUEL MASS FRACTION
C
C          ----------------------------------------------------------------
C          DYP(5)      NO     YES      RATE OF CHANGE OF MASS FRACTION OF
C          ------      --     ---      FRESH CHARGE (1/DEG)
C          DYP(8)      NO     YES      RATE OF HEAT TRANSFER THROUGH
C          -------     --     ---      ROTOR WALL  (KJ/DEG)
C          DYP(9)      NO     YES      RATE OF HEAT TRANSFER THROUGH
C          -------     --     ---      SIDE PLATES (KJ/DEG)
C          DYP(10)     NO     YES      RATE OF HEAT TRANSFER THROUGH
C          -------     --     ---      HOUSING  (KJ/DEG)
C          DYP(11)     NO     YES      RATE OF CHANGE OF CHAMBER
C          ------      --     ---      TEMPERATURE (K/DEG)
C          DYP(12)     NO     YES      RATE OF CHANGE OF CHAMBER
```

```
C        ------      --      ---       PRESSURE (ATM/DEG)
C        DYP(16)     NO      YES       RATE OF TOTAL WORK TRANSFER (KJ/DEG)
C        DYP(18)     NO      YES       RATE OF CHANGE OF MASS LEAKED PAST
C        -------     --      ---       LEAD APEX SEAL  (G/DEG)
C        DYP(19)     NO      YES       RATE OF CHANGE OF MASS LEAKED PAST
C        -------     --      ---       TRAILING APEX SEAL (G/DEG)
C        DYP(20)     NO      YES       RATE OF HEAT TRANSFER TO CREVICE
C        -------     --      ---       VOLUME WALLS  (KJ/DEG)
C        DYP(21)     NO      YES       RATE OF CHANGE OF FRESH CHARGE MASS
C        -------     --      ---       FRACTION IN LEAD CREVICE  (/DEG)
C        DYP(22)     NO      YES       RATE OF CHANGE OF FRESH CHARGE MASS
C        -------     --      ---       FRACTION IN TRAILING CREVICE (/DEG)
C        DYP(23)     NO      YES       RATE OF CHANGE OF TOTAL CHAMBER
C        -------     --      ---       MASS (G/DEG)
C        DYP(24)     NO      YES       NET RATE OF CHANGE OF MASS LEAVING
C        -------     --      ---       CHAMBER TO ENTER LEAD CREVICE AND
C        -------     --      ---       LEAD CHAMBER (G/DEG)
C        DYP(25)     NO      YES       NET RATE OF CHANGE OF MASS LEAVING
C        -------     --      ---       CHAMBER TO ENTER TRAILING CREVICE
C        -------     --      ---       AND TRAILING CHAMBER (G/DEG)
C        DYP(26)     NO      NO        RATE OF CHANGE OF CHAMBER FUEL
C                                      FRACTION
C        DYP(29)     NO      NO        RATE OF CHANGE OF LEADING CREVICE
C                                      FUEL MASS FRACTION
C        DYP(30)     NO      NO        RATE OF CHANGE OF TRAILING CREVICE
C                                      FUEL MASS FRACTION
C
C
C
C     REMARKS
C        NONE
C
C     SUBROUTINE AND FUNCTION SUBPROGRAMS REQUIRED
C        THERMO    CSAVDV    CREVIC    HEATTX
C
C
C     METHOD
C        SEE REPORT
C
C     WRITTEN BY S. H. MANSOURI, S. G. POULOS, AND T. J. NORMAN
C     EDITED BY T. J. NORMAN
C
      SUBROUTINE CMPRES (DT,DY,DYP)
C
      REAL*8 DT, DY(30), DYP(30)
      REAL MW, MWIM, MWIMM, MASS, MSTART, MFUEL
      DIMENSION Y(30), YP(30)
      COMMON/EPARAM/ ECCEN, ROTRAD, DEPTH, VFLANK
      COMMON/TEMPS/TROTOR,TSIDE,THOUS
      COMMON/DTDTH/ ESPDI, RPM
      COMMON/MANFP/ PIM, TIM, EGR, PEM, MSTART
      COMMON/TIMES/ TIPO, TIPC, TEPO, TEPC, THIPO, THEPO, TSPARK
      COMMON/IMTHP/ HIM, MWIM, GIM, RHOIM
      COMMON/FIXX/ INFLAG
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```
      COMMON/HEATS/VELHTX, HTRCOE, HTPARO, HTPASI, HTPAHO, HTXRO,
     &              HTXSI, HTXHO, QFRRO, QFRSI, QFRHO
      COMMON/HTRAN/THTRAN
      COMMON/YYYY1/ VIP, VEP
      COMMON/RHMAS/ RHO, MASS, VOLUME, H, GAMMA
      COMMON/CREV/DRHODP,CSUBT,MW,ITERAS,DVDT,CSUBP,DRHODT,HIMM,RESIDL,
     &             RESFIM,CSUBF,DRHODF
      COMMON/BURN/SPBURN,FIRE,FIREFL
      COMMON/DUMMY/ADUMY,BDUMY,CDUMY
      COMMON/FLOW/FMIN,MFUEL
C
C
      DO 10  I = 1, 30
           Y(I) = DY(I)
   10 CONTINUE
      T = DT
      DO 20 I = 1, 30
           YP(I) = 0.0
   20 CONTINUE
C
C        FIND THERMODYNAMIC AND TRANSPORT PROPERTIES IN CHAMBER
C
      CALL THERMO (T, Y(11), Y(12), Y(26), H, CSUBP, CSUBT, CSUBF,
     &              RHO, DRHODT, DRHODP, DRHODF, GAMMA, MW,
     &              ADUMY, BDUMY, CDUMY, HDUMY)
      MASS = Y(23)
C
C        FIND SURFACE AREAS AND VOLUME OF CHAMBER
C
      CALL CSAVDV (T, VOLUME, DVDT)
C
C                  CALCULATE HEAT TRANSFER RATES
C
C
         CALL HEATTX (T,Y,YP,THTRAN)
C
C
C
C        CALCULATE RATES OF CHANGE OF TEMPERATURE AND PRESSURE IN
C        THE CHAMBER.  THEN CALCULATE RATE OF DOING WORK.
C
   30 CALL CREVIC (T,Y,YP)
      YP(16) = Y(12) * DVDT * .101325E-3
C
C         CONVERT THE HEAT TRANSFER RATES TO KILO JOULES
C
      YP(8)  = YP(8) * 1.E-10
      YP(9)  = YP(9) * 1.E-10
      YP(10) = YP(10) * 1.E-10
      THTRAN = THTRAN * 1.E-10 * ESPDI
C
C        CONVERT ALL TIME DERIVATIVES TO RATE PER CRANK
C        ANGLE DEGREE.
C
```

```
      DO 40 I = 1, 30
           DYP(I) = YP(I) * ESPDI
   40 CONTINUE
C
      DO 50  I = 1, 30
           DY(I) = Y(I)
   50 CONTINUE
C
      RETURN

      END
```

```
C      SUBROUTINE CMBSTN
C
C      PURPOSE
C         CALCULATES OR ASSISTS THE CREVICE AND HEAT TRANSFER SUBROUTINES
C         CALCULATE THE TIME RATE OF CHANGE OF PRESSURE, TEMPERATURE,
C         MASS, HEAT TRANSFER,AND WORK TRANSFERIN THE CHAMBER DURING
C         COMBUSTION.
C
C      USAGE
C         CALL CMBSTN (DT, DY, DYP)
C
C      DESCRIPTION OF PARAMETERS
C
C         PARAMETER  INPUT  OUTPUT   DESCRIPTION
C
C         DT         YES    NO       TIME (DEG)
C         DY(3)      NO     NO       FUEL ENERGY THAT ENTERS EXAUST
C         -----      --     --       CHAMBER (KJ)
C         DY(4)      YES    NO       MASS FRACTION BURNED (-)
C         DY(8)      NO     NO       HEAT TRANSFER TO ROTOR (KJ)
C         DY(9)      NO     NO       HEAT TRANSFER TO SIDE PLATES (KJ)
C         DY(10)     NO     NO       HEAT TRANSFER TO HOUSING (KJ)
C         DY(12)     YES    NO       CYLINDER PRESSURE (ATM)
C         DY(16)     NO     NO       TOTAL WORK TRANSFER (KJ)
C         DY(18)     NO     NO       TOTAL MASS LEAKED PAST LEAD
C         ------     --     --       APEX SEAL  (G)
C         DY(19)     NO     NO       TOTAL MASS LEAKED PAST TRAILING
C         ------     --     --       APEX SEAL  (G)
C         DY(20)     NO     NO       TOTAL HEAT LOSS TO CREVICE VOLUME
C         ------     --     --       WALLS (KJ)
C         DY(21)     NO     NO       MASS FRACTION OF FRESH CHARGE
C         ------     --     --       IN LEAD CREVICE  (-)
C         DY(22)     NO     NO       MASS FRACTION OF FRESH CHARGE
C         ------     --     --       IN TRAILING CREVICE  (-)
C         DY(23)     YES    NO       TOTAL MASS IN CHAMBER  (G)
C         DY(24)     NO     NO       TOTAL MASS THAT HAS LEFT AND ENTERED
C         ------     --     --       LEADING CHAMBER OR CREVICE (G)
C         DY(25)     NO     NO       TOTAL MASS THAT HAS LEFT AND ENTERED
C         ------     --     --       TRAILING CHAMBER OR CREVICE (G)
C         DY(26)     YES    NO       CHAMBER FUEL FRACTION
C         DY(29)     YES    NO       LEADING CREVICE FUEL MASS FRACTION
C         DY(30)     YES    NO       TRAILING CREVICE FUEL MASS FRACTION
C
C         -------------------------------------------------------------
C
C         DYP(3)     NO     YES      RATE OF FUEL ENTERING EXHAUST
C         ------     --     ---      CHAMBER.
C         DYP(4)     NO     YES      RATE OF CHANGE OF MASS FRACTION
C         ------     --     ---      BURNED (1/DEG)
C         DYP(8)     NO     YES      RATE OF HEAT TRANSFER THROUGH
C         -------    --     ---      ROTOR WALL  (KJ/DEG)
C         DYP(9)     NO     YES      RATE OF HEAT TRANSFER THROUGH
C         -------    --     ---      SIDE PLATES (KJ/DEG)
C         DYP(10)    NO     YES      RATE OF HEAT TRANSFER THROUGH
```

```
C        -------     --      ---       HOUSING  (KJ/DEG)
C        DYP(11)     NO      YES       RATE OF CHANGE OF CHAMBER TEMPERATURE
C        DYP(12)     NO      YES       RATE OF CHANGE OF CHAMBER
C        ------      --      ---       PRESSURE (ATM/DEG)
C        DYP(16)     NO      YES       RATE OF TOTAL WORK TRANSFER (KJ/DEG)
C        DYP(18)     NO      YES       RATE OF CHANGE OF MASS LEAKED PAST
C        -------     --      ---       LEAD APEX SEAL (G/DEG)
C        DYP(19)     NO      YES       RATE OF CHANGE OF MASS LEAKED PAST
C        -------     --      ---       TRAILING APEX SEAL  (G/DEG)
C        DYP(20)     NO      YES       RATE OF HEAT TRANSFER TO CREVICE
C        -------     --      ---       VOLUME WALLS  (KJ/DEG)
C        DYP(21)     NO      YES       RATE OF CHANGE OF FRESH CHARGE MASS
C        -------     --      ---       FRACTION IN LEAD CREVICE  (/DEG)
C        DYP(22)     NO      YES       RATE OF CHANGE OF FRESH CHARGE MASS
C        -------     --      ---       FRACTION IN TRAILING CREVICE (/DEG)
C        DYP(23)     NO      YES       RATE OF CHANGE OF TOTAL CHAMBER
C        -------     --      ---       MASS (G/DEG)
C        DYP(24)     NO      YES       NET RATE OF CHANGE OF MASS LEAVING
C        -------     --      ---       CHAMBER TO ENTER LEAD CREVICE AND
C        -------     --      ---       LEAD CHAMBER (G/DEG)
C        DYP(25)     NO      YES       NET RATE OF CHANGE OF MASS LEAVING
C        -------     --      ---       CHAMBER TO ENTER TRAILING CREVICE
C        -------     --      ---       AND TRAILING CHAMBER (G/DEG)
C        DYP(26)     NO      YES       RATE OF CHANGE OF CHAMBER FUEL MASS
C                                      FRACTION
C        DYP(29)     NO      YES       RATE OF CHANGE OF LEADING CREVICE
C                                      FUEL MASS FRACTION
C        DYP(30)     NO      YES       RATE OF CHANGE OF TRAILING CREVICE
C                                      FUEL MASS FRACTION
C
C
C
C     REMARKS
C        NONE
C
C     SUBROUTINE AND FUNCTION SUBPROGRAMS REQUIRED
C        THERMO   CSAVDV    CREVIC    HEATTX
C
C
C     METHOD
C        SEE REPORT
C
C     WRITTEN BY S. H. MANSOURI, K. RADHAKRISHNAN, S. G. POULOS, AND
C                T. J. NORMAN
C     EDITED BY T. J. NORMAN
C     EDITED BY J. M. ROBERTS
C
      SUBROUTINE CMBSTN (DT,DY,DYP)
C
      LOGICAL SPBURN,BURN,FIREFL
      REAL*8 DT,DY(30),DYP(30)
      REAL MW,MWIM,MWIMM,MASS,MSTART,MFUEL
      DIMENSION Y(30),YP(30)
      COMMON/EPARAM/ ECCEN, ROTRAD, DEPTH, VFLANK
```

```
      COMMON/TEMPS/TROTOR,TSIDE,THOUS
      COMMON/BURN/ SPBURN, FIRE, FIREFL
      COMMON/DTDTH/ ESPDI, RPM
      COMMON/MANFP/ PIM,TIM,EGR,PEM, MSTART
      COMMON/TIMES/ TIPO, TIPC, TEPO, TEPC, THIPO, THEPO, TSPARK
      COMMON/IMTHP/ HIM,MWIM,GIM,RHOIM
      COMMON/FIXX/ INFLAG
      COMMON/HEATS/VELHTX, HTRCOE, HTPARO, HTPASI, HTPAHO, HTXRO,
     &             HTXSI, HTXHO,  QFRRO, QFRSI, QFRHO
      COMMON/HTRAN/THTRAN
      COMMON/YYYY1/ VIP, VEP
      COMMON/SPECB/ TMAX, TAU, DQDTMAX
      COMMON/XSTOP/ XBSTOP
      COMMON/CREV/DRHODP,CSUBT,MW,ITERAS,DVDT,CSUBP,DRHODT,HIMM,RESIDL,
     &            RESFIM,CSUBF,DRHODF
      COMMON/RHMAS/RHO,MASS,VOLUME,H,GAMMA
      COMMON/DUMMY/ADUMY,BDUMY,CDUMY
      COMMON/FLOW/FMIN,MFUEL
C
C
CJ    DATA CONSAM,CONSEM/1.0,1.0/
C
      FIREFL = .TRUE.
C
      DO 10  I = 1, 30
           Y(I) = DY(I)
   10 CONTINUE
      T = DT
      DO 20 I = 1, 30
           YP(I) = 0.0
   20 CONTINUE
C
C        FIND THERMODYNAMIC AND TRANSPORT PROPERTIES IN CYLINDER
C
      FR = Y(26)
      CALL THERMO (T, Y(11), Y(12), FR, H, CSUBP, CSUBT, CSUBF,
     &             RHO, DRHODT, DRHODP, DRHODF, GAMMA, MW,
     &            ADUMY, BDUMY, CDUMY, XXA)
C
C
      MASS  = Y(23)
C
C
      CALL CSAVDV (T, VOLUME, DVDT)
C
C        SPECIFIED BURN RATE COMBUSTION MODEL
C
 30   IF ( T .GT. TMAX ) GO TO 35
      YP(4) = ((DQDTMAX/(TMAX-TSPARK))*(T-TSPARK))/ESPDI
      IF(YP(4).LT.0.0)YP(4)=0.0
      GO TO 40
 35   YP(4) = (DQDTMAX*EXP(-(T-TMAX)/TAU))/ESPDI
      IF(YP(4).LT.0.0)YP(4)=0.0
      IF (Y(4) .GE. XBSTOP) YP(4) = YP(4)/1.5
```

```
      IF (Y(4) .GE. 0.998)  YP(4) = YP(4)/1.5
      IF (Y(4) .GE. 0.999)  YP(4) = YP(4)/1.5
      IF (Y(4) .GE. 0.9999) YP(4) = 0.0
C
   40 CONTINUE
C
      MFUEL = FMIN * YP(4)
C
      YP(26) = MFUEL/MASS*(1.-Y(26))
C
      CALL HEATTX (T, Y, YP, THTRAN)
C
C        CALCULATE RATES OF CHANGE OF TEMPERATURE AND PRESSURE IN
C        THE CYLINDER.  THEN CALCULATE RATE OF DOING WORK.
C
      CALL CREVIC (T,Y,YP)
C
      YP(16) = Y(12) * DVDT * .101325E-3
C
C        CONVERT THE TOTAL HEAT TRANSFER RATES TO KJ/SEC
C
      YP(8) = YP(8) * 1.E-10
      YP(9) = YP(9) * 1.E-10
      YP(10)= YP(10)*1.E-10
C
      THTRAN = THTRAN * 1.E-10 * ESPDI
C
C        CONVERT ALL TIME DERIVATIVES TO RATE PER CRANK
C        ANGLE DEGREE.
C
   70 DO 80 I = 1, 30
           DYP(I) = YP(I) * ESPDI
   80 CONTINUE
C
      DO 90  I = 1, 30
           DY(I) = Y(I)
   90 CONTINUE
C
      RETURN
      END
```

```
C     SUBROUTINE EXAUST
C
C     PURPOSE
C        CALCULATES OR ASSISTS THE CREVICE AND HEAT TRANSFER SUBROUTINES
C        CALCULATE THE TIME RATE OF CHANGE OF PRESSURE, TEMPERATURE,
C        MASS, HEAT TRANSFER, AND WORK TRANSFERIN THE CHAMBER DURING
C        EXAUST.
C
C     USAGE
C        CALL EXAUST (DT, DY, DYP)
C
C     DESCRIPTION OF PARAMETERS
C
C        PARAMETER  INPUT  OUTPUT   DESCRIPTION
C
C        DT         YES    NO       TIME (DEG)
C        DY(2)      NO     NO       MASS EXHAUSTED FROM CHAMBER THROUGH
C        -----      ---    --       EXHAUST PORT (G)
C        DY(3)      NO     NO       FUEL ENERGY THAT ENTERS EXAUST (KJ)
C        DY(8)      NO     NO       HEAT TRANSFER TO ROTOR (KJ)
C        DY(9)      NO     NO       HEAT TRANSFER TO SIDE PLATES (KJ)
C        DY(10)     NO     NO       HEAT TRANSFER TO HOUSING (KJ)
C        DY(11)     YES    NO       CHAMBER TEMPERATURE (K)
C        DY(12)     YES    NO       CHAMBER PRESSURE (ATM)
C        DY(16)     NO     NO       TOTAL WORK TRANSFER (KJ)
C        DY(17)     NO     NO       TOTAL ENTHALPY EXHAUSTED (KJ)
C        DY(18)     NO     NO       TOTAL MASS LEAKED PAST LEAD
C        ------     --     --       APEX SEAL  (G)
C        DY(19)     NO     NO       TOTAL MASS LEAKED PAST TRAILING
C        ------     --     --       APEX SEAL  (G)
C        DY(20)     NO     NO       TOTAL HEAT LOSS TO CREVICE VOLUME
C        ------     --     --       WALLS (KJ)
C        DY(21)     NO     NO       MASS FRACTION OF FRESH CHARGE
C        ------     --     --       IN LEAD CREVICE  (-)
C        DY(22)     NO     NO       MASS FRACTION OF FRESH CHARGE
C        ------     --     --       IN TRAILING CREVICE  (-)
C        DY(23)     YES    NO       TOTAL MASS IN CHAMBER  (G)
C        DY(24)     NO     NO       TOTAL MASS THAT HAS LEFT AND ENTERED
C        ------     --     --       LEADING CHAMBER OR CREVICE (G)
C        DY(25)     NO     NO       TOTAL MASS THAT HAS LEFT AND ENTERED
C        ------     --     --       TRAILING CHAMBER OR CREVICE (G)
C        DY(26)     YES    NO       CHAMBER FUEL MASS FRACTION
C        DY(28)     YES    NO       EXHAUST MANIFOLD FUEL MASS FRACTION
C        DY(29)     YES    NO       LEADING CREVICE FUEL MASS FRACTION
C        DY(30)     YES    NO       TRAILING CREVICE FUEL MASS FRACTION
C
C        -------------------------------------------------------------
C
C        DYP(2)     NO     YES      RATE AT WHICH MASS IS EXHAUSTED
C        ------     --     ---      THROUGH THE EXHAUST PORT (G/DEG)
C        DYP(3)     NO     YES      RATE OF FUEL ENERGY ENTERING
C        ------     ---    ---      EXHAUST CHAMBER (KJ/DEG)
C        DYP(8)     NO     YES      RATE OF HEAT TRANSFER THROUGH
C        -------    --     ---      ROTOR WALL  (KJ/DEG)
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```
C        DYP(9)      NO      YES       RATE OF HEAT TRANSFER THROUGH
C        -------     --      ---       SIDE PLATES (KJ/DEG)
C        DYP(10)     NO      YES       RATE OF HEAT TRANSFER THROUGH
C        -------     --      ---       HOUSING  (KJ/DEG)
C        DYP(11)     NO      YES       RATE OF CHANGE OF CHAMBER
C        ------      --      ---       TEMPERATURE (K/DEG)
C        DYP(12)     NO      YES       RATE OF CHANGE OF CHAMBER
C        ------      --      ---       PRESSURE (ATM/DEG)
C        DYP(16)     NO      YES       RATE OF TOTAL WORK TRANSFER (KJ/DEG)
C        DYP(17)     NO      YES       RATE AT WHICH TOTAL ENTHALPY IS
C        -------     --      ---       EXHAUSTED (KJ/DEG)
C        DYP(18)     NO      YES       RATE OF CHANGE OF MASS LEAKED PAST
C        -------     --      ---       LEAD APEX SEAL (G/DEG)
C        DYP(19)     NO      YES       RATE OF CHANGE OF MASS LEAKED PAST
C        -------     --      ---       TRAILING APEX SEAL (G/DEG)
C        DYP(20)     NO      YES       RATE OF HEAT TRANSFER TO CREVICE
C        -------     --      ---       VOLUME WALLS (KJ/DEG)
C        DYP(21)     NO      YES       RATE OF CHANGE OF FRESH CHARGE MASS
C        -------     --      ---       FRACTION IN LEAD CREVICE (/DEG)
C        DYP(22)     NO      YES       RATE OF CHANGE OF FRESH CHARGE MASS
C        -------     --      ---       FRACTION IN TRAILING CREVICE (/DEG)
C        DYP(23)     NO      YES       RATE OF CHANGE OF TOTAL CHAMBER
C        -------     --      ---       MASS (G/DEG)
C        DYP(24)     NO      YES       NET RATE OF CHANGE OF MASS LEAVING
C        -------     --      ---       CHAMBER TO ENTER LEAD CREVICE AND
C        -------     --      ---       LEAD CHAMBER (G/DEG)
C        DYP(25)     NO      YES       NET RATE OF CHANGE OF MASS LEAVING
C        -------     --      ---       CHAMBER TO ENTER TRAILING CREVICE
C        -------     --      ---       AND TRAILING CHAMBER  (G/DEG)
C        DYP(26)     NO      YES       RATE OF CHANGE OF CHAMBER FUEL MASS
C                                      FRACTION
C        DYP(29)     NO      YES       RATE OF CHANGE OF LEADING CREVICE
C                                      FUEL MASS FRACTION
C        DYP(30)     NO      YES       RATE OF CHANGE OF TRAILING CREVICE
C                                      FUEL MASS FRACTION
C
C
C
C     REMARKS
C        NONE
C
C     SUBROUTINE AND FUNCTION SUBPROGRAMS REQUIRED
C        THERMO     MFLRT     CREVIC
C        CSAVDV     EPACD      HEATTX
C
C
C     METHOD
C        SEE REPORT
C
C     WRITTEN BY S. H. MANSOURI, S. G. POULOS, AND T. J. NORMAN
C     EDITED BY T. J. NORMAN
C     EDITED BY J. M. ROBERTS
C
      SUBROUTINE EXAUST (DT, DY, DYP)
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```
C
      LOGICAL FIRE
      REAL*8 DT, DY(30), DYP(30)
      REAL MW, MWIM, MWIMM, MASS, MSTART, MFUEL
      DIMENSION Y(30), YP(30)
      COMMON/EPARAM/ ECCEN, ROTRAD, DEPTH, VFLANK
      COMMON/BURN/ SPBURN, FIRE, FIREFL
      COMMON/TEMPS/TROTOR,TSIDE,THOUS
      COMMON/DTDTH/ ESPDI, RPM
      COMMON/MANFP/ PIM, TIM, EGR, PEM, MSTART
      COMMON/TIMES/ TIPO, TIPC, TEPO, TEPC, THIPO, THEPO, TSPARK
      COMMON/IMTHP/ HIM, MWIM, GIM, RHOIM
      COMMON/FIXX/ INFLAG
      COMMON/HEATS/VELHTX, HTRCOE, HTPARO, HTPASI, HTPAHO, HTXRO,
     &             HTXSI, HTXHO, QFRRO, QFRSI, QFRHO
      COMMON/HTRAN/THTRAN
      COMMON/YYYY1/ VIP, VEP
      COMMON/RHMAS/ RHO, MASS, VOLUME, H, GAMMA
      COMMON/CREV/DRHODP,CSUBT,MW,ITERAS,DVDT,CSUBP,DRHODT,HIMM,RESIDL,
     &            RESFIM,CSUBF,DRHODF
      COMMON/FLFR/FSTART
      COMMON/DUMMY/ADUMY,BDUMY,CDUMY
      COMMON/FLOW/FMIN,MFUEL
C
      VEP = 0.0
      FIREFL = .FALSE.
C
      DO 10  I = 1, 30
           Y(I) = DY(I)
   10 CONTINUE
      T = DT
      DO 20 I = 1, 30
           YP(I) = 0.0
   20 CONTINUE
C
C         FIND THERMODYNAMIC AND TRANSPORT PROPERTIES IN CHAMBER
C
      Y(28) = FSTART
      FR = Y(26)
      CALL THERMO (T, Y(11), Y(12), FR, H, CSUBP, CSUBT, CSUBF,
     &             RHO, DRHODT, DRHODP, DRHODF, GAMMA, MW,
     &             ADUMY, BDUMY, CDUMY, HDUMY)
      MASS = Y(23)
C
C         IS EXHAUST PORT STILL OPEN ?
C
      IF (T .GE. TEPC) GO TO 50
C
C         YES IT IS.
C         ANY FLOW ACROSS IT ?
C
      IF (Y(12) - PEM) 30, 50, 40
C
C         YES, FLOW INTO CHAMBER.
```

```
C        FIND CD AND AREA FOR EXHAUST PORT.
C
   30 PR = PEM/Y(12)
      CALL EPACD (T, AREA, CD)
C
C        FIND MASS FLOW RATE.
C
      CALL MFLRT (CD, AREA, PEM, MW, Y(11), Y(12), GAMMA, FRAEV)
C
C        CALCULATE RATES DUE TO THIS FLOW.
C
      YP(2) = -FRAEV
      IF (AREA .LE. 0.0) GO TO 35
      VEP=FRAEV/(RHO*AREA)*10.
 35   YP(26) = YP(26) + (Y(28) - Y(26))*FRAEV/MASS
      GO TO 50
C
C        FLOW FROM CHAMBER INTO EXHAUST MANIFOLD.
C        FIND AREA AND CD FOR EXHAUST PORT.
C
   40 PR = Y(12)/PEM
      CALL EPACD (T, AREA, CD)
C
C        FIND MASS FLOW RATE.
C
      CALL MFLRT (CD, AREA, Y(12), MW, Y(11), PEM, GAMMA, FRAEV)
C
C        CALCULATE RATES DUE TO THIS FLOW
C
      YP(2) = FRAEV
      IF (AREA .LE. 0.0) GO TO 45
      VEP = FRAEV/(RHO * AREA)*10.
   45 CONTINUE
C
C        FIND SURFACE AREAS AND VOLUME OF CHAMBER
C
   50 CALL CSAVDV (T, VOLUME, DVDT)
C
C                CALCULATE HEAT TRANSFER RATES
C
C
C
      CALL HEATTX (T, Y, YP, THTRAN)
C
C        CALCULATE RATES OF CHANGE OF TEMPERATURE AND PRESSURE IN
C        THE CHAMBER.  THEN CALCULATE RATE OF DOING WORK.
C
   60 CALL CREVIC (T,Y,YP)
      YP(16) = Y(12) * DVDT * .101325E-3
C
C CONVERT HEAT TRANSFER RATES TO KJ/SEC
C
      YP(8)  = YP(8) * 1.E-10
      YP(9)  = YP(9) * 1.E-10
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```
      YP(10) = YP(10) * 1.E-10
      THTRAN = THTRAN * 1.E-10 * ESPDI
C
      YP(17) = YP(2) * H/1.E+6
C
C        CONVERT ALL TIME DERIVATIVES TO RATE PER CRANK
C        ANGLE DEGREE.
C
      DO 70 I = 1, 30
          DYP(I) = YP(I) * ESPDI
   70 CONTINUE
C
      DO 80  I = 1, 30
          DY(I) = Y(I)
   80 CONTINUE
C
      RETURN
      END
```

```
C     SUBROUTINE CREVIC
C
C     PURPOSE
C        TO CALCULATE THE LEAKAGE AND CREVICE VOLUME MASS FLOW RATES
C        AND COMPOSITIONS. BECAUSE AN ASSUMPTION FOR NET FLOW DIRECTION
C        AT EACH APEX MUST BE MADE, AND THEN CHECKED, SEVERAL OF THE
C        INTEGRATION VARIABLES ARE EVALUATED IN THIS SUBROUTINE
C        RATHER THAN THE PROCESS SUBROUTINES.
C
C     USAGE
C        CALL CREVIC (T,Y,YP)
C
C     DESCRIPTION OF PARAMETERS
C
C        PARAMETER  INPUT  OUTPUT   DESCRIPTION
C
C        DT          YES    NO       TIME (DEG)
C        DY(3)       NO     NO       FUEL ENERGY THAT ENTERS EXAUST
C        -----       --     --       CHAMBER (KJ)
C        DY(4)       NO     NO       MASS FRACTION BURNED (-)
C        DY(5)       YES    NO       MASS FRACTION OF FRESH CHARGE (-)
C        DY(11)      YES    NO       CHAMBER TEMPERATURE (K)
C        DY(12)      YES    NO       CHAMBER PRESSURE (ATM)
C        DY(18)      NO     NO       TOTAL MASS LEAKED PAST LEAD
C        ------      --     --       APEX SEAL  (G)
C        DY(19)      NO     NO       TOTAL MASS LEAKED PAST TRAILING
C        ------      --     --       APEX SEAL  (G)
C        DY(20)      NO     NO       TOTAL HEAT LOSS TO CREVICE VOLUME
C        ------      --     --       WALLS (KJ)
C        DY(21)      YES    NO       MASS FRACTION OF FRESH CHARGE
C        ------      ---    --       IN LEAD CREVICE  (-)
C        DY(22)      YES    NO       MASS FRACTION OF FRESH CHARGE
C        ------      ---    --       IN TRAILING CREVICE  (-)
C        DY(23)      YES    NO       TOTAL MASS IN CHAMBER  (G)
C        DY(24)      NO     NO       TOTAL MASS IN LEADING CREVICE (G)
C        DY(25)      NO     NO       TOTAL MASS IN TRAILING CREVICE (G)
C        DY(26)      YES    NO       CHAMBER FUEL MASS FRACTION
C        DY(29)      YES    NO       LEADING CREVICE FUEL MASS FRACTION
C        DY(30)      YES    NO       TRAILING CREVICE FUEL MASS FRACTION
C        -----------------------------------------------------------------
C
C        DYP(1)      YES    NO       RATE AT WHICH MASS IS INDUCTED
C        ------      --     --       THROUGH THE INTAKE PORT
C        DYP(2)      YES    NO       RATE AT WHICH MASS IS EXHAUSTED
C        ------      --     --       THROUGH THE EXHAUST PORT
C        DYP(3)      NO     YES      RATE OF FUEL ENTERING EXHAUST
C        ------      --     ---      CHAMBER.
C        DYP(4)      YES    NO       RATE OF CHANGE OF MASS FRACTION
C        ------      --     ---      BURNED
C        DYP(5)      NO     YES      RATE OF CHANGE OF MASS FRACTION OF
C        ------      --     ---      FRESH CHARGE IN CHAMBER
C        DYP(11)     NO     YES      RATE OF CHANGE OF CHAMBER
C        ------      --     ---      TEMPERATURE
C        DYP(12)     NO     YES      RATE OF CHANGE OF CHAMBER
```

```
C        ------      --      ---       PRESSURE
C        DYP(13)     NO      YES       RATE OF CHANGE OF UNBURNED MIXTURE
C        ------      --      ---       TEMPERATURE DURING COMBUSTION
C        DYP(14)     NO      YES       RATE OF CHANGE OF UNBURNED MIXTURE
C        -------     --      ---       VOLUME DURING COMBUSTION
C        DYP(15)     NO      YES       RATE OF CHANGE OF BURNED PRODUCTS
C        ------      --      ---       TEMPERATURE DURING COMBUSTION
C        DYP(18)     NO      YES       RATE OF CHANGE OF MASS LEAKED PAST
C        -------     --      ---       LEAD APEX SEAL
C        DYP(19)     NO      YES       RATE OF CHANGE OF MASS LEAKED PAST
C        -------     --      ---       TRAILING APEX SEAL
C        DYP(20)     NO      YES       RATE OF HEAT TRANSFER TO CREVICE
C        -------     --      ---       VOLUME WALLS
C        DYP(21)     NO      YES       RATE OF CHANGE OF FRESH CHARGE MASS
C        -------     --      ---       FRACTION IN LEAD CREVICE
C        DYP(22)     NO      YES       RATE OF CHANGE OF FRESH CHARGE MASS
C        -------     --      ---       FRACTION IN TRAILING CREVICE
C        DYP(23)     NO      YES       RATE OF CHANGE OF TOTAL CHAMBER
C        -------     --      ---       MASS
C        DYP(24)     NO      YES       NET RATE OF CHANGE OF MASS LEAVING
C        -------     --      ---       CHAMBER TO ENTER LEAD CREVICE AND
C        -------     --      ---       LEAD CHAMBER
C        DYP(25)     NO      YES       NET RATE OF CHANGE OF MASS LEAVING
C        -------     --      ---       CHAMBER TO ENTER TRAILING CREVICE
C        -------     --      ---       AND TRAILING CHAMBER
C        DYP(26)     YES     NO        RATE OF CHANGE OF CHAMBER FUEL MASS
C                                      FRACTION
C        DYP(29)     NO      YES       RATE OF CHANGE OF LEADING CREVICE
C                                      FUEL MASS FRACTION
C        DYP(30)     NO      YES       RATE OF CHANGE OF TRAILING CREVICE
C                                      FUEL MASS FRACTION
C
C
C     REMARKS
C       - LEAD CHAMBER REFERS TO THE CHAMBER AHEAD (IN THE DIRECTION
C         OF ROTATION) OF THE THERMODYNAMIC SYSTEM.
C
C       - LAG (OR TRAILING) CHAMBER REFERS TO THE CHAMBER BEHIND.
C
C       - REFER TO PROCESS ROUTINES FOR UNITS OF INTEGRATION VARIABLES.
C
C     SUBROUTINE AND FUNCTION SUBPROGRAMS REQUIRED
C        THERMO     MFLRT      TABLE
C
C
C     METHOD
C        SEE REPORT
C
C     WRITTEN BY T. J. NORMAN
C
      SUBROUTINE CREVIC(T,Y,YP)
C
      LOGICAL FIRE,FIREFL
      REAL MW, MWLDC, MWLGC, MASS, MASLDC,
```

```
     &     MDOTDC, MASLGC, MDOTGC, LDLEAK, LGLEAK,
     &     MDOTLD, MDOTLG, MFUEL
      DIMENSION Y(30), YP(30)
      COMMON/RHMAS/RHO,MASS,VOLUME,H,GAMMA
      COMMON/TEMPS/TROTOR,TSIDE,THOUS
      COMMON/HEATS/VELHTX, HTRCOE, HTPARO, HTPASI, HTPAHO,
     &       HTXRO, HTXSI, HTXHO, QFRRO, QFRSI, QFRHO
      COMMON/HTRAN/THTRAN
      COMMON/CREV/DRHODP,CSUBT,MW,ITERAS,DVDT,CSUBP,DRHODT,HIMM,
     &            RESIDL,RESFIM,CSUBF,DRHODF
      COMMON/CREV2/ MASLDC, MASLGC
      COMMON/BURN/ SPBURN, FIRE, FIREFL
      COMMON/FIXX/ INFLAG
      COMMON/MANFP/ PIM, TIM, EGR, PEM, MSTART
      COMMON/CREVQ/CRMASD,CRMASG,X1LDC,X1LAGC,ZMAST,ZMASS,ZLEAKD,
     &             ZLEAKG,ZCRCOD,ZCRCOG,FRZCRCOD,FRZCRCOG
      COMMON/CREVIN/AREALK,CREVOL,TCREV,X1LDIN,X1LGIN,FRLDIN,
     &                    FRLGIN
      COMMON/DUMMY/ADUMY,BDUMY,CDUMY
      COMMON/FUEL/FUELTP, ENW, CX, HY, OZ, DEL, PSI, PHICON, PHI,
     &            QLOWER, FASTO, HFORM
      COMMON/FLOW/FMIN,MFUEL
C
C       FIND THE THERMODYNAMIC PROPERTIES OF THE FRESH CHARGE AND THE
C       BURNED GASES IN THE CHAMBER.
C
      TCR  = TCREV
      AREA = AREALK
      MASS = Y(23)
      VOLLDC = CREVOL
      VOLLGC = CREVOL
C
C       DURING THE FIRST ITERATION THE CREVICE AND LEAKAGE MODELS
C       ARE INACTIVE BECAUSE NO PRESSURE HISTORY IS AVAILABLE.
C
          IF (ITERAS .NE. 1) GO TO 300
                MASLDC = 0.0
                MDOTDC = 0.0
                MASLGC = 0.0
                MDOTGC = 0.0
                LDLEAK = 0.0
                LGLEAK = 0.0
C
          GO TO 120
C
C       FIND THE PRESSURES IN THE ADJACENT CHAMBERS AND THE COMPOSITION
C       OF THE TWO CREVICE VOLUMES FROM THE STORED VALUES OF THE LAST
C       ITERATION
C
  300 CALL TABLE (T,Y,PLEAD,PLAG,X1LD,X1LG,FRLD,FRLG)
C
C       BECAUSE OF CHAMBER PRESSURE DIFFERENCES BETWEEN ITERATIONS
C       IT IS POSSIBLE THAT THE TABLE DOES NOT HOLD THE NECESSARY
C       CREVICE COMPOSITION INFORMATION NEAR THE 'SWITCHOVER' POINT
```

```
C       IF THIS OCCURS THE PROGRAM ASSIGNS THE LAST KNOWN VALUE OF
C       THE COMPOSITION FROM THE PREVIOUS ITERATION.
C
          IF (X1LD .LE. 0.0) X1LD = 0.001
          IF (X1LD .GT. 1.0) X1LD = 1.0
          IF (X1LG .LE. 0.0) X1LG = 0.001
          IF (X1LG .GT. 1.0) X1LG = 1.0
          IF(FRLD .GT. 1.0)FRLD = 1.0
          IF(FRLD .LT. 0.0)FRLD = 0.0
          IF(FRLG .GT. 1.0)FRLG = 1.0
          IF(FRLG .LT. 0.0)FRLG = 0.0
C
C
C       DETERMINE THE PRESSURE DIFFERENCE ACROSS EACH APEX SEAL
C
C
      IF (PLEAD .GE. Y(12)) GO TO 40
C
C         THE CHAMBER HAS A HIGHER PRESSURE THAN THE LEAD CHAMBER
C         SO THE LEAD CREVICE IS ASSOCIATED WITH THE CHAMBER AND
C         LEAKAGE FLOWS FROM THE LEAD CREVICE TO THE LEAD CHAMBER.
C
C
      PLEADC = Y(12)
C
C  THERE IS A LEADING CREVICE VOLUME AND IT IS ATTACHED TO THE
C  CHAMBER OF INTEREST.  SINCE THE CREVICE VOLUME MASS IS NOT
C  FELT UNTIL THE SUBSEQUENT CALL TO ODERT, CHECK TO SEE IF A
C  MASS HAS YET BEEN CALCULATED. I.E. IS THIS THE SWITCHOVER POINT?
C
      IF (CREVOL.LE.0.0)GO TO 10
      IF (MASLDC .GT. 0.0.AND.Y(21).GT.0.0)THEN
           X1LDCR = Y(21)
      ELSE
         X1LDCR = X1LD
         Y(21) = X1LDCR
      ENDIF
      IF (MASLDC .GT. 0.0 .AND. Y(29) .GT. 0.0)THEN
         FRLDCR = Y(29)
      ELSE
         FRLDCR = FRLD
         Y(29) = FRLDCR
      ENDIF
C
C OBTAIN THE THERMODYNAMIC STATE OF THE CREVICE VOLUME
C
      CALL THERMO(T,TCR,PLEADC,FRLDCR,HLEADC,XXA,XXB,XXC,
     &              RHOLDC,XXD,XXE,XXF,GAMLDC,MWLDC,XXG,
     &              XXH,XXI,XXJ)
C
      MASLDC = RHOLDC*VOLLDC/1.E+3
C
C WHAT ABOUT LEAKAGE?
C
```

```
 10   IF(AREALK.LE.0.0.AND.CREVOL.LE.0.0)GO TO 30
      IF(AREALK.LE.0.0.AND.CREVOL.GT.0.0)GO TO 15
      IF(AREALK.GT.0.0.AND.CREVOL.GT.0.0)GO TO 20
      IF(AREALK.GT.0.0.AND.CREVOL.LE.0.0)GO TO 35
 15   LDLEAK = 0.0
      GO TO 50
 20   CALL MFLRT (1.0,AREA,PLEADC,MWLDC,TCR,PLEAD,GAMLDC,LDLEAK)
      GO TO 50
 30   MASLDC = 0.0
      LDLEAK = 0.0
      GO TO 50
 35   MASLDC = 0.0
C
C OBTAIN THE STATE OF GASES LEAKED DIRECTLY FROM CHAMBER
C
      CALL THERMO(T,TCR,PLEADC,Y(26),HLEADC,XXA,XXB,XXC,
     &              XXD,XXE,XXF,XXG,GAMLDC,MWLDC,
     &              XXH,XXI,XXJ,XXK)
C
      CALL MFLRT (1.0,AREA,PLEADC,MWLDC,TCR,PLEAD,GAMMA,LDLEAK)
      GO TO 50
C
C THE LEADING CREVICE IS ASSOCIATED WITH THE LEAD CHAMBER.
C
 40   PLEADC = PLEAD
      MASLDC = 0.0
C
C LET THE CREVICE VOLUME COMPOSITION EQUAL THAT OF THE LEAD CHAMBER
C AS AN APPROXIMATION.
C
      X1LDCR = X1LD
      FRLDCR = FRLD
      Y(21) = X1LDCR
      Y(29) = FRLDCR
C
C OBTAIN THE THERMODYNAMIC STATE OF THE CREVICE VOLUME.
C
      CALL THERMO(T,TCR,PLEADC,FRLDCR,HLEADC,XXA,XXB,XXC,
     &              XXD,XXE,XXF,XXG,GAMLDC,MWLDC,XXH,XXI,XXJ,
     &              XXK)
C
C WHAT ABOUT LEAKAGE?
C
      CALL MFLRT(1.0,AREA,PLEADC,MWLDC,TCR,Y(12),GAMLDC,LDLEAK)
      LDLEAK = -LDLEAK
      IF (AREALK.LE.0.0)LDLEAK = 0.0
C
 50   IF (PLAG.GE.Y(12)) GO TO 80
C
C  THE CREVICE IS ASSOCIATED WITH THE CHAMBER OF INTEREST
C
      PLAGC = Y(12)
C
      IF(CREVOL.LE.0.0)GO TO 60
```

```
      IF (MASLGC.GT.0.0.AND.Y(22).GT.0.0)THEN
         X1LGCR = Y(22)
      ELSE
         X1LGCR = X1LG
         Y(22) = X1LGCR
      ENDIF
      IF (MASLGC .GT. 0.0 .AND. Y(30) .GT. 0.0)THEN
         FRLGCR = Y(30)
      ELSE
         FRLGCR = FRLG
         Y(30) = FRLGCR
      ENDIF
C
C OBTAIN THE THERMODYNAMIC STATE OF THE LAG CREVICE
C
      CALL THERMO(T,TCR,PLAGC,FRLGCR,HLAGC,XXA,XXB,XXC,
     &               RHOLGC,XXD,XXE,XXF,GAMLGC,MWLGC,XXG,
     &               XXH,XXI,XXJ)
C
      MASLGC = RHOLGC*VOLLGC/1.E+3
C
C WHAT ABOUT LEAKAGE?
C
 60   IF(AREALK.LE.0.0.AND.CREVOL.LE.0.0)GO TO 70
      IF(AREALK.LE.0.0.AND.CREVOL.GT.0.0)GO TO 65
      IF(AREALK.GT.0.0.AND.CREVOL.GT.0.0)GO TO 68
      IF(AREALK.GT.0.0.AND.CREVOL.LE.0.0)GO TO 75
 65   LGLEAK = 0.0
      GO TO 85
 68   CALL MFLRT(1.0,AREA,PLAGC,MWLGC,TCR,PLAG,GAMLGC,LGLEAK)
      GO TO 85
 70   MASLGC = 0.0
      LGLEAK = 0.0
      GO TO 85
 75   MASLGC = 0.0
C
C OBTAIN THE THERMODYNAMIC STATE OF DIRECT LEAKAGE FROM CHAMBER
C
      CALL THERMO(T,TCR,PLAGC,Y(26),HLAGC,XXA,XXB,XXC,
     &               XXD,XXE,XXF,XXG,GAMLGC,MWLGC,XXH,XXI,
     &               XXJ,XXK)
C
      CALL MFLRT(1.0,AREA,PLAGC,MWLGC,TCR,PLAG,GAMLGC,LGLEAK)
      GO TO 85
C
C THE LAG CREVICE IS ASSOCIATED WITH THE LAG CHAMBER
C
 80   PLAGC = PLAG
      MASLGC = 0.0
C
C LET THE CREVICE COMPOSITION EQUAL THAT OF THE LAG CHAMBER
C AS AN APPROXIMATION
      X1LGCR = X1LG
      FRLGCR = FRLG
```

```
      Y(22) = X1LGCR
      Y(30) = FRLGCR
C
C OBTAIN THE THERMODYNAMIC STATE OF THE CREVICE VOLUME
C
      CALL THERMO(T,TCR,PLAGC,FRLGCR,HLAGC,XXA,XXB,XXC,
     &             XXD,XXE,XXF,XXG,GAMLGC,MWLGC,XXH,XXI,
     &             XXJ,XXK)
C
C WHAT ABOUT LEAKAGE?
C
      CALL MFLRT(1.0,AREA,PLAGC,MWLGC,TCR,Y(12),GAMLGC,LGLEAK)
      LGLEAK = -LGLEAK
      IF(AREALK.LE.0.0)LGLEAK=0.0
C
 85   CONTINUE
C
C
C          ASSUME THAT LEAD AND LAG MASS FLOWS (ALGEBRAIC SUM OF
C          LEAKAGE AND CREVICE VOLUME MASS FLOW) HAVE THE SAME SENSE
C          AS AT THE LAST TIME STEP.
C
      IF (MDOTLD .LE. 0.0) GO TO 90
C
C          LEAD FLOW IS ASSUMED TO BE OUT OF THE CHAMBER
C
             LDFLAG = +1
             X1LEAD = Y(5)
             FRLEAD = Y(26)
             HLEAD  = H
             GO TO 100
C
C          LEAD FLOW IS ASSUMED TO BE FROM THE LEAD CREVICE TO
C          THE CHAMBER.
C
   90        LDFLAG = -1
             X1LEAD = X1LDCR
             FRLEAD = FRLDCR
             HLEAD  = HLEADC
C
  100       IF (MDOTLG .LE. 0.0) GO TO 110
C
C          LAG FLOW IS ASSUMED TO BE OUT OF THE CHAMBER.
C
             LGFLAG = +1
             X1LAG = Y(5)
             FRLAG = Y(26)
             HLAG  = H
             GO TO 120
C
C          LAG FLOW IS ASSUMED TO BE FROM THE LAG CREVICE TO
C          THE CHAMBER
C
  110        LGFLAG = -1
```

```
            X1LAG = X1LGCR
            FRLAG = FRLGCR
            HLAG  = HLAGC
C
C
  120  Y(12) = Y(12) * 1.01325E+5
C
C
      X1INT =(1.- RESFIM) * INFLAG + Y(5) * (1 - INFLAG)
      ASTAR = (1./MASS) *(YP(1)*(X1INT-Y(5)) -MDOTLD*( X1LEAD-Y(5))
     &        - MDOTLG*( X1LAG-Y(5) ) )
      BSTAR = 1./(MASS*Y(12)) * ( MASLDC*( X1LEAD-Y(5) ) + MASLGC*
     &        (X1LAG-Y(5) ) )
      DSTAR = YP(1) - YP(2) - MDOTLD - MDOTLG + MFUEL
      ESTAR = (YP(1)*HIMM - YP(2)*H - MDOTLD*HLEAD -
     &         MDOTLG*HLAG)/1000.
C
C     NOTE FACTOR OF 1000.
C
C     CALCULATE PHIDOT FOR USE IN YP(11) AND YP(12) EQUATIONS
C
      IF (MDOTLD.GT.0.0) GO TO 99
C
      YP(26) = YP(26) -MDOTLD/MASS*(FRLEAD-Y(26))
C
 99   IF (MDOTLG.GT.0.0) GO TO 999
C
      YP(26) = YP(26) -MDOTLG/MASS*(FRLAG-Y(26))
C
 999  PHIDOT = YP(26)/(FASTO * (1. - Y(26))**2)
C
      YP(11) = BDUMY/ADUMY*(DSTAR/MASS*(1.-H/BDUMY)-DVDT/VOLUME-
     &    CDUMY/BDUMY*PHIDOT+1000./(BDUMY*MASS)*(ESTAR+
     &    MFUEL*HFORM-THTRAN*1.E-7))
C
      YP(12) = RHO/DRHODP*(-DVDT/VOLUME-DRHODT*YP(11)/RHO-
     &          DRHODF*PHIDOT/RHO+DSTAR/MASS)
C
      YP(5) = ASTAR - BSTAR*YP(12)
C
      Y(12) = Y(12) / 1.01325E+5
      YP(12) = YP(12)/1.01325E+5
C
      MDOTDC = YP(12) * MASLDC/Y(12)
      MDOTGC = YP(12) * MASLGC/Y(12)
C
C         CHECK THAT THE ASSUMPTIONS MADE ABOUT THE NET FLOW
C         DIRECTIONS AT EACH APEX ARE CORRECT.  IF EITHER OF THE
C         FLOWS HAVE REVERSED THEN FLOW COMPOSITION AND ENTHALPY
C         MUST BE REASSIGNED.
C
      MDOTLD = MDOTDC + LDLEAK
      ICHECD = -1
      IF (MDOTLD .GT. 0.0 ) ICHECD = +1
```

```
      MDOTLG = MDOTGC + LGLEAK
      ICHECG = -1
      IF (MDOTLG .GT. 0.0 ) ICHECG = +1
      IF ( ICHECD .NE. LDFLAG .OR. ICHECG .NE. LGFLAG ) GO TO 85
C
C        THE FLOW ASSUMPTIONS HAVE BEEN CONFIRMED AS CORRECT.  THE
C        RATE OF CHANGE IN CREVICE COMPOSITIONS CAN NOW BE EVALUATED.
C
      IF (MASLDC .LE. 0.0 ) GO TO 93
           YP(21) = (X1LEAD - X1LDCR) * (MDOTLD/MASLDC)
           YP(29) = (FRLEAD - FRLDCR) * (MDOTLD/MASLDC)
           IF ( MDOTLD .LE. 0.0 ) THEN
           YP(21) = 0.0
           YP(29) = 0.0
        ENDIF
      GO TO 94
C
   93 YP(21) = 0.0
      YP(29) = 0.0
C
 94   IF (MASLGC .LE. 0.0) GO TO 95
           YP(22) = (X1LAG - X1LGCR) * (MDOTLG/MASLGC)
           YP(30) = (FRLAG - FRLGCR ) * (MDOTLG/MASLGC)
           IF (MDOTLG .LE. 0.0) THEN
           YP(22) = 0.0
           YP(30) = 0.0
      ENDIF
      GO TO 96
C
   95 YP(22) = 0.0
      YP(30) = 0.0
C
 96   YP(23) = YP(1) - YP(2) - MDOTLD - MDOTLG + MFUEL
      YP(18) = LDLEAK
      YP(19) = LGLEAK
      YP(24) = MDOTLD
      YP(25) = MDOTLG
      YP(20) = (MDOTLD*HLEAD + MDOTLG*HLAG)/1.0E+6
C
C
C        CALCULATE THE FUEL ENERGY THAT ENTERS THE EXHAUST CHAMBER
C
C
      IF ( T .LT. TEPO  .OR.  .NOT. FIRE ) GO TO 500
      IF ( MDOTLD .LE. 0.0 ) YP(3) = MDOTLD * X1LDCR
      IF ( MDOTLG .LE. 0.0 ) YP(3) = YP(3) + MDOTLG * X1LGCR
      YP(3) = ABS(YP(3)*H/1.E+6)
C
  500 CRMASD = MASLDC
      CRMASG = MASLGC
      ZMASS  = MASS
      ZLEAKD = Y(18)
      ZLEAKG = Y(19)
      ZCRCOD = Y(21)
```

```
ZCRCOG = Y(22)
FRZCRCOD = Y(29)
FRZCRCOG = Y(30)
RETURN
END
```

```
C     SUBROUTINE TABLE
C
C     PURPOSE
C        TO INTERPOLATE BETWEEN THE STORED VALUES OF CHAMBER PRESSURE
C        AND CREVICE COMPOSITION AND THEN TO RETURN THE INTERPOLATED
C        VALUES TO SUBROUTINE CREVICE.
C
C     USAGE
C        CALL TABLE (T,Y,PLEAD,PLAG,X1LD,X1LG,FRLD,FRLG)
C
C     DESCRIPTION OF PARAMETERS
C
C        PARAMETER  INPUT  OUTPUT   DESCRIPTION
C
C        DT         YES    NO       TIME (DEG)
C        PLEAD      NO     YES      LEADING CHAMBER PRESSURE (ATM)
C        PLAG       NO     YES      TRAILING CHAMBER PRESSURE (ATM)
C        X1LD       NO     YES      LEAD CREVICE COMPOSITION ( )
C        X1LG       NO     YES      LAG CREVICE COMPOSITION ( )
C        FRLD       NO     YES      LEAD CREVICE FUEL FRACTION COMP.
C        FRLG       NO     YES      LAG CREVICE FUEL FRACTION COMP.
C
C
C     REMARKS
C        NONE
C
C
C     METHOD
C        SEE REPORT
C
C     WRITTEN BY T. J. NORMAN
C     EDITED BY J. M. ROBERTS
C
      SUBROUTINE TABLE (T,Y,PLEAD,PLAG,X1LD,X1LG,FRLD,FRLG)
C
C
      LOGICAL FIREFL, FIRE
      DIMENSION Y(30)
      COMMON/TABLES/ PRES(0:1080), X1(0:1080), FUELFR(0:1080)
      COMMON/TIMES/ TIPO, TIPC, TEPO, TEPC, THIPO, THEPO, TSPARK
C
C         IN THIS SUBROUTINE THE CYCLE BEGINS AT TIPO = 0.0 AND
C         ENDS AT TIPO = 1080.0 DEG. THE LEADING CHAMBER IS 360 CRANK
C         ANGLES AHEAD (TLEAD),AND THE TRAILING CHAMBER IS
C         360 DEGREES BEHIND (TLAG).
C
C
      ABST = T + ABS(TIPO)
      TLEAD = ABST + 360.
      IF ( TLEAD .GE. 1080.) TLEAD = TLEAD - 1080.
      TLAG = ABST - 360.
      IF ( TLAG .LT. 0.0 ) TLAG = TLAG + 1080.
      ITLEAD = INT(TLEAD)
      ITLAG = INT(TLAG)
```

```
C
      PLEAD = PRES(ITLEAD) + (TLEAD - ITLEAD)*( PRES(ITLEAD+1) -
     &        PRES(ITLEAD) )
      PLAG = PRES(ITLAG) + (TLAG - ITLAG)*( PRES(ITLAG+1) -
     &       PRES(ITLAG) )
      X1LD = X1(ITLEAD) + (TLEAD-ITLEAD)*(X1(ITLEAD+1)-
     &         X1(ITLEAD) )
      X1LG = X1(ITLAG) + (TLAG-ITLAG)*(X1(ITLAG+1)-
     &          X1(ITLAG) )
      FRLD = FUELFR(ITLEAD) + (TLEAD-ITLEAD)*(FUELFR(ITLEAD+1)-
     &          FUELFR(ITLEAD) )
      FRLG = FUELFR(ITLAG) + (TLAG-ITLAG)*(FUELFR(ITLAG+1)-
     &          FUELFR(ITLAG) )
C
  200 RETURN
      END
```

```
C     SUBROUTINE BUILD
C
C     PURPOSE
C        TO STORE THE CHAMBER PRESSURE AND CREVICE COMPOSITIONS
C        FROM ONE ITERATION TO THE NEXT.
C
C     USAGE
C        CALL BUILD  (DT, DY)
C
C     DESCRIPTION OF PARAMETERS
C
C        PARAMETER  INPUT  OUTPUT   DESCRIPTION
C
C        DT         YES    NO       TIME (DEG)
C
C     REMARKS
C        IT IS ASSUMED IN BUILD THAT THE STEP SIZE FOR ODERT IS
C        ONE (1.0) DEGREE.  IF THE MAIN PROGRAM IS CHANGED SO THAT
C        THE STEP SIZE IS ALTERED THEN SUBROUTINE BUILD MUST ALSO
C        BE ALTERED.
C
C
C
C     METHOD
C        SEE REPORT
C
C     WRITTEN BY T. J. NORMAN
C     EDITED BY J. M. ROBERTS
C
      SUBROUTINE BUILD (DT,DY)
C
      LOGICAL FIREFL, FIRE
      REAL*8 DT,DY(30)
      DIMENSION Y(30)
      COMMON/TABLES/ PRES(0:1080), X1(0:1080), FUELFR(0:1080)
      COMMON/TIMES/ TIPO, TIPC, TEPO, TEPC, THIPO, THEPO, TSPARK
      COMMON/BURN/SPBURN,FIRE,FIREFL
C
      T = DT
      DO 10 I = 1,30
            Y(I) = DY(I)
   10 CONTINUE
      ABST = T + ABS(TIPO)
      IABST = INT(ABST)
      IF ( IABST .NE. ABST ) GO TO 30
      PRES(IABST) = Y(12)
      X1(IABST) = Y(5)
      IF( FIREFL ) X1(IABST) = 1. - Y(4)
      FUELFR(IABST) = Y(26)
C
   30 RETURN
      END
```

```
C     SUBROUTINE IPACD
C
C     PURPOSE
C        CALCULATES AREA AND DISCHARGE COEFFICIENT
C        OF THE INTAKE PORTS.
C
C     USAGE
C        CALL IPACD  (T, AREA, CD)
C
C     DESCRIPTION OF PARAMETERS
C
C        PARAMETER  INPUT  OUTPUT   DESCRIPTION
C
C        T          YES    NO       TIME (DEG)
C        AREA       NO     YES      EFFECTIVE AREA OF INTAKE
C        ----       --     ---      PORT (CM**2)
C        CD         NO     YES      DISCHARGE COEFFICIENT
C
C
C     REMARKS
C
C        THIPO =   NUMBER OF CRANK ANGLES REQUIRED TO FULLY OPEN
C                  OR CLOSE THE PORT.
C
C        - IT IS ASSUMED THAT THE PORTS OPEN AND CLOSE LINEARLY AND
C          THE DISCHARGE COEFFICIENT IS CONSTANT
C
C        - SEE WARNING ABOUT PORT AREA CHANGES 1/21/83
C
C
C     SUBROUTINE AND FUNCTION SUBPROGRAMS REQUIRED
C        NONE
C
C     METHOD
C        SEE REPORT
C
C     WRITTEN BY T. J. NORMAN
C     EDITED BY T. J. NORMAN
C
      SUBROUTINE IPACD (T, AREA, CD)
      REAL IPA
      COMMON/TIMES/ TIPO, TIPC, TEPO, TEPC, THIPO, THEPO, TSPARK
      COMMON/PORTS/ IPA, EPA
CJ
CJ !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
CJ       THIS ROUTINE HAS BEEN CHANGED SUBSTANTIALLY IN ORDER TO MODEL
CJ       THE ENLARGED INTAKE PORT INSTALLED IN THE NASA TEST ENGINE.
CJ       ANY CHANGES WHATSOEVER TO THE PORT CONFIGURATION MUST BE
CJ       REFLECTED IN THIS ROUTINE
CJ
CJ !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
      IF ( T .GT. (TIPO + 120.0)) GO TO 20
      AREA = IPA *(T - TIPO)/120.0
      GO TO 40
```

```
   20 IF ( T .LT. (TIPC - 180.0)) GO TO 30
      IF ( T .LT. -240.0)   AREA  =  (-12.2/120.0)*(T+360.) + 13.8
      IF (T .GT. -240.) AREA = (1.600073*EXP(-10./60.*(T+240.))-.000073)
      GO TO 40
   30 AREA = IPA
   40 CD= 0.75
C
C     IN ORDER TO AVOID ANY DIVISION BY ZERO THE PORT AREA SHALL BE
C     ASSIGNED AN ARBITRARILY SMALL VALUE
C
      IF (AREA .EQ. 0.0) AREA=1.E-6
C
      RETURN
      END
```

```
C      SUBROUTINE EPACD
C
C      PURPOSE
C         CALCULATES AREA AND DISCHARGE COEFFICIENT
C         OF EXHAUST VALVE
C
C      USAGE
C         CALL EPACD  (T, AREA, CD)
C
C      DESCRIPTION OF PARAMETERS
C
C         PARAMETER  INPUT  OUTPUT   DESCRIPTION
C
C         T          YES    NO       TIME (DEG)
C         AREA       NO     YES      EFFECTIVE AREA OF EXHAUST
C         ----       --     ---      PORT (CM**2)
C         CD         NO     YES      DISCHARGE COEFFICIENT
C
C      REMARKS
C
C         THEVO   = NUMBER OF CRANK ANGLES REQUIRED TO OPEN OR CLOSE
C                   THE EXHAUST PORT
C
C         -  IT IS ASSUMED THAT THE PORT OPENS AND CLOSES LINEARLY AND
C            THE DISCHARGE COEFFICIENT IS CONSTANT.
C      SUBROUTINE AND FUNCTION SUBPROGRAMS REQUIRED
C         NONE
C
C      METHOD
C         SEE REPORT
C
C      WRITTEN BY T. J. NORMAN
C      EDITED BY T. J. NORMAN
C
       SUBROUTINE EPACD (T, AREA, CD)
       REAL IPA
       COMMON/TIMES/ TIPO, TIPC, TEPO, TEPC, THIPO, THEPO, TSPARK
       COMMON/PORTS/ IPA, EPA
       IF (T .GT. (TEPO + THEPO)) GO TO 20
       AREA = EPA *(T - TEPO)/THEPO
       GO TO 40
    20 IF (T .LT. (TEPC - THEPO)) GO TO 30
       AREA = EPA *(TEPC - T)/THEPO
       GO TO 40
    30 AREA = EPA
    40 CD = 0.65
C
C      IN ORDER TO AVOID ANY DIVISION BY ZERO THE PORT AREA SHALL BE
C      ASSIGNED AN ARBITRARILY SMALL VALUE
C
       IF(AREA .EQ. 0.0) AREA = 1.E-6
C
       RETURN
       END
```

```
C     SUBROUTINE HEATTX
C
C     PURPOSE
C        CALCULATES THE RATE OF HEAT TRANSFER FROM THE CHAMBER
C        THROUGH THE WALLS OF THE ROTOR, SIDE PLATES, AND HOUSING.
C
C     USAGE
C        CALL HEATTX (T,Y,YP,THTRAN)
C
C     DESCRIPTION OF PARAMETERS
C
C        PARAMETER  INPUT  OUTPUT   DESCRIPTION
C
C        DT         YES    NO       TIME (DEG)
C        DY(11)     YES    NO       CYLINDER TEMPERATURE (K)
C        DY(12)     YES    NO       CYLINDER PRESSURE (ATM)
C -----------------------------------------------------------------
C        DYP(8)     NO     YES      RATE OF HEAT TRANSFER THROUGH
C        -------    --     ---      ROTOR WALL
C        DYP(9)     NO     YES      RATE OF HEAT TRANSFER THROUGH
C        -------    --     ---      SIDE PLATES
C        DYP(10)    NO     YES      RATE OF HEAT TRANSFER THROUGH
C        -------    --     ---      HOUSING
C
C     REMARKS
C        SEE THE PROCESS SUBROUTINE FOR THE UNITS OF THE INTEGRATION
C        VARIABLES.
C
C     SUBROUTINE AND FUNCTION SUBPROGRAMS REQUIRED
C         BTRANS
C
C
C     METHOD
C        SEE REPORT
C
C     WRITTEN BY T. J. NORMAN
C     EDITED BY  T. J. NORMAN
C     EDITED BY J. M. ROBERTS
C
C
C
C
      SUBROUTINE HEATTX (T,Y,YP,THTRAN)
C
C
      LOGICAL FIRE, FIREFL
      REAL MW, MASS, KINVIS
      DIMENSION Y(30),YP(30)
C
      COMMON/HEATXG/AROTOR,ASIDE,AHOUS,ROTVEL,DCHAR
      COMMON/BURN/SPBURN,FIRE,FIREFL
      COMMON/TIMES/ TIPO, TIPC, TEPO, TEPC, THIPO, THEPO, TSPARK
      COMMON/CREV/DRHODP,CSUBT,MW,ITERAS,DVDT,CSUBP,DRHODT,HIMM,
     &          RESIDL,RESFIM,CSUBF,DRHODF
```

```
      COMMON/HTTXIN/CONHT,EXPHT,CON1,CON2
      COMMON/RHMAS/RHO, MASS, VOLUME, H, GAMMA
      COMMON/TEMPS/TROTOR,TSIDE,THOUS
      COMMON/HEATS/VELHTX, HTRCOE, HTPARO, HTPASI, HTPAHO, HTXRO,
     &             HTXSI, HTXHO, QFRRO, QFRSI, QFRHO
C
C         CALCULATE THE CONSTANTS OF THE POLYTROPIC COMPRESSION
C         ( PV**CONST2 = CONST1)
C
      IF ( T .NE. TIPC ) GO TO 5
           PIPC = Y(12)
           VIPC = VOLUME
    5 IF ( T .NE. INT(TSPARK) ) GO TO 7
           PSPARK = Y(12)
           VSPARK = VOLUME
           TEMPSP = Y(11)
C
      CONST2 = (LOG(PSPARK/PIPC)) / (LOG(VIPC/VSPARK))
      CONST1 = PIPC*VIPC**CONST2
    7 CONTINUE
C
C
      IF ( T .GE. TSPARK .AND. FIREFL ) GO TO 9
           VELHTX = CON1*ROTVEL
           GO TO 10
C
C
    9 PMOTOR = CONST1/(VOLUME**CONST2)
      VELHTX = CON1*ROTVEL + CON2*( Y(12) - PMOTOR ) * (VOLUME*TEMPSP/
     &         (PSPARK*VSPARK))
C
C
   10 CALL BTRANS (Y(11),GAMMA,CSUBP,DYNVIS,THRCON)
C
   20 KINVIS = DYNVIS/RHO*1.E+3    ! CONVERSION NEED CM**2/SEC  5/9
      HTRCOE = (CONHT*((VELHTX*DCHAR)/KINVIS)**EXPHT) * (THRCON/DCHAR)
C
C     UNITS OF HTRCOE ARE ERG/CM**2 SEC K
C
C         CALCULATE THE HEAT TRANSFER RATES PER UNIT AREA
C
                HTPARO = HTRCOE * (Y(11) - TROTOR)/1.E+06
                HTPASI = HTRCOE * (Y(11) - TSIDE)/1.E+06
                HTPAHO = HTRCOE * (Y(11) - THOUS)/1.E+06
C
                HTXRO = HTPARO * AROTOR*1.E+06
                HTXSI = HTPASI * ASIDE*1.E+06
                HTXHO = HTPAHO * AHOUS*1.E+06
C
      YP(8)  =  HTXRO
      YP(9)  =  HTXSI
      YP(10) =  HTXHO
C
C     FIND THE TOTAL HEAT TRANSFER FROM THE CHAMBER
```

```
C
      THTRAN = HTXRO + HTXSI + HTXHO
C
               IF (ABS(THTRAN) .LE. .0002) GO TO 40
               QFRRO = 100.* HTXRO/THTRAN
               QFRSI = 100.* HTXSI/THTRAN
               QFRHO = 100.* HTXHO/THTRAN
C
      GO TO 40
C
C
   40 CONTINUE
C
CJ    QTOTAL = THTRAN
      RETURN
      END
```

```
C     SUBROUTINE MFLRT
C
C     PURPOSE
C        CALCULATES MASS FLOW RATE THROUGH AN ORIFICE.
C
C     USAGE
C        CALL MFLRT  (CD, AREA, PO, MW, TO, PS, GAMMA, FLRT)
C
C     DESCRIPTION OF PARAMETERS
C
C        PARAMETER  INPUT  OUTPUT   DESCRIPTION
C
C        CD         YES    NO       DISCHARGE COEFFICIENT
C        AREA       YES    NO       AREA OF RESTRICTION (CM**2)
C        PO         YES    NO       UPSTREAM PRESSURE (ATM)
C        PS         YES    NO       DOWNSTREAM PRESSURE (ATM)
C        MW         YES    NO       MOLECULAR WEIGHT (G/MOLE)
C        TO         YES    NO       UPSTREAM TEMPERATURE (K)
C        GAMMA      YES    NO       RATIO OF SPECIFIC HEATS, CP/CV
C        FLRT       NO     YES      MASS FLOW RATE (G/S)
C
C     REMARKS
C        NONE
C
C     SUBROUTINE AND FUNCTION SUBPROGRAM REQUIRED
C        NONE
C
C     METHOD
C        FLOW THROUGH THE ORIFICE IS TREATED AS ONE-DIMENSIONAL,
C        QUASI-STEADY, AND ISENTROPIC (MODIFIED BY A DISCHARGE
C        COEFFICIENT)
C
C     WRITTEN BY S. H. MANSOURI AND K. RADHAKRISHNAN
C     EDITED BY S. H. MANSOURI AND S. G. POULOS
C
      SUBROUTINE MFLRT (CD, AREA, PO, MW, TO, PS, GAMMA, FLRT)
C
      REAL MW
C
      FLRT  = 0.0
      IF (PO .EQ. PS) GO TO 20
      GI    = 1.0/GAMMA
      SUM   = GAMMA * MW/TO
      CONST = 111.12272 * CD * AREA * PO * SQRT(SUM)
C
      RATIO = PS/PO
      CRIT  = ( 2./(GAMMA + 1.) )**( GAMMA/(GAMMA - 1.) )
C
C        CHECK IF FLOW IS CHOKED
C
      IF (RATIO .LT. CRIT) GO TO 10
C
C        SUBSONIC FLOW
C
```

```
      SUN  = 2./(GAMMA - 1.) * ( RATIO**(GI + GI) - RATIO**(GI + 1.) )
      FLRT = CONST * SQRT(SUN)
      GO TO 20
C
C        CHOKED FLOW
C
   10 FLRT = CONST * CRIT**( 0.5 * (1.0 + GI) )
C
   20 RETURN
      END
```

```
C     SUBROUTINE CSAVDV
C
C     PURPOSE
C        CALCULATES SURFACE AREA, VOLUME, AND TIME RATE OF CHANGE OF
C        VOLUME OF COMBUSTION CHAMBER.
C
C     USAGE
C        CALL CSAVDV (T, VOLUME, DVDT)
C
C     DESCRIPTION OF PARAMETERS
C
C        PARAMETER  INPUT  OUTPUT   DESCRIPTION
C
C        T          YES    NO       TIME (DEG)
C        ASIDE      NO     YES      SIDE SURFACE AREA (CM**2)
C        AROTOR     NO     YES      ROTOR SURFACE AREA (CM**2)
C        AHOUS      NO     YES      HOUSING SURFACE AREA (CM**2)
C        VOLUME     NO     YES      CHAMBER VOLUME (CM**3)
C        DVDT       NO     YES      TIME RATE OF CHANGE OF VOLUME OF
C        -----      --     ---      CHAMBER (CM**3/SEC)
C        ROTVEL     NO     YES      AVERAGE ROTOR SPEED (CM/SEC)
C        DCHAR      NO     YES      CHARACTERISTIC DIMENSION FOR
C        ------     --     ---      HEAT TRANSFER CALCULATIONS (CM)
C
C     REMARKS
C        NONE
C
C     SUBROUTINE AND FUNCTION SUBPROGRAMS REQUIRED
C        NONE
C
C     METHOD
C        SEE REPORT
C
C     WRITTEN BY T. J. NORMAN
C     EDITED BY T. J. NORMAN
C
      SUBROUTINE CSAVDV (T, VOLUME, DVDT)
      COMMON/EPARAM/ ECCEN, ROTRAD, DEPTH, VFLANK
      COMMON/DTDTH/ ESPDI, RPM
      COMMON/HEATXG/AROTOR, ASIDE, AHOUS, ROTVEL, DCHAR
C
      PI=3.1415926
      ROOT3 = SQRT(3.)
C
C     THETA IS THE CRANK ANGLE (OFFSET BY 90 DEGREES) IN RADIANS
C     ALPHA IS THE "FOLLOWING" APEX SEAL ANGLE IN RADIANS
C
      THETA =(T+90.) * PI/180.
      ALPHA = THETA/3.
      BETA  = 2.* ALPHA
C
C          ALEAN IS THE MAXIMUM ANGLE OF INCLINATION OF THE APEX SEAL
C          FROM THE NORMAL TO THE HOUSING.
C
```

```
      ALEAN = ASIN(3.* ECCEN/ROTRAD )
      FT    = (ECCEN*ECCEN + ROTRAD*ROTRAD/3.) * PI -
     &        ROOT3 * ECCEN * ROTRAD * SIN( BETA+PI/6.)
      DFTDTH = -2*ROOT3/3.* ECCEN * ROTRAD * COS( BETA + PI/6.)
C
      FR      = PI/3.* (ROTRAD*ROTRAD + 2.*ECCEN*ECCEN)
     &          -2. * ECCEN * ROTRAD * COS(ALEAN)
     &          -ALEAN * (ROTRAD*ROTRAD*2./9. + 4.*ECCEN*ECCEN )
      DFRDTH = 0.0
C
      FR1     = ECCEN * ROTRAD * SIN(BETA)/2.
      DFR1DT  = (1/3.) * ECCEN * ROTRAD * COS( BETA )
C
      FR2     = ECCEN * ROTRAD * SIN(BETA+PI/3.)/2.
      DFR2DT  = (1/3.) * ECCEN * ROTRAD * COS( BETA + PI/3.)
C
      ASIDE   = FT-FR-FR1-FR2
      DASDTH  = DFTDTH - DFRDTH - DFR1DT  - DFR2DT
C
      VOLUME  = ASIDE * DEPTH + VFLANK
      DVDTH   = DASDTH * DEPTH
      DVDT    = DVDTH * RPM * PI/30.
C
C           FIND THE SURFACE AREAS OF THE HOUSING, ROTOR AND SIDES.
C
      ASIDE  = 2.* ASIDE
      RPRIME = ROTRAD - ECCEN + 3.*ECCEN*ROTRAD/(ROTRAD - 4.*ECCEN)
      BETA2  = ROOT3*ROTRAD/((6.*ECCEN*ROTRAD)/(ROTRAD-4.*ECCEN) +
     &         ROTRAD + 2.*ECCEN)
      ROTORL = RPRIME * 2.* BETA2
      AROTOR = ROTORL * DEPTH
C
C          AN APPROXIMATION IS USED TO FIND THE TOTAL SURFACE AREA
C          THE CORRECTION FACTOR SHOULD BE CHECKED IF THE ENGINE
C          GEOMETRY DIFFERS GREATLY FROM THE TEST CONDITIONS:
C          (ROTRAD = 10.5 , ECCEN = 1.5 , DEPTH = 7.0).
C
C
      AREA  = 2.* (VOLUME/ROTORL + VOLUME/DEPTH + ROTORL*DEPTH )
     &        + .151 * VOLUME
      AHOUS = AREA - AROTOR - ASIDE
C
C        DEFINE A CHARACTERISTIC ROTOR VELOCITY AND DIMENSION
C        FOR HEAT TRANSFER PURPOSES.
C
      ROTVEL = RPM*PI*ROTRAD/90.
      DCHAR  = DEPTH
C
C        COMPONENT AREAS ARE PASSED IN THE CALL STATEMENT AND
C        IN THE COMMON STATEMENT HEATXG.
C
      RETURN
      END
```

```
      FUNCTION GINT1 (DT, DY, DYP)
      REAL*8 DT,DY(30),DYP(30),GINT1
C
      GINT1 = DYP(1)
C
      RETURN
      END
C_______________________________________________________________
C
      FUNCTION GINT2 (DT, DY, DYP)
      REAL*8 DT,DY(30),DYP(30),GINT2
C
      GINT2 = DY(1)
C
      RETURN
      END
C_______________________________________________________________
C
      FUNCTION GCMP (DT, DY, DYP)
      REAL*8 DT,DY(30),DYP(30),GCMP
C
      GCMP = 10.0
C
      RETURN
      END
C_______________________________________________________________
C
      FUNCTION GEXH (DT, DY, DYP)
      REAL*8 DT,DY(30),DYP(30),GEXH
C
      GEXH =10.00
C
      RETURN
      END
C_______________________________________________________________
      FUNCTION GCMB (DT, DY, DYP)
      REAL*8 DT,DY(30),DYP(30),GCMB
C
      GCMB = 10.0
C
      RETURN
      END
```

```
C     SUBROUTINE HELPHT
C
C     PURPOSE
C        CALLS EITHER 'INTAKE', 'CMPRES', 'CMBSTN', OR 'EXAUST',
C        AFTER EVERY CALL TO 'ODERT'.  'ODERT' MAY OVERSHOOT IT'S
C        STOPPING POINT (TOUT) FOR IMPROVED ACCURACY.  IF THIS
C        OCCURS, 'ODERT' WILL RETURN WITH THE CORRECT VECTOR (DY),
C        BUT THE HEAT TRANSFER DATA CALCULATED BY THE EXTERNAL
C        FUNCTIONS WILL CORRESPOND TO THE LAST OVERSHOT VALUE
C        OF T AND NOT TO TOUT.  IT IS THEN NECESSARY TO CALL
C        THE EXTERNAL FUNCTIONS ONCE AFTER EACH CALL TO ODERT IF
C        THE CORRECT HEAT TRANSFER DATA IS TO BE AVAILABLE FOR
C        PRINTING OUT.  THIS PROCEDURE DOES NOT AFFECT THE NOR-
C        MAL CALCULATION PROCESS PERFORMED BY 'ODERT'.
C
C     USAGE
C        CALL HELPHT (DT, DY, IWHERE)
C
C     DESCRIPTION OF PARAMETERS
C        PARAMETER  INPUT  OUTPUT  DESCRIPTION
C
C        DT         YES    NO      CURRENT TIME (DEG)
C        DY         YES    NO      CURRENT SOLUTION VECTOR
C        IWHERE     YES    NO      1 = INTAKE; 2 = CMPRES;
C        ------     ---    --      3 = CMBSTN; 4 = EXAUST
C        XXX        NO     NO      DUMMY VARIABLE
C
C     REMARKS
C        NONE
C
C     SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED
C        INTAKE     CMPRES     CMBSTN     EXAUST
C
C     METHOD
C        SEE PURPOSE, ABOVE
C
C     WRITTEN BY S. G. POULOS
C     EDITED BY S. G. POULOS
C
      SUBROUTINE HELPHT (DT, DY, IWHERE)
      REAL*8 DT, DY(30), XXX(30)
C
      IF (IWHERE.EQ.1) CALL INTAKE (DT, DY, XXX)
      IF (IWHERE.EQ.2) CALL CMPRES (DT, DY, XXX)
      IF (IWHERE.EQ.3) CALL CMBSTN (DT, DY, XXX)
      IF (IWHERE.EQ.4) CALL EXAUST (DT, DY, XXX)
C
      RETURN
      END
```

```
C     SUBROUTINE BTRANS
C
C     PURPOSE
C        CALCULATES DYNAMIC VISCOSITY AND THERMAL CONDUCTIVITY
C        OF BURNED PRODUCTS
C
C     USAGE
C        CALL BTRANS (TEMP, GAMMA, CP, DYNVIS, THRCON)
C
C     DESCRIPTION OF PARAMETERS
C        PARAMETER  INPUT  OUTPUT   DESCRIPTION
C
C        TEMP       YES    NO       TEMPERATURE (K)
C        CP         YES    NO       HEAT CAPACITY AT CONSTANT PRESSURE
C        --         ---    --       OF BURNED PRODUCTS (ERG/G K)
C        DYNVIS     NO     YES      DYNAMIC VISCOSITY OF
C        ------     --     ---      BURNED PRODUCTS (G/SEC CM)
C        THRCON     NO     YES      THERMAL CONDUCTIVITY OF
C        ------     --     ---      BURNED PRODUCTS (ERG/SEC CM K)
C
C     REMARKS
C        NONE
C
C     SUBROUTINE AND FUNCTION SUBPROGRAMS REQUIRED
C        NONE
C
C     METHOD
C        SEE S. H. MANSOURI AND J. B. HEYWOOD, " CORRELATIONS FOR THE
C        VISCOSITY AND PRANDTL NUMBER OF HYDROCARBON-AIR COMBUSTION
C        PRODUCTS," COMBUSTION SCIENCE AND TECHNOLOGY, 1980, VOL. 23,
C        PP. 251-256
C
C     WRITTEN BY S. H. MANSOURI
C     EDITED BY S. G. POULOS
C
      SUBROUTINE BTRANS (TEMP, GAMMA, CP, DYNVIS, THRCON)
C
      COMMON/FUEL/ FUELTP, ENW, CX, HY, OZ, DEL, PSI, PHICON, PHI,
     &             QLOWER, FASTO, HFORM
C
      DYNVIS = 3.3E-6 * (TEMP**.7)/(1.0 + .027 * PHI)
      PRNDTL = 0.05 + 4.2 * (GAMMA - 1.0) - 6.7 * (GAMMA - 1.0) *
     &         (GAMMA - 1.0)
      THRCON = DYNVIS * CP*1.E+4/PRNDTL
      IF ((PHI .LE. 1.0) .OR. (TEMP .LE. 1500.)) RETURN
      PRNDTL = PRNDTL/(1.0 + 1.5E-8 * PHI * PHI * TEMP * TEMP)
      THRCON = DYNVIS * CP*1.E+4/PRNDTL
C
      RETURN
      END
```

```
C     SUBROUTINE THERMO
C
C     PURPOSE
C        'THERMO' IS CALLED BY THE THE 4 PROCESS ROUTINES AND BY
C        'MAIN' AND RETURNS WITH THE REQUIRED THERMODYNAMIC PROPER-
C        TIES IN EACH CASE.  IT CALLS 'UPROP' AND OR 'BPROP' AS
C        REQUIRED FOR EACH PROCESS, AND THEN CALCULATES FROM THE
C        RETURNED DATA ANY ADDITIONAL PROPERTIES OR COMBINATIONS
C        OF PROPERTIES OF INTEREST.  'THERMO' ALSO CONVERTS ALL
C        VALUES TO UNITS THAT ARE CONSISTENT WITH THOSE USED IN
C        THE REST OF THE PROGRAM.
C
C     USAGE
C        CALL THERMO ( T, TEMP, P, FR, ENTHLP,
C              CSUBP, CSUBT, CSUBF,
C              RHO, DRHODT, DRHODP, DRHODF,
C              GAMMA, MW, EDUMY, FDUMY, GDUMY, HDUMY)
C
C     DESCRIPTION OF PARAMETERS
C        PARAMETER  INPUT  OUTPUT  DESCRIPTION
C
C        T          YES    NO      CRANK ANGLE (DEG)
C        TEMP       YES    NO      TEMPERATURE (K)
C        P          YES    NO      PRESSURE (ATM)
C        ------     ---    --      ( =1. FOR BURNED ZONE  )
C        FR         YES    NO      CHAMBER FUEL FRACTION
C        ENTHLP     NO     YES     ENTHALPY  ------
C        CSUBP      NO     YES     --------
C        CSUBT      NO     YES     --------
C        CSUBF      NO     YES     --------
C        RHO        NO     YES     DENSITY
C        DRHODT     NO     YES     --------
C        DRHODP     NO     YES     --------
C        DRHODF     NO     YES     --------
C        MW         NO     YES     MOLECULAR WEIGHT
C        GAMMA      NO     YES     RATIO OF SPECIFIC HEATS
C        EDUMY      NO     YES     SEE ASSIGNMENT STATEMENTS BELOW
C        FDUMY      NO     YES     SEE ASSIGNMENT STATEMENTS BELOW
C        GDUMY      NO     YES     SEE ASSIGNMENT STATEMENTS BELOW
C        HDUMY      NO     YES     SEE ASSIGNMENT STATEMENTS BELOW
C
C     REMARKS
C        HDUMY IS NOT USED IN THE WANKEL PROGRAM
C        BUT HAS BEEN LEFT INTACT FOR FUTURE USE, IF NECESSARY.
C
C     SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED
C        HPROD    CLDPRD
C
C     METHOD
C        SEE PURPOSE, ABOVE
C
C     WRITTEN BY S. G. POULOS
C     EDITED BY S. G. POULOS, AND T. J. NORMAN
C
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```
C
      SUBROUTINE THERMO (T, TEMP, P, FR, ENTHLP,
     &             CSUBP, CSUBT, CSUBF,
     &             RHO, DRHODT, DRHODP, DRHODF,
     &             GAMMA, MW, EDUMY, FDUMY, GDUMY, HDUMY)
C
      REAL MW
C
       CALL HPROD (P, TEMP, FR, ENTHLP,
     &        CSUBP, CSUBT, CSUBF,
     &        RHO, DRHODT, DRHODP ,DRHODF)
C
C        CONVERT TO UNITS NEEDED IN MAIN PROGRAM
C
      ENTHLP = ENTHLP * 4.184E+6
      CSUBP = CSUBP * 4.184E+3
      CSUBT = CSUBT/1000.
      CSUBF = CSUBF * 4.184E+6
C
      RHO = RHO*1000.
      DRHODP = DRHODP/101.325
      DRHODT = DRHODT*1000.
      DRHODF = DRHODF * 1000.
C
C CALCULATE GAS CONSTANT, MOLECULAR WEIGHT AND GAMMA
C
      RGAS = 1.01325E+5*P/(RHO*TEMP)
      MW = 8.3145E+3/RGAS
      GAMMA = CSUBP/( CSUBP - RGAS )
C
C CALCULATE THE DUMMY VARIABLES
C
      EDUMY = CSUBP + ( DRHODT/DRHODP )*( 1./RHO - CSUBT)
      FDUMY = ( 1. - RHO*CSUBT)/DRHODP
      GDUMY = CSUBF + ( DRHODF/DRHODP )*(1./RHO - CSUBT)
C
      RETURN
      END
```

```
C       SUBROUTINE HPROD
C
C       PURPOSE
C          TO CALCULATE THE PROPERTIES OF THE PRODUCTS OF HYDROCARBON-
C          AIR COMBUSTION AS A FUNCTION OF TEMPERATURE AND PRESSURE,
C          USING AN APPROXIMATE CORRECTION FOR DISSOCIATION.
C          H AND RHO ARE CALCULATED AS FUNCTIONS OF R, T, AND PHI.
C          THE PARTIAL DERIVATIVES OF H AND RHO WITH RESPECT TO
C          P, T AND PHI ARE ALSO CALCULATED
C
C        USAGE
C           CALL HPROD (P, T, FR, H, CP, CT, CF
C                       RHO, DRHODT, DRHODP, DRHODF)
C
C        DESCRIPTION OF PARAMETERS
C        GIVEN:
C          P      : ABSOLUTE PRESSURE OF PRODUCTS (ATM)
C          T      : TEMPERATURE OF PRODUCTS (DEG K)
C          PHI    : EQUIVALENCE RATIO
C          DEL    : MOLAR C:H RATIO OF PRODUCTS
C          PSI    : MOLAR N:O RATIO OF PRODUCTS
C
C        RETURNS:
C          H      : SPECIFIC ENTHALPY OF PRODUCTS (ATM)
C          CP     : PARTIAL DERIVATIVE OF H WITH RESPECT TO T
C                   (CAL/G-DEG K)
C          CT     : PARTIAL DERIVATIVE OF H WITH RESPECT TO P (CC/G)
C          CF     : PARTIAL DERIVATIVE OF H WITH REPSECT TO PHI (KCAL/G)
C          RHO    : DENSITY OF THE PRODUCTS (G/CC)
C          DRHODT: PARTIAL DERIVATIVE OF RHO WITH RESPECT TO T
C                   (G/CC-DEG K)
C          DRHODP: PARTIAL DERIVATIVE OF RHO WITH RESPECT TO P
C                 (G/CC-ATM)
C          DRHODF: PARTIAL DERIVATIVE OF RHO WITH RESPECT TO PHI
C                 (G/CM**3)
C
C        RETURNS IN COMMON AREA /FROZEN/:
C          CPFROZ: FROZEN SPECIFIC HEAT (CAL/G-DEG K)
C        RETURNS IN COMMON AREA /MBARB/:
C          MBARB : AVERAGE MOLECULAR WEIGHT OF BURNED GASES
C
C        REMARKS
C           1) ENTHALPY DATUM STATE IS AT T = 0 ABSOLUTE WITH
C              O2, N2, H2 GASEOUS AND C SOLID GRAPHITE
C           2) MULTIPLY ATM-CC BY 0.0242173 TO CONVERT TO CAL
C           3) MODIFIED VERSION OF MIKE MARTIN'S PROGRAM
C           4) COMMON BLOCK MBARB ADDED BY B. BEARD 5/10/79
C           5) EXACTLY THE SAME LOGIC AS VERSION 3.5 (5/10/79),
C              BUT WITH CLEANED UP CODE AND DOCUMENTATION BY
C              S. POULOS. 2/12/82
C
C        SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED
C          CLDPRD
C
```

```
C       METHOD
C         SEE MARTIN AND HEYWOOD 'APPROXIMATE RELATIONSHIPS FOR THE
C         THERMODYNAMIC PROPERTIES OF HYDROCARBON-AIR COMBUSTION
C         PRODUCTS'
C
C
      SUBROUTINE HPROD (P, T, FR, H, CP, CT, CF,
     &                 RHO, DRHODT, DRHODP, DRHODF)
C
      LOGICAL RICH, LEAN, NOTHOT, NOTWRM, NOTCLD
      REAL MCP, MWT, K1, K2
      REAL MBARB
      COMMON/FUEL/ FUELTP, ENW, CX, HY, OZ, DEL, PSI, PHICON, PHI,
     &             QLOWER, FASTO,HFORM
      COMMON/FROZEN/ CPFROZ
      COMMON/MBARB/ MBARB
C
C        INITIALIZE PARAMETERS USED IN THE CALCULATION
C
      DATA R,ROVER2 /1.9869,0.99345/, PSCALE /2.42173E-2/
      DATA TCOLD,THOT /1000.,1100./
C
      PHI = FR / (FASTO * ( 1. - FR))
      RICH   = PHI .GE. 1.0
      LEAN   = .NOT. RICH
      NOTHOT = T .LT. THOT
      NOTCLD = T .GT.TCOLD
      NOTWRM = .NOT. (NOTCLD .AND. NOTHOT)
      EPS    = (4.*DEL)/(1. + 4.*DEL)
C
C        USE SIMPLE ROUTINE FOR LOW TEMPERATURE MIXES
C
      IF (NOTCLD) GO TO 5
      CALL CLDPRD (P, T, FR, H, CP, CT, CF,
     &            RHO, DRHODT, DRHODP, DRHODF, IER)
      RETURN
C
C        CALCULATE EQUILIBRIUM CONSTANTS FOR DISSOCIATION (EQS. 3.9
C        & 3.10) (NOTE THAT THESE HAVE UNITS ATM**(.5) )
C
    5 K1 = 5.819E-6 * EXP(0.9674*EPS + 35810./T)
      K2 = 2.961E-5 * EXP(2.593*EPS  + 28980./T)
C
C        CALCULATE A, X, Y, & U AS IN EQS. 5.24, 3.6, 5.25, 3.7, 2.18,
C        2.19, & 3.8
C
      C5 = 2.- EPS + PSI
      A  = (C5/(4.*P*K1*K1*EPS))**(.33333333)
C
      C6 = EPS + 2.*C5
      X  = A*EPS*(3.*C5 + C6*A)/(3.*(1.+ 2.*A)*C5 + 2.*C6*A*A)
C
      Z  = ABS((1.-PHI)/X)
      IF (LEAN) Y = X/SQRT(1.+ .666667*Z + 1.3333333*(1.-PHI))
```

```
      IF (RICH) Y = X/(1.+.6666667*Z +.3333333*Z*Z -.6666667*(PHI-1.))
      U   = C5*(EPS - 2.*X)/(4.*K1*K2*P*X)
C
C     CALCULATE THE ENTHALPY OF FORMATION FOR THIS APPROXIMATE
C     COMPOSITION AS IN EQS. 3.21, 3.22, & 5.7
C     ALSO GET THE COEFFICIENTS FOR T & TV TERMS IN 3.15 USING 5.3 & 5.4
C
      HF    = 1000.*((121.5 + 29.59*EPS)*Y + 117.5*U)
      HF    = HF + (20372.*EPS - 114942.)*PHI
      C1    = 7.*PSI + 5.*Y + 3.*U
      C2    = 2.*(PSI - 3.*Y - U)
C
      IF (LEAN) GO TO 10
C
C        RICH CASE
C
      HF = HF + 1000.*(134.39 - 6.5/EPS)*(PHI - 1.)
      C1 = 2. + 2.*(7.- 4.*EPS)*PHI + C1
      C2 = 8. + 2.*(2.- 3.*EPS)*PHI + C2
      GO TO 20
C
C        LEAN CASE
C
   10 C1 = 7. +     (9.- 8.*EPS)*PHI + C1
      C2 = 2. + 2.* (5.- 3.*EPS)*PHI + C2
C
C        ADD IN TRANSLATIONAL, VIBRATIONAL, AND ROTATIONAL TERMS
C        TO GET TOTAL ENTHALPY, USING EQS. 3.16, 5.6, 3.11, & 3.15
C
   20 TV      = (3256.- 2400.*EPS + 300.*PSI)/(1.- .5*EPS + .09*PSI)
      EXPTVT  = EXP(TV/T)
      TVTIL   = TV/(EXPTVT - 1.)
      MCP     = (8.*EPS + 4.)*PHI + 32. + 28.*PSI
C
C NOTE MULTIPLICATION OF H BY 0.001 TO CONVERT UNITS FROM
C CAL/G TO KCAL/G
C
      H       = 0.001*ROVER2*(C1*T + C2*TVTIL + HF)/MCP
C
C        CALCULATE THE AVERAGE MOLECULAR WEIGHT, AND GET DENSITY
C        BY USING THE PERFECT GAS LAW - EQS. 3.12, 3.13, & 3.14
C
      IF (LEAN) MWT = MCP/(1. + (1.- EPS)*PHI + PSI + Y + U)
      IF (RICH) MWT = MCP/(     (2.- EPS)*PHI + PSI + Y + U)
C
      MBARB = MWT
C
      RHO = MWT*P*PSCALE/(R*T)
C
C        GET PARTIAL DERIVATIVES IF DESIRED
C
C        THE FOLLOWING USES IN ORDER EQS. 5.8, 5.9, 5.32, 5.31, 5.30,
C        5.29, 5.28, & 5.26
C
```

```
      C3 = (121.5 + 29.59*EPS)*1000.
      C4 = 1.175E5
C
      DUDTPX = 64790.*U/(T*T)
      DUDPTX = -U/P
      DUDXPT = -U*EPS/(X*(EPS - 2.*X))
C
      DADTP  = 23873.*A/(T*T)
      DADPT  = -A/(3.*P)
C
      T5 = 3.*C5
      DXDA = T5*EPS*(T5 + 2.*C6*A)/(T5*(1. + 2.*A) + 2.*C6*A*A)**2
C
C        FOLLOWING USES EQS. 5.23, 5.19-5.22, 5.18-5.14, 5.12, & 5.13
C
      IF (LEAN) DYDX = (Y*Y*Y)/(X*X*X) * (1.+ Z + 1.333333*(1.-PHI))
      IF (RICH) DYDX = (Y*Y)/(X*X)*(1.+ 4.*Z/3. + Z*Z -2.*(PHI-1.)/3.)
C
      DYDTP = DYDX*DXDA*DADTP
      DYDPT = DYDX*DXDA*DADPT
      DUDTP = DUDXPT*DXDA*DADTP + DUDTPX
      DUDPT = DUDXPT*DXDA*DADPT + DUDPTX
C
      DHFDPT = C3*DYDPT + C4*DUDPT
      DC2DPT = -2.*(3.*DYDPT + DUDPT)
      DC1DPT = 5.*DYDPT + 3.*DUDPT
      DHFDTP = C3*DYDTP + C4*DUDTP
      DC2DTP = -2.*(3.*DYDTP + DUDTP)
      DC1DTP = 5.*DYDTP + 3.*DUDTP
C
      DTVDTP = (TVTIL*TVTIL)/(T*T)*EXPTVT
C
C        FOLLOWING USES EQS. 5.10, & 5.11
C
      CPFROZ = ROVER2/MCP*(C1 + C2*DTVDTP)
C
      CP = ROVER2/MCP*(C1 + T*DC1DTP + C2*DTVDTP + TVTIL*DC2DTP
     &      + DHFDTP)
      CT = ROVER2/MCP*(T*DC1DPT + TVTIL*DC2DPT + DHFDPT)*PSCALE
C
C        FOLLOWING USES EQS. 5.46, 5.35-5.37, 5.33, & 5.34
C
      DMCPDF = 8. * EPS + 4.
C
      IF(RICH)GO TO 55
C
C     LEAN CASE
C
      DYDF = 1./3. * (Y/X)**3 * (1.+2.*X)
      DC1DF = (9. - 8 *EPS) + 5.*DYDF
      DC2DF = 2. * (5. - 3. *EPS) - 6.*DYDF
      DHFDF = 20732. * EPS - 114942. + C3 * DYDF
      D = 1. + (1.- EPS)*PHI + PSI + Y + U
      DDDF =  1. - EPS + DYDF
```

```
      GO TO 65
C
C     RICH CASE
C
 55   DYDF = -2./3. * (Y/X)**2 * (1. + Z - X)
      DC1DF = 2. * (7. - 4. *EPS) + 5. * DYDF
      DC2DF = 2. * (2. - 3. *EPS) - 6. * DYDF
      DHFDF = 20732. * EPS + 19448. + C3 * DYDF - 6500./EPS
      D =      (2.- EPS)*PHI + PSI + Y + U
      DDDF = 2. - EPS + DYDF
C
C MULTIPLICATION OF CF BY 0.001 IS TO CONVERT UNITS FROM CAL/G TO
C KCAL/G
C
 65   CF = 0.001 * ROVER2/MCP * ((DC1DF - C1/MCP*DMCPDF) * T +
     &       (DC2DF - C2/MCP*DMCPDF) * TVTIL + (DHFDF - HF/
     &       MCP*DMCPDF))
C
      G     = -MCP/(D*D)
      DMWDT = G*(DYDTP + DUDTP)
      DMWDP = G*(DYDPT + DUDPT)
      DMWDF = - MCP/D/D * (DDDF - D/MCP*DMCPDF)
C
      DRHODT = PSCALE*P*(DMWDT - MWT/T)/(R*T)
      DRHODP = PSCALE*(MWT + P*DMWDP)/(R*T)
      DRHODF = PSCALE * P * DMWDF / (R*T)
C
C        IF CALCULATING FOR AN INTERMEDIATE TEMPERATURE, USE A
C        WEIGHTED AVERAGE OF THE RESULTS FROM THIS ROUTINE AND
C        THOSE FROM THE SIMPLE ROUTINE
C
      IF (NOTWRM) RETURN
C
      CALL CLDPRD (P, T, FR, TH, TCP, TCT, TCF,
     &             TRHO, TDRT, TDRP, TDRF, IER)
      W1 = (T - TCOLD)/(THOT - TCOLD)
      W2 = 1.0 - W1
C
      H   = W1*H   + W2*TH
      RHO = W1*RHO + W2*TRHO
      CP  = W1*CP  + W2*TCP
      CT  = W1*CT  + W2*TCT
      DRHODT = W1*DRHODT + W2*TDRT
      DRHODP = W1*DRHODP + W2*TDRP
      DRHODF = W1*DRHODF + W2*TDRF
C
      RETURN
      END
```

```
C       SUBROUTINE CLDPRD
C
C       PURPOSE
C        TO CALCULATE THE SPECIFIC ENTHALPY OF THE PRODUCTS OF HC-AIR
C        COMBUSTION AT TEMPERATURES AND PRESSURES WHERE DISSOCIATION
C        OF THE PRODUCT GASES MAY BE IGNORED.  THE DENSITY OF THE
C        PRODUCT GAS IS ALSO CALCULATED, AS ARE THE PARTIAL
C        DERIVATIVES OF BOTH OF THESE QUANTITIES WITH RESPECT TO
C        PRESSURE AND TEMPERATURE.
C
C       USAGE
C          CALL CLDPRD (P, T, FR, ENTHLP, CP, CT, CF,
C         &             RHO, DRHODT, DRHODP, DRHODF, IER)
C
C       DESCRIPTION OF PARAMETERS
C       GIVEN:
C          P      : ABSOLUTE PRESSURE OF PRODUCTS (ATM)
C          T      : TEMPERATURE OF PRODUCTS (DEG K)
C          PHI    : EQUIVALENCE RATIO
C          DEL    : MOLAR C:H RATIO OF PRODUCTS
C          PSI    : MOLAR N:O RATIO OF PRODUCTS
C
C       RETURNS:
C          H      : SPECIFIC ENTHALPY OF PRODUCTS (KCAL/G)
C          CP     : PARTIAL DERIVATIVE OF H WITH RESPECT TO T
C                   (CAL/G-DEG K)
C          CT     : PARTIAL DERIVATIVE OF H WITH RESPECT TO P (CC/G)
C          CF     : PARTIAL DERIVATIVE OF H WITH RESPECT TO PHI (KCAL/G)
C          RHO    : DENSITY OF THE PRODUCTS (G/CC)
C          DRHODT: PARTIAL DERIVATIVE OF RHO WITH RESPECT TO T
C                   (G/CC-DEG K)
C          DRHODP: PARTIAL DERIVATIVE OF RHO WITH RESPECT TO P
C                   (G/CC-ATM)
C          DRHODF: PARTIAL DERIVATIVE OF RHO WITH RESPECT TO PHI
C                   (G/CC)
C          IER    : FLAG, SET TO 1 FOR T < 100 DEG K
C                                2 FOR T > 6000 DEG K
C                                0 OTHERWISE
C
C       RETURNS IN COMMON AREA /FROZEN/:
C         CPFROZ: FROZEN SPECIFIC HEAT (CAL/G-DEG K)
C       RETURNS IN COMMON AREA /MBARB/:
C         MBARB : AVERAGE MOLECULAR WEIGHT OF BURNED GASES
C
C       REMARKS
C          1) ENTHALPY DATUM STATE IS AT T = 0 ABSOLUTE WITH
C             O2,N2,H2 GASEOUS AND C SOLID GRAPHITE
C          2) MULTIPLY ATM-CC BY 0.0242173 TO CONVERT TO CAL
C          3) MODIFIED VERSION OF MIKE MARTIN'S PROGRAM
C          4) COMMON BLOCK MBARB ADDED BY B. BEARD 5/10/79
C          5) EXACTLY THE SAME LOGIC AS VERSION 3.1 (5/10/79),
C             BUT WITH CLEANED UP CODE AND DOCUMENTATION BY
C             S. POULOS. 2/12/82
C
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C       SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED
C          NONE
C
C       METHOD
C         SEE MARTIN & HEYWOOD 'APPROXIMATE RELATIONSHIPS FOR THE
C         THERMODYNAMIC PROPERTIES OF HYDROCARBON-AIR COMBUSTION
C         PRODUCTS'
C
C
      SUBROUTINE CLDPRD (P, T, FR, ENTHLP, CP, CT, CF,
     &                  RHO, DRHODT, DRHODP, DRHODF, IER)
C
      LOGICAL RICH, LEAN
      REAL*4 MBAR, K
      REAL MBARB,MCP
      DIMENSION A(6,6,2), X(6), DX(6)
      DIMENSION A1(36), A2(36)
      DIMENSION TABLE(7)
      COMMON/FUEL/ FUELTP, ENW, CX, HY, OZ, DEL, PSI, PHICON, PHI,
     &             QLOWER, FASTO, HFORM
      COMMON/FROZEN/ CPFROZ
      COMMON/MBARB/ MBARB
      EQUIVALENCE (A1(1), A(1,1,1)), (A2(1), A(1,1,2))
C
C        INITIALIZE PARAMETERS, AND CHECK TO SEE IN WHAT TEMPERATURE
C        RANGE WE ARE SO THAT THE CORRECT FITTED COEFFICIENTS WILL BE
C        USED. FLAG TEMPERATURES TOO HIGH OR TOO LOW.
C
      DATA A1/11.94033,2.088581,-0.47029,.037363,-.589447,-97.1418,
     1 6.139094,4.60783,-.9356009,6.669498E-02,.0335801,-56.62588,
     2 7.099556,1.275957,-.2877457,.022356,-.1598696,-27.73464,
     3 5.555680,1.787191,-.2881342,1.951547E-02,.1611828,.76498,
     4 7.865847,.6883719,-.031944,-2.68708E-03,-.2013873,-.893455,
     5 6.807771,1.453404,-.328985,2.561035E-02,-.1189462,-.331835/
      DATA A2/4.737305,16.65283,-11.23249,2.828001,6.76702E-03,
     1 -93.75793,7.809672,-.2023519,3.418708,-1.179013,1.43629E-03,
     2 -57.08004,6.97393,-.8238319,2.942042,-1.176239,4.132409E-04,
     3 -27.19597,6.991878,.1617044,-.2182071,.2968197,-1.625234E-02,
     4 -.118189,6.295715,2.388387,-.0314788,-.3267433,4.35925E-03,
     5 .103637,7.092199,-1.295825,3.20688,-1.202212,-3.457938E-04,
     6 -.013967/
      DATA TABLE /-1.,1.,1.,-1.,0.,0.,0./
C
      PHI = FR / (FASTO * ( 1. - FR ))
      RICH = PHI .GT. 1.0
      LEAN = .NOT. RICH
      EPS  = 4.*DEL/(1. + 4.*DEL)
      IER  = 0
      IR = 1
      IF (T .LT. 500.)  IR  = 2
C
C        GET THE COMPOSITION IN MOLES/MOLE OXYGEN
C
      IF (RICH) GO TO 10
```

```
      X(1) = EPS*PHI
      X(2) = 2.*(1.- EPS)*PHI
      X(3) = 0.
      X(4) = 0.
      X(5) = 1.- PHI
C
      DX(1) = EPS
      DX(2) = 2. * (1. - EPS)
      DX(3) = 0.
      DX(4) = 0.
      DX(5) = -1.
C
      GO TO 20
C
   10 K      = 3.5
      ALPHA = 1. - K
      BETA  = (2.*(1.-EPS*PHI) + K*(2.*(PHI - 1.) + EPS*PHI))
      GAMMAB = 2.*K*EPS*PHI*(PHI - 1.)
      C      = ( -BETA + SQRT(BETA*BETA + 4.*ALPHA*GAMMAB))/(2.*ALPHA)
      X(1)   = EPS*PHI - C
      X(2)   = 2.*(1. - EPS*PHI) + C
      X(3)   = C
      X(4)   = 2.*(PHI - 1.) - C
      X(5)   = 0.
C
      DX(1) = 0.
      DX(2) = 0.
      DX(3) = 0.
      DX(4) = 0.
      DX(5) = 0.
C
   20 X(6)  = PSI
      DX(6) = 0.
C
C        CONVERT COMPOSITION TO MOLE FRACTIONS AND CALCULATE AVERAGE
C        MOLECULAR WEIGHT
C
      IF (LEAN) TMOLES = 1. + PSI + PHI*(1.-EPS)
      IF (RICH) TMOLES = PSI + PHI*(2.-EPS)
      DO 30 J = 1, 6
      X(J) = X(J)/TMOLES
   30 CONTINUE
      MBAR = ((8.*EPS + 4.)*PHI + 32. + 28.*PSI)/TMOLES
C*****
      MBARB = MBAR
C*****
      MCP = MBAR * TMOLES
      DMCPDF = ( 8. *EPS + 4. )
C
C        CALCULATE H, CP, AND CT AS IN WRITEUP, USING FITTED
C        COEFFICIENTS FROM JANAF TABLES
C
      ENTHLP = 0.
      CP  = 0.
```

```
      CT  = 0.
      CF  = 0.
      CPFROZ = 0.
      ST     = T/1000.
      DO 40 J = 1,6
         TH     = ((( A(4,J,IR)/4.*ST + A(3,J,IR)/3.)*ST
     &              + A(2,J,IR)/2.)*ST + A(1,J,IR) )*ST
         TCP    = (( A(4,J,IR)*ST + A(3,J,IR) )*ST
     &              + A(2,J,IR) )*ST + A(1,J,IR)
         TH     = TH - A(5,J,IR)/ST + A(6,J,IR)
         TCP    = TCP + A(5,J,IR)/ST**2
         ENTHLP = ENTHLP + TH*X(J)
         CP   = CP + TCP*X(J)
         CF = CF + 1./MCP * ( TH*DX(J) - DMCPDF/MCP*TH*X(J) )
   40 CONTINUE
      ENTHLP = ENTHLP/MBAR
      CP   = CP/MBAR
C
C        NOW CALULATE RHO AND ITS PARTIAL DERIVATIVES
C        USING PERFECT GAS LAW
C
      RHO    = .012187*MBAR*P/T
      DRHODT = -RHO/T
      DRHODP = RHO/P
C
      IF(RICH) GO TO 60
C
C     LEAN CASE
C
 50   D = 1. + ( 1. - EPS ) * PHI + PSI
      DDDF = 1. - EPS
      GO TO 70
C
C     RICH CASE
C
 60   D = ( 2. - EPS ) * PHI + PSI
      DDDF = 2. - EPS
C
 70   DMWDF = -MCP/D/D * (DDDF - D/MCP*DMCPDF)
      DRHODF = 0.012187 * DMWDF / T
C
      RETURN
      END
```

```
C     SUBROUTINE ITRATE
C
C     PURPOSE
C        THIS SUBROUTINE IS CALLED TO OBTAIN T GIVEN P, H, RESFRK,
C        AND A GUESS FOR T.  'ITRATE' CALLS 'THERMO' WITH TGUESS.
C        'THERMO' RETURNS WITH THE ENTHALPY CORRESPONDING TO THE
C        GIVEN TGUESS.  THEN A NEW CORRECTED VALUE FOR TGUESS
C        IS CALCULATED BY USING THE DEFINITION OF CSUBP AND THE
C        KNOWN VALUES OF CORRECT H AND RETURNED HGUESS.  THIS PRO-
C        CEDURE IS REPEATED AT MOST MAXTRY TIMES, OR FEWER TIMES
C        IF ACCURACY MAXERR IS ACHIEVED.
C
C     USAGE
C        CALL ITRATE (T, TGUESS, P, RESFRK, ENTHLP, CSUBP, CSUBT,
C       &     CSUBF, RHO, DRHODT, DRHODP, DRHODF, GAMMA, MW)
C
C     DESCRIPTION OF PARAMETERS
C        PARAMETER  INPUT  OUTPUT  DESCRIPTION
C
C        T           YES    NO      CRANK ANGLE (DEG)
C        TGUESS      YES    YES     TEMPERATURE GUESS (K)
C        ------      ---    --      (CORRECTED VALUE IS RETURNED)
C        P           YES    NO      PRESSURE (ATM)
C        RESFRK      YES    NO      MASS BURNED / TOTAL MASS
C        ------      ---    --      ( <1. FOR UNBURNED ZONE ONLY )
C        ENTHLP      YES    NO      ENTHALPY ON WHICH TO ITERATE (ERG)
C        HGUESS      NO     NO      ENTHALPY GUESS (ERG)
C        CSUBP       NO     YES     DH/DT @ CONSTANT P (ERG/K)
C        CSUBT       NO     YES     DH/DP @ CONSTANT T (ERG/ATM)
C        CSUBF       NO     YES     DH/DPHI @ CONSTANT P AND T
C        RHO         NO     YES     DENSITY
C        DRHODT      NO     YES     PARTIAL OF RHO WITH RESPECT TO T
C        DRHODP      NO     YES     PARTIAL OF RHO WITH RESPECT TO P
C        DRHODF      NO     YES     PARTIAL OF RHO WITH RESPECT TO PHI
C        MW          NO     YES     MOLECULAR WEIGHT
C        GAMMA       NO     YES     RATIO OF SPECIFIC HEATS
C
C     REMARKS
C        NONE
C
C     SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED
C        THERMO
C
C     METHOD
C        SEE PURPOSE, ABOVE
C
C     WRITTEN BY S. G. POULOS
C     EDITED BY S. G. POULOS
C
      SUBROUTINE ITRATE (T, TGUESS, P, RESFRK, ENTHLP, CSUBP, CSUBT,
     &        CSUBF, RHO, DRHODT, DRHODP, DRHODF, GAMMA, MW)
C
      REAL MW, MAXERR
      COMMON/ITRLIM/ MAXTRY, MAXERR
```

```
C
      DO 10 I = 1, MAXTRY
      CALL THERMO (T, TGUESS, P, RESFRK, HGUESS, CSUBP, CSUBT, CSUBF,
     &       RHO, DRHODT, DRHODP, DRHODF, GAMMA, MW,
     &       XXA, XXB, XXC, XXD)
      TOLD = TGUESS
      TGUESS = TOLD + (ENTHLP - HGUESS)/CSUBP
      IF( ABS((TGUESS - TOLD)/TGUESS ) .LE. MAXERR ) GO TO 20
   10 CONTINUE
C
   20 CALL THERMO (T, TGUESS, P, RESFRK, ENTHLP, CSUBP, CSUBT, CSUBF,
     &    RHO, DRHODT, DRHODP, DRHODF, GAMMA, MW,
     &    XXA, XXB, XXC, XXD)
C
      RETURN
      END
```

```
C     SUBROUTINE FUELDT
C
C     PURPOSE
C        THIS SUBROUTINE IS CALLED TO SET THE VALUES OF THE FUEL
C        RELATED PARAMETERS AT THE START OF PROGRAM EXECUTION. THE
C        ONLY INPUT REQUIRED IS THE FUEL TYPE.  THE PARAMETERS WHICH
C        ARE SET ARE: I) THE ATOM RATIOS WHICH SPECIFY THE PROPERTIES
C        OF THE FUEL- AIR MIXTURE, THE SET OF ENTHALPY COEFFICIENTS
C        ASSOCIATED WITH THE FUEL (USED IN THE PROPERTY ROUTINES), AND
C        THE FUEL HEATING VALUE AND STOICHIOMETRIC FUEL/AIR RATIO;
C        II) THE ATOM RATIOS REQUIRED BY SUBROUTINE 'PTCHEM' FOR
C        CALCULATION OF EQUILIBRIUM BURNED GAS COMPOSITION.
C
C     USAGE
C        CALL FUELDT
C
C     DESCRIPTION OF PARAMETERS
C        PARAMETER  INPUT  OUTPUT  DESCRIPTION
C
C        FUELTP     YES    NO      FUEL TYPE
C        PSI        NO     YES     MOLAR N2 TO O2 RATIO FOR AIR
C        XI         NO     YES     MOLAR N2 TO O2 RATIO FOR AIR
C        CX         NO     YES     # OF CARBON ATOMS/FUEL MOLECULE
C        DEL        NO     YES     CARBON/HYDROGEN RATIO OF FUEL
C        HY         NO     YES     HYDROGEN ATOMS PER FUEL MOLECULE
C        ENW        NO     YES     NITROGEN ATOMS PER FUEL MOLECULE
C        OZ         NO     YES     OXYGEN ATOMS PER FUEL MOLECULE
C        QLOWER     NO     YES     LOWER HEATING VALUE OF THE FUEL
C        FASTO      NO     YES     STOICHIOMETRIC FUEL/AIR RATIO
C        AF(I)      NO     YES     FUEL COEFFICIENT ARRAY
C        HFORM      NO     YES     HEAT OF FORMATION (DATUM IS 0 K)
C
C     REMARKS
C        ONLY ISSOCTANE AND PROPANE ARE AVAILABLE FOR
C        USE AS FUELS.
C
C     SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED
C
C        ______    ______    ______    ______
C
C     METHOD
C        SEE PURPOSE, ABOVE
C
C     WRITTEN BY S. G. POULOS
C     EDITED BY S. G. POULOS
C
      SUBROUTINE FUELDT
C
      INTEGER FUELTP
      REAL AF(6)
C
      COMMON/FUEL/ FUELTP, ENW, CX, HY, OZ, DEL, PSI, PHICON, PHI,
     &            QLOWER, FASTO, HFORM
      COMMON/FUPRP/ AF
      COMMON/OXDANT/ XI
```

```
C
      PSI = 3.76
      XI = 3.76
      IF (FUELTP .GT. 1) GO TO 10
C
C        FOLLOWING DATA FOR ISOOCTANE (FUELTP = 1)
C
      CX = 8.0
      DEL = 8.0/18.0
      HY = 18.0
      ENW = 0.0
      OZ = 0.0
      QLOWER = 44.392
      FASTO = 1./15.11
      HFORM = -2.156E+3
C
      AF(1) =   -0.55313
      AF(2) =  181.62
      AF(3) =  -97.787
      AF(4) =   20.402
      AF(5) =   -0.03095
      AF(6) =  -40.519
C
      GO TO 20
C
C        FOLLOWING DATA FOR PROPANE (FUELTP = 2)
C
   10 CX = 3.0
      DEL = 3.0/8.0
      HY = 8.0
      ENW = 0.0
      OZ = 0.0
      QLOWER = 46.3
      FASTO = 0.0638
      HFORM = -2.707E+3
C
      AF(1) =  - 1.4867
      AF(2) =   74.339
      AF(3) =  -39.0649
      AF(4) =    8.05426
      AF(5) =    0.0121948
      AF(6) =  -18.4611
C
   20 PHICON = (32. + 28. * PSI) * (DEL + .25)/(12. * DEL + 1.0)
C
      RETURN
      END
```

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C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C
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C
C
C   WRITTEN BY M. K. GORDON, 5122
C
C***********************************************************************
C   ABSTRACT
C***********************************************************************
C   SUBROUTINE  ODERT  INTEGRATES A SYSTEM OF  NEQN  FIRST ORDER
C   ORDINARY DIFFERENTIAL EQUATIONS OF THE FORM
C             DY(I)/DT = F(T,Y(1),...,Y(NEQN))
C             Y(I) GIVEN AT T.
C   THE SUBROUTINE INTEGRATES FROM  T  IN THE DIRECTION OF  TOUT  UNTIL
C   IT LOCATES THE FIRST ROOT OF THE NONLINEAR EQUATION
C         G(T,Y(1),...,Y(NEQN),YP(1),...,YP(NEQN)) = 0.
C   UPON FINDING THE ROOT, THE CODE RETURNS WITH ALL PARAMETERS IN THE
C   CALL LIST SET FOR CONTINUING THE INTEGRATION TO THE NEXT ROOT OR
C   THE FIRST ROOT OF A NEW FUNCTION  G  .  IF NO ROOT IS FOUND, THE
C   INTEGRATION PROCEEDS TO  TOUT .  AGAIN ALL PARAMETERS ARE SET TO
C   CONTINUE.
C
C   THE DIFFERENTIAL EQUATIONS ARE ACTUALLY SOLVED BY A SUITE OF CODES,
C   DERT1 ,STEP1 , AND INTRP .  ODERT ALLOCATES VIRTUAL STORAGE IN
```

```
C   THE WORK ARRAYS  WORK  AND  IWORK  AND CALLS  DERT1 .  DERT1  IS A
C   SUPERVISOR WHICH DIRECTS THE INTEGRATION.  IT CALLS ON  STEP1  TO
C   ADVANCE THE SOLUTION AND  INTRP  TO INTERPOLATE THE SOLUTION AND
C   ITS DERIVATIVE.  STEP1  USES A MODIFIED DIVIDED DIFFERENCE FORM OF
C   THE ADAMS PECE FORMULAS AND LOCAL EXTRAPOLATION.  IT ADJUSTS THE
C   ORDER AND STEP SIZE TO CONTROL THE LOCAL ERROR PER UNIT STEP IN A
C   GENERALIZED SENSE.  NORMALLY EACH CALL TO  STEP1  ADVANCES THE
C   SOLUTION ONE STEP IN THE DIRECTION OF  TOUT .  FOR REASONS OF
C   EFFICIENCY  ODERT  INTEGRATES BEYOND  TOUT  INTERNALLY, THOUGH
C   NEVER BEYOND T+10*(TOUT-T), AND CALLS  INTRP  TO INTERPOLATE THE
C   SOLUTION AND DERIVATIVE AT  TOUT .  AN OPTION IS PROVIDED TO STOP
C   THE INTEGRATION AT  TOUT  BUT IT SHOULD BE USED ONLY IF IT IS
C   IMPOSSIBLE TO CONTINUE THE INTEGRATION BEYOND  TOUT .
C
C   AFTER EACH INTERNAL STEP,  DERT1  EVALUATES THE FUNCTION  G  AND
C   CHECKS FOR A CHANGE IN SIGN IN THE FUNCTION VALUE FROM THE
C   PRECEDING STEP.  SUCH A CHANGE INDICATES A ROOT LIES IN THE
C   INTERVAL OF THE STEP JUST COMPLETED.  DERT1 THEN CALLS SUBROUTINE
C   ROOT  TO REDUCE THE BRACKETING INTERVAL UNTIL THE ROOT IS
C   DETERMINED TO THE DESIRED ACCURACY.  SUBROUTINE  ROOT  USES A
C   COMBINATION OF THE SECANT RULE AND BISECTION TO DO THIS.  THE
C   SOLUTION AND DERIVATIVE VALUES REQUIRED ARE OBTAINED BY
C   INTERPOLATION WITH  INTRP .  THE CODE LOCATES ONLY THOSE ROOTS
C   FOR WHICH  G  CHANGES SIGN IN  (T,TOUT)  AND FOR WHICH A
C   BRACKETING INTERVAL EXISTS.  IN PARTICULAR, IT WILL NOT DETECT A
C   ROOT AT THE INITIAL POINT  T .
C
C   THE CODES  STEP1 , INTRP , ROOT , AND THAT PORTION OF  DERT1
C   WHICH DIRECTS THE INTEGRATION ARE EXPLAINED AND DOCUMENTED IN THE
C   TEXT, COMPUTER SOLUTION OF ORDINARY DIFFERENTIAL EQUATIONS, THE
C   INITIAL VALUE PROBLEM, BY L. F. SHAMPINE AND M. K. GORDON.
C
C   DETAILS OF THE USE OF ODERT ARE GIVEN IN SAND-75-0211.
C
C**********************************************************************
C   THE PARAMETERS FOR  ODERT  ARE
C**********************************************************************
C      F -- SUBROUTINE F(T,Y,YP) TO EVALUATE DERIVATIVES YP(I)=DY(I)/DT
C      NEQN -- NUMBER OF EQUATIONS TO BE INTEGRATED
C      Y(*) -- SOLUTION VECTOR AT  T
C      T -- INDEPENDENT VARIABLE
C      TOUT -- ARBITRARY POINT BEYOND THE ROOT DESIRED
C      RELERR,ABSERR -- RELATIVE AND ABSOLUTE ERROR TOLERANCES FOR LOCAL
C           ERROR TEST.  AT EACH STEP THE CODE REQUIRES
C             ABS(LOCAL ERROR) .LE. ABS(Y)*RELERR + ABSERR
C           FOR EACH COMPONENT OF THE LOCAL ERROR AND SOLUTION VECTORS
C      IFLAG -- INDICATES STATUS OF INTEGRATION
C      WORK,IWORK -- ARRAYS TO HOLD INFORMATION INTERNAL TO THE CODE
C           WHICH IS NECESSARY FOR SUBSEQUENT CALLS
C      G - FUNCTION OF T, Y(*), YP(*) WHOSE ROOT IS DESIRED.
C      REROOT, AEROOT -- RELATIVE AND ABSOLUTE ERROR TOLERANCES FOR
C           ACCEPTING THE ROOT.  THE INTERVAL CONTAINING THE ROOT IS
C           REDUCED UNTIL IT SATISFIES
C            0.5*ABS(LENGTH OF INTERVAL) .LE. REROOT*ABS(ROOT)+AEROOT
```

```
C           WHERE ROOT IS THAT ENDPOINT YIELDING THE SMALLER VALUE OF
C           G  IN MAGNITUDE.  PURE RELATIVE ERROR IS NOT RECOMMENDED
C           IF THE ROOT MIGHT BE ZERO.
C***********************************************************************
C   FIRST CALL TO  ODERT --
C***********************************************************************
C   THE USER MUST PROVIDE STORAGE IN HIS CALLING PROGRAM FOR THE
C   ARRAYS IN THE CALL LIST,
C              Y(NEQN), WORK(100+21*NEQN), IWORK(5)
C   AND DECLARE  F , G  IN AN EXTERNAL STATEMENT.  HE MUST SUPPLY THE
C   SUBROUTINE  F(T,Y,YP)  TO EVALUATE
C           DY(I)/DT = YP(I) = F(T,Y(1),...,Y(NEQN))
C   AND THE FUNCTION  G(T,Y,YP)  TO EVALUATE
C           G = G(T,Y(1),...,Y(NEQN),YP(1),...,YP(NEQN)).
C   NOTE THAT THE ARRAY YP IS AN INPUT ARGUMENT AND SHOULD NOT BE
C   COMPUTED IN THE FUNCTION SUBPROGRAM.  FINALLY THE USER MUST
C   INITIALIZE THE PARAMETERS
C      NEQN -- NUMBER OF EQUATIONS TO BE INTEGRATED
C      Y(*) -- VECTOR OF INITIAL CONDITIONS
C      T -- STARTING POINT OF INTEGRATION
C      TOUT -- ARBITRARY POINT BEYOND THE ROOT DESIRED
C      RELERR,ABSERR -- RELATIVE AND ABSOLUTE LOCAL ERROR TOLERANCES
C                       FOR INTEGRATING THE EQUATIONS
C      IFLAG -- +1,-1.  INDICATOR TO INITIALIZE THE CODE.  NORMAL INPUT
C           IS +1.  THE USER SHOULD SET IFLAG=-1 ONLY IF IT IS
C           IMPOSSIBLE TO CONTINUE THE INTEGRATION BEYOND  TOUT .
C      REROOT,AEROOT -- RELATIVE AND ABSOLUTE ERROR TOLERANCES FOR
C                       COMPUTING THE ROOT OF  G
C
C   ALL PARAMETERS EXCEPT F, G, NEQN, TOUT, REROOT AND AEROOT MAY BE
C   ALTERED BY THE CODE ON OUTPUT SO MUST BE VARIABLES IN THE CALLING
C   PROGRAM.
C***********************************************************************
C   OUTPUT FROM  ODERT --
C***********************************************************************
C      NEQN -- UNCHANGED
C      Y(*) -- SOLUTION AT  T
C      T -- LAST POINT REACHED IN INTEGRATION.  NORMAL RETURN HAS
C           T = TOUT OR T = ROOT
C      TOUT -- UNCHANGED
C      RELERR,ABSERR -- NORMAL RETURN HAS TOLERANCES UNCHANGED.  IFLAG=3
C           SIGNALS TOLERANCES INCREASED
C      IFLAG = 2 -- NORMAL RETURN.  INTEGRATION REACHED  TOUT
C            = 3 -- INTEGRATION DID NOT REACH  TOUT  BECAUSE ERROR
C                   TOLERANCES TOO SMALL.  RELERR ,  ABSERR  INCREASED
C                   APPROPRIATELY FOR CONTINUING
C            = 4 -- INTEGRATION DID NOT REACH  TOUT  BECAUSE MORE THAN
C                   500 STEPS NEEDED
C            = 5 -- INTEGRATION DID NOT REACH  TOUT  BECAUSE EQUATIONS
C                   APPEAR TO BE STIFF
C            = 6 -- INTEGRATION DID NOT REACH  TOUT  BECAUSE SOLUTION
C                   VANISHED MAKING PURE RELATIVE ERROR IMPOSSIBLE.
C                   MUST USE NON-ZERO  ABSERR  TO CONTINUE
C            = 7 -- INVALID INPUT PARAMETERS (FATAL ERROR)
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C            = 8 -- NORMAL RETURN.  A ROOT WAS FOUND WHICH SATISFIED
C                   THE ERROR CRITERION OR HAD A ZERO RESIDUAL
C            = 9 -- ABNORMAL RETURN.  AN ODD ORDER POLE OF  G  WAS
C                   FOUND.
C            =10 -- ABNORMAL RETURN.  TOO MANY EVALUATIONS OF  G  WERE
C                   REQUIRED (AS PROGRAMMED 500 ARE ALLOWED.)
C           THE VALUE OF  IFLAG  IS RETURNED NEGATIVE WHEN THE INPUT
C           VALUE IS NEGATIVE AND THE INTEGRATION DOES NOT REACH
C           TOUT , I.E., -3,...,-6,-8,-9,-10.
C      WORK(*),IWORK(*) -- INFORMATION GENERALLY OF NO INTEREST TO THE
C                          USER BUT NECESSARY FOR SUBSEQUENT CALLS
C      REROOT,AEROOT -- UNCHANGED
C***********************************************************************
C   SUBSEQUENT CALLS TO  ODERT --
C***********************************************************************
C   SUBROUTINE  ODERT  RETURNS WITH ALL INFORMATION NEEDED TO CONTINUE
C   THE INTEGRATION.  IF THE INTEGRATION DID NOT REACH  TOUT  AND THE
C   USER WANTS TO CONTINUE, HE JUST CALLS AGAIN.  IF THE INTEGRATION
C   REACHED  TOUT , THE USER NEED ONLY DEFINE A NEW  TOUT  AND CALL
C   AGAIN.  THE OUTPUT VALUE OF  IFLAG  IS THE APPROPRIATE INPUT VALUE
C   FOR SUBSEQUENT CALLS.  THE ONLY SITUATION IN WHICH IT SHOULD BE
C   ALTERED IS TO STOP THE INTEGRATION INTERNALLY AT THE NEW  TOUT ,
C   I.E., CHANGE OUTPUT  IFLAG=2  TO INPUT  IFLAG=-2 .  ONLY THE ERROR
C   TOLERANCES AND THE FUNCTION  G  MAY BE CHANGED BY THE USER BEFORE
C   CONTINUING.  ALL OTHER PARAMETERS MUST REMAIN UNCHANGED.  A NEW
C   FUNCTION  G  IS DETECTED AUTOMATICALLY.
C
      SUBROUTINE ODERT(F,NEQN,Y,T,TOUT,RELERR,ABSERR,IFLAG,WORK,IWORK,
     1  G,REROOT,AEROOT)
      IMPLICIT REAL*8 (A-H,O-Z)
D     IMPLICIT INTEGER*2 (I-N)
C
C
CCCCC GENERIC
      LOGICAL START,PHASE1,NORND
      DIMENSION Y(30),WORK(730),IWORK(5)
      EXTERNAL F,G
      DATA IALPHA,IBETA,ISIG,IV,IW,IGG,IPHASE,IPSI,IX,IH,IHOLD,ISTART,
     1  ITOLD,IDELSN,IGX,ITROOT/1,13,25,38,50,62,75,76,88,89,90,91,
     2  92,93,94,95/
      IYY = 100
      IWT = IYY + NEQN
      IP = IWT + NEQN
      IYP = IP + NEQN
      IYPOUT = IYP + NEQN
      IPHI = IYPOUT + NEQN
      IF(IABS(IFLAG) .EQ. 1) GO TO 1
      START = WORK(ISTART) .GT. 0.0
      PHASE1 = WORK(IPHASE) .GT. 0.0
      NORND = IWORK(2) .NE. -1
1     CALL DERT1(F,NEQN,Y,T,TOUT,RELERR,ABSERR,IFLAG,G,REROOT,AEROOT,
     1  WORK(IYY),WORK(IWT),WORK(IP),WORK(IYP),WORK(IYPOUT),WORK(IPHI),
     2  WORK(IALPHA),WORK(IBETA),WORK(ISIG),WORK(IV),WORK(IW),WORK(IGG),
     3  PHASE1,WORK(IPSI),WORK(IX),WORK(IH),WORK(IHOLD),START,
```

```
     4  WORK(ITOLD),WORK(IDELSN),WORK(IGX),WORK(ITROOT),IWORK(1),
     5  NORND,IWORK(3),IWORK(4),IWORK(5))
      WORK(ISTART) = -1.0
      IF(START) WORK(ISTART) = 1.0
      WORK(IPHASE) = -1.0
      IF(PHASE1) WORK(IPHASE) = 1.0
      IWORK(2) = -1
      IF(NORND) IWORK(2) = 1
      RETURN
      END
C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C
      SUBROUTINE DERT1(F,NEQN,Y,T,TOUT,RELERR,ABSERR,IFLAG,G,REROOT,
     1  AEROOT,YY,WT,P,YP,YPOUT,PHI,ALPHA,BETA,SIG,V,W,GG,PHASE1,PSI,
     2  X,H,HOLD,START,TOLD,DELSGN,GX,TROOT,NS,NORND,K,KOLD,ISNOLD)
C ***NAME CHANGED FROM DERT TO DERT1 TO AVOID A NAMING CONFLICT.
C
C   ODERT  MERELY ALLOCATES STORAGE FOR  DERT  TO RELIEVE THE USER OF
C   THE INCONVENIENCE OF A LONG CALL LIST.  CONSEQUENTLY  DERT  IS USED
C   AS DESCRIBED IN THE COMMENTS FOR  ODERT .
C
C   THE CODES STEP, INTRP AND ROOT AND THAT PORTION OF DERT DIRECTING
C   THE INTEGRATION ARE COMPLETELY EXPLAINED AND DOCUMENTED IN THE TEXT,
C   COMPUTER SOLUTION OF ORDINARY DIFFERENTIAL EQUATIONS, THE INITIAL
C   VALUE PROBLEM BY L. F. SHAMPINE AND M. K. GORDON.
C
      IMPLICIT REAL*8 (A-H,O-Z)
C
CCCCC GENERIC
D       IMPLICIT INTEGER*2 (I-N)
      LOGICAL STIFF,CRASH,START,PHASE1,NORND
      DIMENSION Y(30),YY(30),WT(30),PHI(30,16),P(30),YP(30),
     1  YPOUT(30),PSI(12),ALPHA(12),BETA(12),SIG(13),V(12),W(12),
     2  GG(13)
      COMMON/MLDRT/SPACE(10)
      EXTERNAL F,G
C
C***********************************************************************
C*  THE ONLY MACHINE DEPENDENT CONSTANT IS BASED ON THE MACHINE UNIT   *
C*  ROUNDOFF ERROR  U  WHICH IS THE SMALLEST POSITIVE NUMBER SUCH THAT *
C*  1.0+U .GT. 1.0 .  U  MUST BE CALCULATED AND  FOURU=4.0*U  INSERTED *
C*  IN THE FOLLOWING STATEMENT BEFORE USING  ODERT .  THE SUBROUTINE   *
C*  MACHIN  CALCULATES  U .  FOURU  AND  TWOU=2.0*U  MUST ALSO BE      *
C*  INSERTED IN SUBROUTINE  STEP  BEFORE CALLING  ODERT .              *
C***********************************************************************
      DATA FOURU/8.8E-16/
C***********************************************************************
C
C   THE CONSTANT  MAXNUM  IS THE MAXIMUM NUMBER OF STEPS ALLOWED IN ONE
C   CALL TO  ODERT .  THE USER MAY CHANGE THIS LIMIT BY ALTERING THE
C   FOLLOWING STATEMENT
      DATA MAXNUM/500/
C
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```
C           ***              ***              ***
C   TEST FOR IMPROPER PARAMETERS
C
      IF(IABS(IFLAG) .EQ. 7) CALL ERRCHK(-31,
     1  31HIN ODERT, ENTERED WITH IFLAG=7.)
      IF(NEQN .LT. 1) CALL ERRCHK(32,
     1  32HIN ODERT, NEQN MUST BE POSITIVE.)
      IF(NEQN .LT. 1) GO TO 10
      IF(T .EQ. TOUT) CALL ERRCHK(61,
     1 61HIN ODERT, ENDPOINTS OF INTEGRATION INTERVAL MUST BE DISTINCT.)
      IF(T .EQ. TOUT) GO TO 10
      IF(RELERR .LT. 0.0  .OR.  ABSERR .LT. 0.0)  CALL ERRCHK(49,
     1  49HIN ODERT, RELERR AND ABSERR MUST BE NON-NEGATIVE.)
      IF(RELERR .LT. 0.0  .OR.  ABSERR .LT. 0.0) GO TO 10
      EPS = MAX(RELERR,ABSERR)
      IF(EPS .LE. 0.0) CALL ERRCHK(51,
     1  51HIN ODERT, EITHER RELERR OR ABSERR MUST BE POSITIVE.)
      IF(EPS .LE. 0.0) GO TO 10
      IF(REROOT .LT. 0.0  .OR.  AEROOT .LT. 0.0) CALL ERRCHK(49,
     1  49HIN ODERT, REROOT AND AEROOT MUST BE NON-NEGATIVE.)
      IF(REROOT .LT. 0.0  .OR.  AEROOT .LT. 0.0) GO TO 10
      IF(REROOT+AEROOT .LE. 0.0) CALL ERRCHK(51,
     1  51HIN ODERT, EITHER REROOT OR AEROOT MUST BE POSITIVE.)
      IF(REROOT+AEROOT .LE. 0.0) GO TO 10
      IF(IFLAG .EQ. 0) CALL ERRCHK(34,
     1  34HIN ODERT, INVALID INPUT FOR IFLAG.)
      IF(IFLAG .EQ. 0) GO TO 10
      ISN = ISIGN(1,IFLAG)
      IFLAG = IABS(IFLAG)
      IF(IFLAG .EQ. 1) GO TO 20
      IF(T .NE. TOLD) CALL ERRCHK(68,
     1  68HIN ODERT, INPUT VALUE OF T MUST BE OUTPUT VALUE FROM PRECEDIN
     2G CALL.)
      IF(T .NE. TOLD) GO TO 10
      IF(IFLAG .GE. 2  .AND.  IFLAG .LE. 6) GO TO 15
      IF(IFLAG .GE. 8  .AND.  IFLAG .LE. 10) GO TO 15
      CALL ERRCHK(-34,34HIN ODERT, INVALID INPUT FOR IFLAG.)
   10 IFLAG = 7
      RETURN
C
15    CONTINUE
      IF (ISNOLD.LT.0 .OR. DELSGN*(TOUT-T).LT.0.) GO TO 20
C--      EVALUATE  G  AT EITHER TOUT (OUTPUT POINT THIS CALL)  OR AT
C--         X (POINT TO WHICH INTERNAL INTEGRATION HAS ALREADY
C--         PROCEEDED), WHICHEVER OCCURS FIRST.
      T2=X
      IF((X-T.GT.0..AND.X-TOUT.GT.0.).OR.(X-T.LT.0..AND.X-TOUT.LT.0.))
     1            T2=TOUT
      CALL INTRP(X,YY,T2,Y,YPOUT,NEQN,KOLD,PHI,PSI)
      GOFT2=G(T2,Y,YPOUT)
C--   NOW EVALUATE AT T1=T
      T1=T
      CALL INTRP(X,YY,T1,Y,YPOUT,NEQN,KOLD,PHI,PSI)
      GOFT1=G(T1,Y,YPOUT)
```

```
C--      NOW SEE IF A ROOT OF  G  OCCURS IN CLOSED INTERVAL (T1,T2).
      IF( GOFT1.EQ.0. .OR. GOFT2.EQ.0.)                GO TO 134
      IF( SIGN(1.DO,GOFT1)  * SIGN(1.DO,GOFT2) .LT. 0.DO ) GO TO 134
                   GO TO 21
C
C   ON EACH CALL SET INTERVAL OF INTEGRATION AND COUNTER FOR NUMBER OF
C   STEPS.  ADJUST INPUT ERROR TOLERANCES TO DEFINE WEIGHT VECTOR FOR
C   SUBROUTINE  STEP
C
20    T2=T
      CALL F(T2,Y,YPOUT)
      GOFT2 = G(T2,Y,YPOUT)
   21 CONTINUE
      DEL = TOUT - T
      ABSDEL = ABS(DEL)
      TEND = T + 10.0*DEL
      IF(ISN .LT. 0) TEND = TOUT
      NOSTEP = 0
      KLE4 = 0
      STIFF = .FALSE.
      RELEPS = RELERR/EPS
      ABSEPS = ABSERR/EPS
      IF(IFLAG .EQ. 1) GO TO 30
      IF(ISNOLD .LT. 0) GO TO 30
      IF(DELSGN*DEL .GT. 0.0) GO TO 50
C
C   ON START AND RESTART ALSO SET WORK VARIABLES X AND YY(*), STORE THE
C   DIRECTION OF INTEGRATION, AND INITIALIZE THE STEP SIZE.
C
   30 START = .TRUE.
      X = T
      TROOT = T
      DO 40 L = 1,NEQN
   40   YY(L) = Y(L)
      DELSGN = SIGN(1.0D0,DEL)
      H = SIGN(MAX(ABS(TOUT-X),FOURU*ABS(X)),TOUT-X)
C
C   IF ALREADY PAST OUTPUT POINT, INTERPOLATE AND RETURN
C
50    CONTINUE
      IF(ABS(X-T) .LT. ABSDEL) GO TO 60
      CALL INTRP(X,YY,TOUT,Y,YPOUT,NEQN,KOLD,PHI,PSI)
      IFLAG = 2
      T = TOUT
      TOLD = T
      ISNOLD = ISN
      RETURN
C
C   IF CANNOT GO PAST OUTPUT POINT AND SUFFICIENTLY CLOSE,
C   EXTRAPOLATE AND RETURN
C
   60 IF(ISN .GT. 0  .OR.  ABS(TOUT-X) .GE. FOURU*ABS(X)) GO TO 80
      H = TOUT - X
      CALL F(X,YY,YP)
```

```
      DO 70 L = 1,NEQN
   70   Y(L) = YY(L) + H*YP(L)
C *** NEXT STMT ADDED BY LIENESCH TO ENSURE YPOUT VALUES WILL ALWAYS BE
C *** AVAILABLE UNDER ANY CIRCUMSTANCES
      CALL F(X,Y,YPOUT)
      IFLAG = 2
      T = TOUT
      TOLD = T
      ISNOLD = ISN
      RETURN
C
C   TEST FOR TOO MUCH WORK
C
   80 IF(NOSTEP .LT. MAXNUM) GO TO 100
      IFLAG = ISN*4
      IF(STIFF) IFLAG = ISN*5
      DO 90 L = 1,NEQN
   90   Y(L) = YY(L)
      T = X
      TOLD = T
      ISNOLD = 1
      RETURN
C
C   LIMIT STEP SIZE, SET WEIGHT VECTOR AND TAKE A STEP
C
  100 H = SIGN(MIN(ABS(H),ABS(TEND-X)),H)
      DO 110 L = 1,NEQN
        WT(L) = RELEPS*ABS(YY(L)) + ABSEPS
        IF(WT(L) .LE. 0.0) GO TO 160
  110 CONTINUE
      CALL STEP1(F,NEQN,YY,X,H,EPS,WT,START,
     1  HOLD,K,KOLD,CRASH,PHI,P,YP,PSI,
     2  ALPHA,BETA,SIG,V,W,GG,PHASE1,NS,NORND)
C
C   TEST FOR TOLERANCES TOO SMALL.  IF SO, SET THE DERIVATIVE AT X
C   BEFORE RETURNING
C
      IF(.NOT.CRASH) GO TO 130
      IFLAG = ISN*3
      RELERR = EPS*RELEPS
      ABSERR = EPS*ABSEPS
      DO 120 L = 1,NEQN
        YP(L) = PHI(L,1)
  120   Y(L) = YY(L)
      T = X
      TOLD = T
      ISNOLD = 1
      RETURN
C
C   AUGMENT COUNTER ON WORK AND TEST FOR STIFFNESS.  ALSO TEST FOR A
C   ROOT IN THE STEP JUST COMPLETED
C
  130 NOSTEP = NOSTEP + 1
      KLE4 = KLE4 + 1
```

```
      IF(KOLD .GT. 4) KLE4 = 0
      IF(KLE4 .GE. 50) STIFF = .TRUE.
      T1=T2
      GOFT1=GOFT2
      T2=TOUT
C--     EVALUATE G AT INTERNAL INTEGRATION POINT X UNLESS X IS PAST TOUT
C--     IF X IS PAST TOUT EVALUATE G AT TOUT.
      IF( ABS(X-T).LT.ABSDEL) T2=X
      CALL INTRP(X,YY,T2,Y,YPOUT,NEQN,KOLD,PHI,PSI)
      GOFT2=G(T2,Y,YPOUT)
      IF(GOFT1.EQ.0. .OR. GOFT2.EQ.0.) GO TO 134
      IF( SIGN(1.DO,GOFT1)*SIGN(1.0DO,GOFT2) .LT.0.DO)GO TO 134
      GO TO 50
C
C   LOCATE ROOT OF G.  INTERPOLATE WITH  INTRP  FOR SOLUTION AND
C   DERIVATIVE VALUES
C
134   JFLAG=1
C--      HERE ROOT IS BETWEEN  T1 AND T2
      B=T1
      IF(GOFT1.EQ.0.)GO TO 150
      B=T2
      IF(GOFT2.EQ.0.)GO TO 150
      C=T1
  140 CALL ROOT(T,GT,B,C,REROOT,AEROOT,JFLAG)
      IF(JFLAG .GT. 0) GO TO 150
        IF( T.EQ.T1)GT=GOFT1
        IF( T.EQ.T2)GT=GOFT2
        IF( T.EQ.T1 .OR.T.EQ.T2)GO TO 140
      CALL INTRP(X,YY,T,Y,YPOUT,NEQN,KOLD,PHI,PSI)
      GT = G(T,Y,YPOUT)
      GO TO 140
  150 CONTINUE
      IFLAG = JFLAG+7
      IF(JFLAG .EQ. 2  .OR.  JFLAG .EQ. 4) IFLAG = 8
      IF(JFLAG .EQ. 3) IFLAG = 9
      IF(JFLAG .EQ. 5) IFLAG = 10
      IFLAG = IFLAG*ISN
      CALL INTRP(X,YY,B,Y,YPOUT,NEQN,KOLD,PHI,PSI)
      T = B
      IF(ABS(T-TROOT) .LE. REROOT*ABS(T) + AEROOT) GO TO 50
      TROOT = T
      TOLD = T
      ISNOLD = 1
      RETURN
  160 CALL ERRCHK(72,72HIN ODERT, PURE ABSOLUTE ERROR IMPOSSIBLE.  USE N
     1ON-ZERO VALUE OF ABSERR.)
      IFLAG = 6
      RETURN
      END

C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C
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C   * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C
C   WRITTEN BY L. F. SHAMPINE AND M. K. GORDON
C
C   ABSTRACT
C
C   SUBROUTINE  STEP1  IS NORMALLY USED INDIRECTLY THROUGH SUBROUTINE
C   ODE .  BECAUSE  ODE  SUFFICES FOR MOST PROBLEMS AND IS MUCH EASIER
C   TO USE, USING IT SHOULD BE CONSIDERED BEFORE USING  STEP1  ALONE.
C
C   SUBROUTINE STEP1 INTEGRATES A SYSTEM OF  NEQN  FIRST ORDER ORDINARY
C   DIFFERENTIAL EQUATIONS ONE STEP, NORMALLY FROM X TO X+H, USING A
C   MODIFIED DIVIDED DIFFERENCE FORM OF THE ADAMS PECE FORMULAS.  LOCAL
C   EXTRAPOLATION IS USED TO IMPROVE ABSOLUTE STABILITY AND ACCURACY.
C   THE CODE ADJUSTS ITS ORDER AND STEP SIZE TO CONTROL THE LOCAL ERROR
C   PER UNIT STEP IN A GENERALIZED SENSE.  SPECIAL DEVICES ARE INCLUDED
C   TO CONTROL ROUNDOFF ERROR AND TO DETECT WHEN THE USER IS REQUESTING
C   TOO MUCH ACCURACY.
C
C   THIS CODE IS COMPLETELY EXPLAINED AND DOCUMENTED IN THE TEXT,
C   COMPUTER SOLUTION OF ORDINARY DIFFERENTIAL EQUATIONS, THE INITIAL
C   VALUE PROBLEM  BY L. F. SHAMPINE AND M. K. GORDON.
C   FURTHER DETAILS ON USE OF THIS CODE ARE AVAILABLE IN *SOLVING
C   ORDINARY DIFFERENTIAL EQUATIONS WITH ODE, STEP, AND INTRP*,
C   BY L. F. SHAMPINE AND M. K. GORDON, SLA-73-1060.
C
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```
C
C   THE PARAMETERS REPRESENT --
C      F -- SUBROUTINE TO EVALUATE DERIVATIVES
C      NEQN -- NUMBER OF EQUATIONS TO BE INTEGRATED
C      Y(*) -- SOLUTION VECTOR AT X
C      X -- INDEPENDENT VARIABLE
C      H -- APPROPRIATE STEP SIZE FOR NEXT STEP.  NORMALLY DETERMINED BY
C           CODE
C      EPS -- LOCAL ERROR TOLERANCE
C      WT(*) -- VECTOR OF WEIGHTS FOR ERROR CRITERION
C      START -- LOGICAL VARIABLE SET .TRUE. FOR FIRST STEP,  .FALSE.
C           OTHERWISE
C      HOLD -- STEP SIZE USED FOR LAST SUCCESSFUL STEP
C      K -- APPROPRIATE ORDER FOR NEXT STEP (DETERMINED BY CODE)
C      KOLD -- ORDER USED FOR LAST SUCCESSFUL STEP
C      CRASH -- LOGICAL VARIABLE SET .TRUE. WHEN NO STEP CAN BE TAKEN,
C           .FALSE. OTHERWISE.
C      YP(*) -- DERIVATIVE OF SOLUTION VECTOR AT  X  AFTER SUCCESSFUL
C           STEP
C   THE ARRAYS  PHI, PSI  ARE REQUIRED FOR THE INTERPOLATION SUBROUTINE
C   INTRP .  THE ARRAY  P  IS INTERNAL TO THE CODE.  THE REMAINING NINE
C   VARIABLES AND ARRAYS ARE INCLUDED IN THE CALL LIST ONLY TO ELIMINATE
C   LOCAL RETENTION OF VARIABLES BETWEEN CALLS.
C
C   INPUT TO STEP1
C
C      FIRST CALL --
C
C   THE USER MUST PROVIDE STORAGE IN HIS CALLING PROGRAM FOR ALL ARRAYS
C   IN THE CALL LIST, NAMELY
C
C     DIMENSION Y(30),WT(30),PHI(30,16),P(30),YP(30),PSI(12),
C    1  ALPHA(12),BETA(12),SIG(13),V(12),W(12),G(13)
C                                --                 --    **NOTE**
C
C   THE USER MUST ALSO DECLARE  START ,  CRASH ,  PHASE1  AND  NORND
C   LOGICAL VARIABLES AND  F  AN EXTERNAL SUBROUTINE, SUPPLY THE
C   SUBROUTINE  F(X,Y,YP)  TO EVALUATE
C      DY(I)/DX = YP(I) = F(X,Y(1),Y(2),...,Y(NEQN))
C   AND INITIALIZE ONLY THE FOLLOWING PARAMETERS.
C      NEQN -- NUMBER OF EQUATIONS TO BE INTEGRATED
C      Y(*) -- VECTOR OF INITIAL VALUES OF DEPENDENT VARIABLES
C      X -- INITIAL VALUE OF THE INDEPENDENT VARIABLE
C      H -- NOMINAL STEP SIZE INDICATING DIRECTION OF INTEGRATION
C           AND MAXIMUM SIZE OF STEP.  MUST BE VARIABLE
C      EPS -- LOCAL ERROR TOLERANCE PER STEP.  MUST BE VARIABLE
C      WT(*) -- VECTOR OF NON-ZERO WEIGHTS FOR ERROR CRITERION
C      START -- .TRUE.
C
C   STEP1  REQUIRES THAT THE L2 NORM OF THE VECTOR WITH COMPONENTS
C   LOCAL ERROR(L)/WT(L)  BE LESS THAN  EPS  FOR A SUCCESSFUL STEP.  THE
C   ARRAY  WT  ALLOWS THE USER TO SPECIFY AN ERROR TEST APPROPRIATE
C   FOR HIS PROBLEM.  FOR EXAMPLE,
C      WT(L) = 1.0  SPECIFIES ABSOLUTE ERROR,
```

```
C            = ABS(Y(L))  ERROR RELATIVE TO THE MOST RECENT VALUE OF THE
C                L-TH COMPONENT OF THE SOLUTION,
C            = ABS(YP(L))  ERROR RELATIVE TO THE MOST RECENT VALUE OF
C                THE L-TH COMPONENT OF THE DERIVATIVE,
C            = AMAX1(WT(L),ABS(Y(L)))  ERROR RELATIVE TO THE LARGEST
C                MAGNITUDE OF L-TH COMPONENT OBTAINED SO FAR,
C            = ABS(Y(L))*RELERR/EPS + ABSERR/EPS  SPECIFIES A MIXED
C                RELATIVE-ABSOLUTE TEST WHERE  RELERR  IS RELATIVE
C                ERROR,  ABSERR  IS ABSOLUTE ERROR AND  EPS =
C                AMAX1(RELERR,ABSERR) .
C
C      SUBSEQUENT CALLS --
C
C   SUBROUTINE  STEP1  IS DESIGNED SO THAT ALL INFORMATION NEEDED TO
C   CONTINUE THE INTEGRATION, INCLUDING THE STEP SIZE  H  AND THE ORDER
C   K , IS RETURNED WITH EACH STEP.  WITH THE EXCEPTION OF THE STEP
C   SIZE, THE ERROR TOLERANCE, AND THE WEIGHTS, NONE OF THE PARAMETERS
C   SHOULD BE ALTERED.  THE ARRAY  WT  MUST BE UPDATED AFTER EACH STEP
C   TO MAINTAIN RELATIVE ERROR TESTS LIKE THOSE ABOVE.  NORMALLY THE
C   INTEGRATION IS CONTINUED JUST BEYOND THE DESIRED ENDPOINT AND THE
C   SOLUTION INTERPOLATED THERE WITH SUBROUTINE  INTRP .  IF IT IS
C   IMPOSSIBLE TO INTEGRATE BEYOND THE ENDPOINT, THE STEP SIZE MAY BE
C   REDUCED TO HIT THE ENDPOINT SINCE THE CODE WILL NOT TAKE A STEP
C   LARGER THAN THE  H  INPUT.  CHANGING THE DIRECTION OF INTEGRATION,
C   I.E., THE SIGN OF  H , REQUIRES THE USER SET  START = .TRUE. BEFORE
C   CALLING  STEP1  AGAIN.  THIS IS THE ONLY SITUATION IN WHICH  START
C   SHOULD BE ALTERED.
C
C   OUTPUT FROM STEP1
C
C      SUCCESSFUL STEP --
C
C   THE SUBROUTINE RETURNS AFTER EACH SUCCESSFUL STEP WITH  START  AND
C   CRASH  SET .FALSE. .  X  REPRESENTS THE INDEPENDENT VARIABLE
C   ADVANCED ONE STEP OF LENGTH  HOLD  FROM ITS VALUE ON INPUT AND  Y
C   THE SOLUTION VECTOR AT THE NEW VALUE OF  X .  ALL OTHER PARAMETERS
C   REPRESENT INFORMATION CORRESPONDING TO THE NEW  X  NEEDED TO
C   CONTINUE THE INTEGRATION.
C
C      UNSUCCESSFUL STEP --
C
C   WHEN THE ERROR TOLERANCE IS TOO SMALL FOR THE MACHINE PRECISION,
C   THE SUBROUTINE RETURNS WITHOUT TAKING A STEP AND  CRASH = .TRUE. .
C   AN APPROPRIATE STEP SIZE AND ERROR TOLERANCE FOR CONTINUING ARE
C   ESTIMATED AND ALL OTHER INFORMATION IS RESTORED AS UPON INPUT
C   BEFORE RETURNING.  TO CONTINUE WITH THE LARGER TOLERANCE, THE USER
C   JUST CALLS THE CODE AGAIN.  A RESTART IS NEITHER REQUIRED NOR
C   DESIRABLE.
C
      SUBROUTINE STEP1(F,NEQN,Y,X,H,EPS,WT,START,
     1 HOLD,K,KOLD,CRASH,PHI,P,YP,PSI,
     2 ALPHA,BETA,SIG,V,W,G,PHASE1,NS,NORND)
C
      IMPLICIT REAL*8 (A-H,O-Z)
```

```
D       IMPLICIT INTEGER*2 (I-N)
CCCCC GENERIC
      LOGICAL START,CRASH,PHASE1,NORND
      DIMENSION Y(30),WT(30),PHI(30,16),P(30),YP(30),PSI(12),
     1  ALPHA(12),BETA(12),SIG(13),V(12),W(12),G(13)
      DIMENSION TWO(13),GSTR(13)
      EXTERNAL F
C*********************************************************************
C*  THE ONLY MACHINE DEPENDENT CONSTANTS ARE BASED ON THE MACHINE UNIT *
C*  ROUNDOFF ERROR  U  WHICH IS THE SMALLEST POSITIVE NUMBER SUCH THAT *
C*  1.0+U .GT. 1.0  .  THE USER MUST CALCULATE  U  AND INSERT          *
C*  TWOU=2.0*U  AND  FOURU=4.0*U  IN THE DATA STATEMENT BEFORE CALLING *
C*  THE CODE.  THE ROUTINE  MACHIN  CALCULATES  U .                    *
      DATA TWOU,FOURU/4.4E-16,8.8E-16/
C*********************************************************************
C
      DATA TWO/2.0,4.0,8.0,16.0,32.0,64.0,128.0,256.0,512.0,1024.0,
     1  2048.0,4096.0,8192.0/
      DATA GSTR/0.500,0.0833,0.0417,0.0264,0.0188,0.0143,0.0114,0.00936,
     1  0.00789,0.00679,0.00592,0.00524,0.00468/
C
C
C       ***     BEGIN BLOCK 0     ***
C   CHECK IF STEP SIZE OR ERROR TOLERANCE IS TOO SMALL FOR MACHINE
C   PRECISION.  IF FIRST STEP, INITIALIZE PHI ARRAY AND ESTIMATE A
C   STARTING STEP SIZE.
C                   ***
C
C   IF STEP SIZE IS TOO SMALL, DETERMINE AN ACCEPTABLE ONE
C
      CRASH = .TRUE.
      IF(ABS(H) .GE. FOURU*ABS(X)) GO TO 5
      H = SIGN(FOURU*ABS(X),H)
      RETURN
 5    P5EPS = 0.5*EPS
C
C   IF ERROR TOLERANCE IS TOO SMALL, INCREASE IT TO AN ACCEPTABLE VALUE
C
      ROUND = 0.0
      DO 10 L = 1,NEQN
 10     ROUND = ROUND + (Y(L)/WT(L))**2
      ROUND = TWOU*SQRT(ROUND)
      IF(P5EPS .GE. ROUND) GO TO 15
      EPS = 2.0*ROUND*(1.0 + FOURU)
      RETURN
 15   CRASH = .FALSE.
      G(1) = 1.0
      G(2) = 0.5
      SIG(1) = 1.0
      IF(.NOT.START) GO TO 99
C
C   INITIALIZE.  COMPUTE APPROPRIATE STEP SIZE FOR FIRST STEP
C
      CALL F(X,Y,YP)
```

```
      SUM = 0.0
      DO 20 L = 1,NEQN
        PHI(L,1) = YP(L)
        PHI(L,2) = 0.0
 20     SUM = SUM + (YP(L)/WT(L))**2
      SUM = SQRT(SUM)
      ABSH = ABS(H)
      IF(EPS .LT. 16.0*SUM*H*H) ABSH = 0.25*SQRT(EPS/SUM)
      H = SIGN(MAX(ABSH,FOURU*ABS(X)),H)
      HOLD = 0.0
      K = 1
      KOLD = 0
      START = .FALSE.
      PHASE1 = .TRUE.
      NORND = .TRUE.
      IF(P5EPS .GT. 100.0*ROUND) GO TO 99
      NORND = .FALSE.
      DO 25 L = 1,NEQN
 25     PHI(L,15) = 0.0
 99   IFAIL = 0
C       ***     END BLOCK 0     ***
C
C       ***     BEGIN BLOCK 1     ***
C   COMPUTE COEFFICIENTS OF FORMULAS FOR THIS STEP.  AVOID COMPUTING
C   THOSE QUANTITIES NOT CHANGED WHEN STEP SIZE IS NOT CHANGED.
C                     ***
C
 100  KP1 = K+1
      KP2 = K+2
      KM1 = K-1
      KM2 = K-2
C
C   NS IS THE NUMBER OF STEPS TAKEN WITH SIZE H, INCLUDING THE CURRENT
C   ONE.  WHEN K.LT.NS, NO COEFFICIENTS CHANGE
C
      IF(H .NE. HOLD) NS = 0
      IF (NS.LE.KOLD) NS = NS+1
      NSP1 = NS+1
      IF (K .LT. NS) GO TO 199
C
C   COMPUTE THOSE COMPONENTS OF ALPHA(*),BETA(*),PSI(*),SIG(*) WHICH
C   ARE CHANGED
C
      BETA(NS) = 1.0
      REALNS = NS
      ALPHA(NS) = 1.0/REALNS
      TEMP1 = H*REALNS
      SIG(NSP1) = 1.0
      IF(K .LT. NSP1) GO TO 110
      DO 105 I = NSP1,K
        IM1 = I-1
        TEMP2 = PSI(IM1)
        PSI(IM1) = TEMP1
        BETA(I) = BETA(IM1)*PSI(IM1)/TEMP2
```

```
      TEMP1 = TEMP2 + H
      ALPHA(I) = H/TEMP1
      REALI = I
105   SIG(I+1) = REALI*ALPHA(I)*SIG(I)
110 PSI(K) = TEMP1
C
C  COMPUTE COEFFICIENTS G(*)
C
C  INITIALIZE V(*) AND SET W(*).
C
    IF(NS .GT. 1) GO TO 120
    DO 115 IQ = 1,K
      TEMP3 = IQ*(IQ+1)
      V(IQ) = 1.0/TEMP3
115   W(IQ) = V(IQ)
    GO TO 140
C
C  IF ORDER WAS RAISED, UPDATE DIAGONAL PART OF V(*)
C
120 IF(K .LE. KOLD) GO TO 130
    TEMP4 = K*KP1
    V(K) = 1.0/TEMP4
    NSM2 = NS-2
    IF(NSM2 .LT. 1) GO TO 130
    DO 125 J = 1,NSM2
      I = K-J
125   V(I) = V(I) - ALPHA(J+1)*V(I+1)
C
C  UPDATE V(*) AND SET W(*)
C
130 LIMIT1 = KP1 - NS
    TEMP5 = ALPHA(NS)
    DO 135 IQ = 1,LIMIT1
      V(IQ) = V(IQ) - TEMP5*V(IQ+1)
135   W(IQ) = V(IQ)
    G(NSP1) = W(1)
C
C  COMPUTE THE G(*) IN THE WORK VECTOR W(*)
C
140 NSP2 = NS + 2
    IF(KP1 .LT. NSP2) GO TO 199
    DO 150 I = NSP2,KP1
      LIMIT2 = KP2 - I
      TEMP6 = ALPHA(I-1)
      DO 145 IQ = 1,LIMIT2
145     W(IQ) = W(IQ) - TEMP6*W(IQ+1)
150   G(I) = W(1)
199   CONTINUE
C     ***     END BLOCK 1     ***
C
C     ***     BEGIN BLOCK 2     ***
C  PREDICT A SOLUTION P(*), EVALUATE DERIVATIVES USING PREDICTED
C  SOLUTION, ESTIMATE LOCAL ERROR AT ORDER K AND ERRORS AT ORDERS K,
C  K-1, K-2 AS IF CONSTANT STEP SIZE WERE USED.
```

```
C                   ***
C
C   CHANGE PHI TO PHI STAR
C
      IF(K .LT. NSP1) GO TO 215
      DO 210 I = NSP1,K
        TEMP1 = BETA(I)
        DO 205 L = 1,NEQN
 205      PHI(L,I) = TEMP1*PHI(L,I)
 210    CONTINUE
C
C   PREDICT SOLUTION AND DIFFERENCES
C
 215  DO 220 L = 1,NEQN
        PHI(L,KP2) = PHI(L,KP1)
        PHI(L,KP1) = 0.0
 220    P(L) = 0.0
      DO 230 J = 1,K
        I = KP1 - J
        IP1 = I+1
        TEMP2 = G(I)
        DO 225 L = 1,NEQN
          P(L) = P(L) + TEMP2*PHI(L,I)
 225      PHI(L,I) = PHI(L,I) + PHI(L,IP1)
 230    CONTINUE
      IF(NORND) GO TO 240
      DO 235 L = 1,NEQN
        TAU = H*P(L) - PHI(L,15)
        P(L) = Y(L) + TAU
 235    PHI(L,16) = (P(L) - Y(L)) - TAU
      GO TO 250
 240  DO 245 L = 1,NEQN
 245    P(L) = Y(L) + H*P(L)
 250  XOLD = X
      X = X + H
      ABSH = ABS(H)
      CALL F(X,P,YP)
C
C   ESTIMATE ERRORS AT ORDERS K,K-1,K-2
C
      ERKM2 = 0.0
      ERKM1 = 0.0
      ERK = 0.0
      DO 265 L = 1,NEQN
        TEMP3 = 1.0/WT(L)
        TEMP4 = YP(L) - PHI(L,1)
        IF(KM2)265,260,255
 255    ERKM2 = ERKM2 + ((PHI(L,KM1)+TEMP4)*TEMP3)**2
 260    ERKM1 = ERKM1 + ((PHI(L,K)+TEMP4)*TEMP3)**2
 265    ERK = ERK + (TEMP4*TEMP3)**2
        IF(KM2)280,275,270
 270  ERKM2 = ABSH*SIG(KM1)*GSTR(KM2)*SQRT(ERKM2)
 275  ERKM1 = ABSH*SIG(K)*GSTR(KM1)*SQRT(ERKM1)
 280  TEMP5 = ABSH*SQRT(ERK)
```

```
      ERR = TEMP5*(G(K)-G(KP1))
      ERK = TEMP5*SIG(KP1)*GSTR(K)
      KNEW = K
C
C   TEST IF ORDER SHOULD BE LOWERED
C
      IF(KM2)299,290,285
 285  IF(MAX(ERKM1,ERKM2) .LE. ERK) KNEW = KM1
      GO TO 299
 290  IF(ERKM1 .LE. 0.5*ERK) KNEW = KM1
C
C   TEST IF STEP SUCCESSFUL
C
 299  IF(ERR .LE. EPS) GO TO 400
C       ***      END BLOCK 2      ***
C
C       ***      BEGIN BLOCK 3      ***
C   THE STEP IS UNSUCCESSFUL.  RESTORE  X, PHI(*,*), PSI(*) .
C   IF THIRD CONSECUTIVE FAILURE, SET ORDER TO ONE.  IF STEP FAILS MORE
C   THAN THREE TIMES, CONSIDER AN OPTIMAL STEP SIZE.  DOUBLE ERROR
C   TOLERANCE AND RETURN IF ESTIMATED STEP SIZE IS TOO SMALL FOR MACHINE
C   PRECISION.
C                    ***
C
C   RESTORE X, PHI(*,*) AND PSI(*)
C
      PHASE1 = .FALSE.
      X = XOLD
      DO 310 I = 1,K
        TEMP1 = 1.0/BETA(I)
        IP1 = I+1
        DO 305 L = 1,NEQN
 305      PHI(L,I) = TEMP1*(PHI(L,I) - PHI(L,IP1))
 310    CONTINUE
      IF(K .LT. 2) GO TO 320
      DO 315 I = 2,K
 315    PSI(I-1) = PSI(I) - H
C
C   ON THIRD FAILURE, SET ORDER TO ONE.  THEREAFTER, USE OPTIMAL STEP
C   SIZE
C
 320  IFAIL = IFAIL + 1
      TEMP2 = 0.5
      IF(IFAIL - 3) 335,330,325
 325  IF(P5EPS .LT. 0.25*ERK) TEMP2 = SQRT(P5EPS/ERK)
 330  KNEW = 1
 335  H = TEMP2*H
      K = KNEW
      IF(ABS(H) .GE. FOURU*ABS(X)) GO TO 340
      CRASH = .TRUE.
      H = SIGN(FOURU*ABS(X),H)
      EPS = EPS + EPS
      RETURN
 340  GO TO 100
```

```
C        ***      END BLOCK 3      ***
C
C        ***      BEGIN BLOCK 4      ***
C    THE STEP IS SUCCESSFUL.  CORRECT THE PREDICTED SOLUTION, EVALUATE
C    THE DERIVATIVES USING THE CORRECTED SOLUTION AND UPDATE THE
C    DIFFERENCES.  DETERMINE BEST ORDER AND STEP SIZE FOR NEXT STEP.
C                       ***
 400  KOLD = K
      HOLD = H
C
C    CORRECT AND EVALUATE
C
      TEMP1 = H*G(KP1)
      IF(NORND) GO TO 410
      DO 405 L = 1,NEQN
        RHO = TEMP1*(YP(L) - PHI(L,1)) - PHI(L,16)
        Y(L) = P(L) + RHO
 405    PHI(L,15) = (Y(L) - P(L)) - RHO
      GO TO 420
 410  DO 415 L = 1,NEQN
 415    Y(L) = P(L) + TEMP1*(YP(L) - PHI(L,1))
 420  CALL F(X,Y,YP)
C
C    UPDATE DIFFERENCES FOR NEXT STEP
C
      DO 425 L = 1,NEQN
        PHI(L,KP1) = YP(L) - PHI(L,1)
 425    PHI(L,KP2) = PHI(L,KP1) - PHI(L,KP2)
      DO 435 I = 1,K
        DO 430 L = 1,NEQN
 430      PHI(L,I) = PHI(L,I) + PHI(L,KP1)
 435    CONTINUE
C
C    ESTIMATE ERROR AT ORDER K+1 UNLESS:
C      IN FIRST PHASE WHEN ALWAYS RAISE ORDER,
C      ALREADY DECIDED TO LOWER ORDER,
C      STEP SIZE NOT CONSTANT SO ESTIMATE UNRELIABLE
C
      ERKP1 = 0.0
      IF(KNEW .EQ. KM1  .OR.  K .EQ. 12) PHASE1 = .FALSE.
      IF(PHASE1) GO TO 450
      IF(KNEW .EQ. KM1) GO TO 455
      IF(KP1 .GT. NS) GO TO 460
      DO 440 L = 1,NEQN
 440    ERKP1 = ERKP1 + (PHI(L,KP2)/WT(L))**2
      ERKP1 = ABSH*GSTR(KP1)*SQRT(ERKP1)
C
C    USING ESTIMATED ERROR AT ORDER K+1, DETERMINE APPROPRIATE ORDER
C    FOR NEXT STEP
C
      IF(K .GT. 1) GO TO 445
      IF(ERKP1 .GE. 0.5*ERK) GO TO 460
      GO TO 450
 445  IF(ERKM1 .LE. MIN(ERK,ERKP1)) GO TO 455
```

```
      IF(ERKP1 .GE. ERK  .OR.  K .EQ. 12) GO TO 460
C
C   HERE ERKP1 .LT. ERK .LT. AMAX1(ERKM1,ERKM2) ELSE ORDER WOULD HAVE
C   BEEN LOWERED IN BLOCK 2.  THUS ORDER IS TO BE RAISED
C
C   RAISE ORDER
C
 450  K = KP1
      ERK = ERKP1
      GO TO 460
C
C   LOWER ORDER
C
 455  K = KM1
      ERK = ERKM1
C
C   WITH NEW ORDER DETERMINE APPROPRIATE STEP SIZE FOR NEXT STEP
C
 460  HNEW = H + H
      IF(PHASE1) GO TO 465
      IF(P5EPS .GE. ERK*TWO(K+1)) GO TO 465
      HNEW = H
      IF(P5EPS .GE. ERK) GO TO 465
      TEMP2 = K+1
      R = (P5EPS/ERK)**(1.0/TEMP2)
      HNEW = ABSH*MAX(0.5D0,MIN(0.9D0,R))
      HNEW = SIGN(MAX(HNEW,FOURU*ABS(X)),H)
 465  H = HNEW
      RETURN
C       ***     END BLOCK 4      ***
      END
C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C
C  ROOT COMPUTES A ROOT OF THE NONLINEAR EQUATION F(X)=0
C  WHERE F(X) IS A CONTINUOUS REAL FUNCTION OF A SINGLE REAL
C  VARIABLE X.  THE METHOD USED IS A COMBINATION OF BISECTION
C  AND THE SECANT RULE.
C
C  NORMAL INPUT CONSISTS OF A CONTINUOUS FUNCTION F AND AN
C  INTERVAL (B,C) SUCH THAT F(B)*F(C).LE.0.0.  EACH ITERATION
C  FINDS NEW VALUES OF B AND C SUCH THAT THE INTERVAL (B,C) IS
C  SHRUNK AND F(B)*F(C).LE.0.0.  THE STOPPING CRITERION IS
C
C          ABS(B-C).LE.2.0*(RELERR*ABS(B)+ABSERR)
C
C  WHERE RELERR=RELATIVE ERROR AND ABSERR=ABSOLUTE ERROR ARE
C  INPUT QUANTITIES.  SET THE FLAG, IFLAG, POSITIVE TO INITIALIZE
C  THE COMPUTATION.  AS B,C AND IFLAG ARE USED FOR BOTH INPUT AND
C  OUTPUT, THEY MUST BE VARIABLES IN THE CALLING PROGRAM.
C
C  IF 0 IS A POSSIBLE ROOT, ONE SHOULD NOT CHOOSE ABSERR=0.0.
C
C  THE OUTPUT VALUE OF B IS THE BETTER APPROXIMATION TO A ROOT
C  AS B AND C ARE ALWAYS REDEFINED SO THAT ABS(F(B)).LE.ABS(F(C)).
```

```
C
C  TO SOLVE THE EQUATION, ROOT MUST EVALUATE F(X) REPEATEDLY. THIS
C  IS DONE IN THE CALLING PROGRAM.  WHEN AN EVALUATION OF F IS
C  NEEDED AT T, ROOT RETURNS WITH IFLAG NEGATIVE.  EVALUATE FT=F(T)
C  AND CALL ROOT AGAIN.  DO NOT ALTER IFLAG.
C
C  WHEN THE COMPUTATION IS COMPLETE, ROOT RETURNS TO THE CALLING
C  PROGRAM WITH IFLAG POSITIVE.
C
C      IFLAG=1  IF F(B)*F(C).LT.0 AND THE STOPPING CRITERION IS MET.
C
C           =2  IF A VALUE B IS FOUND SUCH THAT THE COMPUTED VALUE
C               F(B) IS EXACTLY ZERO.  THE INTERVAL (B,C) MAY NOT
C               SATISFY THE STOPPING CRITERION.
C
C           =3  IF ABS(F(B)) EXCEEDS THE INPUT VALUES ABS(F(B)),
C               ABS(F(C)).   IN THIS CASE IT IS LIKELY THAT B IS CLOSE
C               TO A POLE OF F.
C
C           =4  IF NO ODD ORDER ROOT WAS FOUND IN THE INTERVAL.  A
C               LOCAL MINIMUM MAY HAVE BEEN OBTAINED.
C
C           =5  IF TOO MANY FUNCTION EVALUATIONS WERE MADE.
C               (AS PROGRAMMED, 500 ARE ALLOWED.)
C
C THIS CODE IS A MODIFICATION OF THE CODE  ZEROIN  WHICH IS COMPLETELY
C EXPLAINED AND DOCUMENTED IN THE TEXT, NUMERICAL COMPUTING, AN
C INTRODUCTION  BY L. F. SHAMPINE AND R. C. ALLEN.
C
      SUBROUTINE ROOT(T,FT,B,C,RELERR,ABSERR,IFLAG)
C
      IMPLICIT REAL*8 (A-H,O-Z)
CCCCC GENERIC
      COMMON/MLDRT/A,ACBS,AE,FA,FB,FC,FX,IC,KOUNT,RE
C***********************************************************************
C*  THE ONLY MACHINE DEPENDENT CONSTANT IS BASED ON THE MACHINE UNIT   *
C*  ROUNDOFF ERROR  U  WHICH IS THE SMALLEST POSITIVE NUMBER SUCH THAT *
C*  1.0+U .GT. 1.0 .  U  MUST BE CALCULATED AND INSERTED IN THE        *
C*  FOLLOWING DATA STATEMENT BEFORE USING  ROOT .  THE ROUTINE  MACHIN *
C*  CALCULATES  U .                                                    *
C***********************************************************************
      DATA U /2.2E-16/
C***********************************************************************
C
      IF(IFLAG.LT.0.0) GO TO 100
      RE=MAX(RELERR,U)
      AE=MAX(ABSERR,0.0D0)
      IC=0
      ACBS=ABS(B-C)
      A=C
      T=A
      IFLAG=-1
      RETURN
  100 IFLAG=IABS(IFLAG)
```

```
      GO TO (200,300,400),IFLAG
  200 FA=FT
      T=B
      IFLAG=-2
      RETURN
  300 FB=FT
      FC=FA
      KOUNT=2
      FX=MAX(ABS(FB),ABS(FC))
      GO TO 1
  400 FB=FT
      IF(FB.EQ.0.0) GO TO 9
      KOUNT=KOUNT+1
      IF(SIGN(1.0D0,FB).NE.SIGN(1.0D0,FC))GO TO 1
      C=A
      FC=FA
    1 IF(ABS(FC).GE.ABS(FB))GO TO 2
C
C  INTERCHANGE B AND C SO THAT ABS(F(B)).LE.ABS(F(C)).
C
      A=B
      FA=FB
      B=C
      FB=FC
      C=A
      FC=FA
    2 CMB=0.5*(C-B)
      ACMB=ABS(CMB)
      TOL=RE*ABS(B)+AE
C
C  TEST STOPPING CRITERION AND FUNCTION COUNT.
C
      IF(ACMB.LE.TOL)GO TO 8
      IF(KOUNT.GE.500)GO TO 12
C
C  CALCULATE NEW ITERATE IMPLICITLY AS B+P/Q
C  WHERE WE ARRANGE P.GE.0.  THE IMPLICIT
C  FORM IS USED TO PREVENT OVERFLOW.
C
      P=(B-A)*FB
      Q=FA-FB
      IF(P.GE.0.0)GO TO 3
      P=-P
      Q=-Q
C
C  UPDATE A, CHECK IF REDUCTION IN THE SIZE OF BRACKETING
C  INTERVAL IS SATISFACTORY.  IF NOT, BISECT UNTIL IT IS.
C
    3 A=B
      FA=FB
      IC=IC+1
      IF(IC.LT.4)GO TO 4
      IF(8.0*ACMB.GE.ACBS)GO TO 6
      IC=0
```

```
      ACBS=ACMB
C
C  TEST FOR TOO SMALL A CHANGE.
C
    4 IF(P.GT.ABS(Q)*TOL)GO TO 5
C
C  INCREMENT BY TOLERANCE.
C
      B=B+SIGN(TOL,CMB)
      GO TO 7
C
C  ROOT OUGHT TO BE BETWEEN B AND (C+B)/2.
C
    5 IF(P.GE.CMB*Q)GO TO 6
C
C  USE SECANT RULE.
C
      B=B+P/Q
      GO TO 7
C
C  USE BISECTION.
C
    6 B=0.5*(C+B)
C
C  HAVE COMPLETED COMPUTATION FOR NEW ITERATE B.
C
    7 T=B
      IFLAG=-3
      RETURN
C
C  FINISHED.  SET IFLAG.
C
    8 IF(SIGN(1.0D0,FB).EQ.SIGN(1.0D0,FC))GO TO 11
      IF(ABS(FB).GT.FX)GO TO 10
      IFLAG=1
      RETURN
    9 IFLAG=2
      RETURN
   10 IFLAG=3
      RETURN
   11 IFLAG=4
      RETURN
   12 IFLAG=5
      RETURN
      END
C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C
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C     CONTROL DATA 6600/7600 VERSION 7.2  SEPTEMBER 1977
C
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C   *                                                                     *
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C   * A PART IS SAND75-0545.                                              *
C   *                                                                     *
C   * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C
C   WRITTEN BY L. F. SHAMPINE AND M. K. GORDON
C
C   ABSTRACT
C
C
C   THE METHODS IN SUBROUTINE  STEP1  APPROXIMATE THE SOLUTION NEAR  X
C   BY A POLYNOMIAL.  SUBROUTINE  INTRP  APPROXIMATES THE SOLUTION AT
C   XOUT  BY EVALUATING THE POLYNOMIAL THERE.  INFORMATION DEFINING THIS
C   POLYNOMIAL IS PASSED FROM  STEP1  SO  INTRP  CANNOT BE USED ALONE.
C
C   THIS CODE IS COMPLETELY EXPLAINED AND DOCUMENTED IN THE TEXT,
C   COMPUTER SOLUTION OF ORDINARY DIFFERENTIAL EQUATIONS, THE INITIAL
C   VALUE PROBLEM  BY L. F. SHAMPINE AND M. K. GORDON.
C   FURTHER DETAILS ON USE OF THIS CODE ARE AVAILABLE IN *SOLVING
C   ORDINARY DIFFERENTIAL EQUATIONS WITH ODE, STEP, AND INTRP*,
C   BY L. F. SHAMPINE AND M. K. GORDON, SLA-73-1060.
C
C   INPUT TO INTRP --
C
C   THE USER PROVIDES STORAGE IN THE CALLING PROGRAM FOR THE ARRAYS IN
C   THE CALL LIST
C      DIMENSION Y(NEQN),YOUT(NEQN),YPOUT(NEQN),PHI(NEQN,16),PSI(12)
C   AND DEFINES
C      XOUT -- POINT AT WHICH SOLUTION IS DESIRED.
C   THE REMAINING PARAMETERS ARE DEFINED IN  STEP1  AND PASSED TO
C   INTRP  FROM THAT SUBROUTINE
C
C   OUTPUT FROM  INTRP --
C
```

```
C      YOUT(*) -- SOLUTION AT  XOUT
C      YPOUT(*) -- DERIVATIVE OF SOLUTION AT  XOUT
C   THE REMAINING PARAMETERS ARE RETURNED UNALTERED FROM THEIR INPUT
C   VALUES.  INTEGRATION WITH  STEP1  MAY BE CONTINUED.
C
      SUBROUTINE INTRP(X,Y,XOUT,YOUT,YPOUT,NEQN,KOLD,PHI,PSI)
      IMPLICIT REAL *8 (A-H,O-Z)
D      IMPLICIT INTEGER*2 (I-N)
C
C
CCCCC GENERIC
      DIMENSION Y(30),YOUT(30),YPOUT(30),PHI(30,16),PSI(12)
      DIMENSION G(13),W(13),RHO(13)
      DATA G(1)/1.0/,RHO(1)/1.0/
C
      HI = XOUT - X
      KI = KOLD + 1
      KIP1 = KI + 1
C
C   INITIALIZE W(*) FOR COMPUTING G(*)
C
      DO 5 I = 1,KI
        TEMP1 = I
 5      W(I) = 1.0/TEMP1
      TERM = 0.0
C
C   COMPUTE G(*)
C
      DO 15 J = 2,KI
        JM1 = J - 1
        PSIJM1 = PSI(JM1)
        GAMMA = (HI + TERM)/PSIJM1
        ETA = HI/PSIJM1
        LIMIT1 = KIP1 - J
        DO 10 I = 1,LIMIT1
 10       W(I) = GAMMA*W(I) - ETA*W(I+1)
        G(J) = W(1)
        RHO(J) = GAMMA*RHO(JM1)
 15     TERM = PSIJM1
C
C   INTERPOLATE
C
      DO 20 L = 1,NEQN
        YPOUT(L) = 0.0
 20     YOUT(L) = 0.0
      DO 30 J = 1,KI
        I = KIP1 - J
        TEMP2 = G(I)
        TEMP3 = RHO(I)
        DO 25 L = 1,NEQN
          YOUT(L) = YOUT(L) + TEMP2*PHI(L,I)
 25       YPOUT(L) = YPOUT(L) + TEMP3*PHI(L,I)
 30     CONTINUE
      DO 35 L = 1,NEQN
```

```
 35     YOUT(L) = Y(L) + HI*YOUT(L)
      RETURN
      END
C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C
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C   *                                                                   *
C   * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C
      SUBROUTINE ERRCHK(N,M)
      INTEGER*2 M
      DIMENSION M(100)
      NWDS = (IABS(N)+1)/2
      PRINT 10, (M(I), I=1,NWDS)
   10 FORMAT(1H0, 60A2)
      IF (N .GT. 0) RETURN
      STOP
      END
```

```
$INPUT
     FIRE    = .TRUE.
     SPBURN  = .TRUE.
     FUELTP  = 1
     PHISTA  = 0.80
     ECCEN   = 1.50
     ROTRAD= 10.5
     DEPTH   = 7.00
     VFLANK  = 35.00
     RPM     = 3000.
     TIPO    = -530.0
     TIPC    = -180.0
     TEPO    = 199.0
     TEPC    = 588.5
     TSPARK  = -25.00
     THIPO   = 120.0
     THEPO   = 40.0
     IPA     = 13.8
     EPA     = 6.5
     XBZERO  = 0.0003
     XBSTOP  = 0.995
     TMAX    = 0.0
     DQDTMAX= 0.0381
     PATM    = 1.000
     TATM    = 300.0
     PIM     = 0.980
     TFRESH  = 300.0
     TEGR    = 300.0
     EGR     = 0.0
     PEM     = 1.02
     TROTOR  = 370.
     TSIDE   = 370.
     THOUS   = 370.
     CONHT   = 0.037
     EXPHT   = .8
     TPRINT  = 10.0
     TPRINX  = 1.0
     AREROT  = 1.E-4
     CIINTG  = 1.E-4
     CCINTG  = 1.E-4
     CBINTG  = 1.E-5
     CEINTG  = 1.E-4
     MXTRY   = 1
     REL     = .0002
     MAXITS  = 3
     MAXERR  = 0.03
     MAXTRY  = 10
     AREALK  = 0.01
     CREVOL  = 0.875
     TCREV   = 370.
     CON1    = 0.75
     CON2    = 0.324
$END
```

M.I.T. ZERO-DIMENSIONAL WANKEL ENGINE CYCLE SIMULATION

>>>>> INPUT DATA <<<<<

>>>>> OPERATING MODE

FIRING CYCLE

SPECIFIED BURN RATE

MAXIMUM NORMALIZED HEAT RELEASE RATE = 0.038
ANGLE OF DQMAX = 0.000

>>>>> OPERATING CONDITIONS

FUEL USED IS ISOOCTANE

F/A EQUIVALENCE RATIO = 0.800

SPARK TIMING = -25.00 DEG CA

ENGINE SPEED = 3000.0 RPM

>>>>> MANIFOLD CONDITIONS

INTAKE MANIFOLD PRESSURE = 0.9800 ATM

EXHAUST MANIFOLD PRESSURE = 1.0200 ATM

FRESH CHARGE TEMPERATURE = 300.00 K

EXHAUST GAS RECIRCULATION = 0.00 %

```
EGR TEMPERATURE            =   300.00   K
INTAKE CHARGE TEMPERATURE =    300.00   K
ATMOSPHERIC PRESSURE       =     1.0000 ATM
ATMOSPHERIC TEMPERATURE    =   300.00   K
```

```
>>>>> HEAT TRANSFER AND TURBULENCE PARAMETERS

      HEAT TRANSFER CONSTANT        =     0.0370
      HEAT TRANSFER EXPONENT        =     0.8000
      ROTOR TEMPERATURE             =   370.00    K
      SIDE WALL TEMPERATURE         =   370.00    K
      HOUSING WALL TEMPERATURE      =   370.00    K
```

```
>>>>> ENGINE DESIGN PARAMETERS

      ECCENTRICITY OF ROTOR   =     1.500 CM
      RADIUS OF ROTOR         =    10.500 CM
      DEPTH OF CHAMBER        =     7.000 CM
      COMPRESSION RATIO       =     9.407
      DISPLACED VOLUME        =   572.876 CC
      VOLUME OF ROTOR POCKET  =    35.000 CC
      INTAKE PORT OPENS      =  -530.0   DEG CA
      INTAKE PORT CLOSES     =  -180.0   DEG CA
      EXHAUST PORT OPENS     =   199.0   DEG CA
      EXHAUST PORT CLOSES    =   588.5   DEG CA
```

```
>>>>> LEAKAGE AND CREVICE VOLUME PARAMETERS

      LEAK AREA PER APEX     =     0.010000  CM*CM
      CREVICE VOLUME PER APEX=     0.875000  CC
```

CREVICE GAS TEMPERATURE= 370.000000 K

>>>>> COMPUTATIONAL PARAMETERS

MAXIMUM # OF ITERATIONS = 3

OUTPUT AT ITERATION # = 3

TPRINT	=	10.00
TPRINX	=	1.00
XBZERO	=	0.00030
XESTOP	=	0.00000
XBSTOP	=	0.99500
CIINTG	=	0.000100
CCINTG	=	0.000100
CBINTG	=	0.000010
CEINTG	=	0.000100
AREROT	=	0.000100
REL	=	0.000200
ERMAX	=	0.000000
MAXERR	=	0.030000
MAXTRY	=	10

>>>>> START OF INTAKE PROCESS

CA (DEG)	P (ATM)	TEMP (K)	MIN (G)	MEX (G)	VIV (CM/SEC)	VEV (CM/SEC)	X1 (-)	Q DOT (KJ/DEG)	WORK (KJ)	IMF	IFG
-530.0	1.0193	654.25	0.00000	0.00000	0.0		0.00000		0.000000		
-520.0	1.0080	643.74	-0.00143	-0.00416	-7521.3	-4333.0	0.00383	0.000022	0.000595	0	2
-510.0	0.9841	633.31	-0.00409	-0.01107	-2921.2	-7513.4	0.00770	0.000021	0.001557	0	2
-508.3	0.9805	631.83	-0.00431	-0.01219	-1042.3	-7880.5	0.00835	0.000021	0.001753	0	8
-503.8	0.7369	428.21	-0.00001	-0.01631	21134.3	-19717.2	0.01002	0.000005	0.002285	0	8
-500.0	0.8677	431.35	0.00918	-0.02022	9888.6	-13503.6	0.14161	0.000006	0.002722	1	2
-490.0	0.9382	423.62	0.02602	-0.02281	8293.1	0.0	0.30641	0.000005	0.004295	1	2
-480.0	0.9328	394.89	0.04795	-0.02281	6664.5	0.0	0.44312	0.000003	0.006175	1	2
-470.0	0.9387	375.46	0.07404	-0.02281	6259.2	0.0	0.54828	0.000001	0.008343	1	2
-460.0	0.9440	361.95	0.10288	-0.02281	5856.1	0.0	0.62595	-0.000001	0.010777	1	2
-450.0	0.9483	352.20	0.13407	-0.02281	5511.8	0.0	0.68440	-0.000002	0.013445	1	2
-440.0	0.9521	344.97	0.16730	-0.02281	5184.7	0.0	0.72934	-0.000003	0.016312	1	2
-430.0	0.9555	339.50	0.20218	-0.02281	4869.7	0.0	0.76446	-0.000004	0.019338	1	2
-420.0	0.9583	335.28	0.23810	-0.02281	4586.6	0.0	0.79215	-0.000005	0.022482	1	2
-410.0	0.9621	332.09	0.27487	-0.02281	4179.0	0.0	0.81437	-0.000006	0.025702	1	2

-400.0	0.9625	329.39	0.31080	-0.02281	4133.2	0.0	0.83182	-0.000007	0.028951	1	2
-390.0	0.9640	327.36	0.34651	-0.02281	3946.7	0.0	0.84608	-0.000007	0.032180	1	2
-380.0	0.9652	325.75	0.38102	-0.02281	3800.9	0.0	0.85778	-0.900008	0.035347	1	2
-370.0	0.9668	324.60	0.41370	-0.02281	3589.2	0.0	0.86743	-0.000008	0.038410	1	2
-360.0	0.9690	323.91	0.44342	-0.02281	3279.8	0.0	0.87356	-0.000009	0.041331	1	2
-350.0	0.9714	323.64	0.46919	-0.02281	2910.3	0.0	0.8[illegible]455	-0.000009	0.044068	1	2
-340.0	0.9725	323.49	0.49132	-0.02281	2720.1	0.0	0.87244	-0.000009	0.046580	1	2
-330.0	0.9731	323.39	0.51067	-0.02281	2607.0	0.0	0.86957	-0.000010	0.048833	1	2
-320.0	0.9738	323.34	0.52755	-0.02281	2478.6	0.0	0.86694	-0.000010	0.050795	1	2
-310.0	0.9745	323.35	0.54181	-0.02281	2319.9	0.0	0.86482	-0.000010	0.052438	1	2
-300.0	0.9759	323.46	0.55324	-0.02281	2019.3	0.0	0.86303	-0.000010	0.053742	1	2
-290.0	0.9776	323.68	0.56147	-0.02281	1529.7	0.0	0.86135	-0.000010	0.054687	1	2
-280.0	0.9794	323.98	0.56604	-0.02281	772.6	0.0	0.85959	-0.000010	0.055261	1	2
-272.4	0.9800	324.21	0.56654	-0.02281	-203.9	0.0	0.85795	-0.000010	0.055442	1	8
-270.0	0.9804	324.28	0.56638	-0.02281	-677.2	0.0	0.85742	-0.000010	0.055453	0	2
-260.0	0.9830	324.78	0.56355	-0.02281	-1796.2	0.0	0.85553	-0.000010	0.055260	0	2
-250.0	0.9899	325.65	0.55903	-0.02281	-3240.0	0.0	0.85392	-0.000010	0.054682	0	2
-240.0	1.0040	327.17	0.55400	-0.02281	-4973.5	0.0	0.85249	-0.000009	0.053718	0	2
-230.0	1.0324	330.30	0.55106	-0.02281	-7173.6	0.0	0.85133	-0.000009	0.052359	0	2
-220.0	1.0737	334.14	0.55033	-0.02281	-9262.8	0.0	0.85034	-0.000008	0.050582	0	2
-210.0	1.1275	338.93	0.55016	-0.02281	-11122.0	0.0	0.84946	-0.000007	0.048365	0	2
-200.0	1.1949	344.63	0.55012	-0.02281	-12737.8	0.0	0.84867	-0.000006	0.045677	0	2
-190.0	1.2779	351.30	0.55011	-0.02281	-14112.6	0.0	0.84794	-0.000004	0.042482	0	2
-180.0	1.3795	359.00	0.55011	-0.02281	0.0	0.0	0.84729	-0.000003	0.038738	0	2
-180.0	1.3795	359.00	0.55011	-0.02281	0.0	0.0	0.84729	-0.000003	0.038738	0	2

>>>>> START OF COMPRESSION PROCESS

CA (DEG)	P (ATM)	TEMP (K)	Q DOT (KJ/DEG)	WORK (KJ)	IFG
-180.0	1.3795	359.00	-0.000003	0.038738	2
-170.0	1.5039	367.83	-0.000001	0.034394	2
-160.0	1.6561	377.89	0.000002	0.029390	2
-150.0	1.8432	389.32	0.000005	0.023653	2
-140.0	2.0741	402.26	0.000009	0.017100	2
-130.0	2.3605	416.85	0.000013	0.009635	2
-120.0	2.7153	433.16	0.000018	0.001150	2
-110.0	3.1601	451.45	0.000025	-0.008466	2
-100.0	3.7229	471.94	0.000034	-0.019339	2
-90.0	4.4393	494.80	0.000044	-0.031592	2
-80.0	5.3577	520.55	0.000057	-0.045335	2
-70.0	6.5256	548.50	0.000075	-0.060611	2
-60.0	7.9973	578.37	0.000096	-0.077329	2
-50.0	9.8126	609.42	0.000123	-0.095165	2
-40.0	11.9365	640.01	0.000153	-0.113412	2
-30.0	14.2288	667.89	0.000186	-0.130828	2

>>>>> START OF COMBUSTION AND EXPANSION PROCESSES

CA (DEG)	P (ATM)	TEMP (K)	XBURND (-)	Q DOT (KJ/DEG)	WORK (KJ)	IFG
-25.0	15.3403	679.80	0.00030	0.000202	-0.138675	2
-24.0	15.5946	683.80	0.00106	0.000206	-0.140143	2
-23.0	15.9272	691.37	0.00335	0.000214	-0.141580	2
-22.0	16.3392	702.47	0.00716	0.000224	-0.142989	2
-21.0	16.8315	717.08	0.01249	0.000237	-0.144375	2
-20.0	17.4039	735.14	0.01935	0.000254	-0.145740	2
-19.0	18.0550	756.57	0.02773	0.000274	-0.147086	2
-18.0	18.7840	781.30	0.03764	0.000297	-0.148414	2
-17.0	19.5895	809.26	0.04907	0.000324	-0.149723	2
-16.0	20.4693	840.34	0.06202	0.000355	-0.151013	2
-15.0	21.4205	874.47	0.07650	0.000389	-0.152281	2
-14.0	22.4397	911.52	0.09250	0.000428	-0.153524	2
-13.0	23.5241	951.41	0.11003	0.000472	-0.154738	2
-12.0	24.6705	994.06	0.12908	0.000520	-0.155916	2
-11.0	25.8788	1039.55	0.14965	0.000575	-0.157054	2
-10.0	27.1347	1087.25	0.17175	0.000637	-0.158145	2
-9.0	28.4335	1137.07	0.19537	0.000702	-0.159179	2
-8.0	29.7759	1189.14	0.22052	0.000772	-0.160149	2
-7.0	31.1574	1243.40	0.24719	0.000846	-0.161045	2
-6.0	32.5725	1299.75	0.27538	0.000926	-0.161858	2
-5.0	34.0171	1358.08	0.30510	0.001012	-0.162576	2
-4.0	35.4859	1418.32	0.33634	0.001104	-0.163190	2
-3.0	36.9744	1480.38	0.36911	0.001201	-0.163688	2
-2.0	38.4775	1544.16	0.40340	0.001304	-0.164058	2
-1.0	39.9906	1609.57	0.43921	0.001413	-0.164288	2
0.0	41.5099	1676.53	0.47655	0.001528	-0.164368	2
1.0	42.9377	1741.07	0.51332	0.001643	-0.164284	2
2.0	44.1909	1799.54	0.54745	0.001749	-0.164027	2
3.0	45.2851	1852.52	0.57916	0.001849	-0.163587	2
4.0	46.2314	1900.46	0.60863	0.001941	-0.162958	2
5.0	47.0391	1943.76	0.63602	0.002026	-0.162133	2
6.0	47.7191	1982.81	0.66146	0.002106	-0.161109	2
7.0	48.2798	2017.92	0.68510	0.002179	-0.159884	2
8.0	48.7281	2049.39	0.70707	0.002247	-0.158456	2
9.0	49.0739	2077.53	0.72749	0.002309	-0.156825	2
10.0	49.3241	2102.58	0.74645	0.002365	-0.154992	2
11.0	49.4861	2124.80	0.76408	0.002416	-0.152958	2
12.0	49.5643	2144.40	0.78045	0.00[illegible]462	-0.150726	2
13.0	49.5686	2161.60	0.79567	0.0[illegible]3	-0.148300	2
14.0	49.5003	2176.57	0.80981	0.002538	-0.145683	2
15.0	49.3667	2189.51	0.82294	0.002568	-0.142880	2
16.0	49.1739	2200.57	0.83515	0.002593	-0.139895	2
17.0	48.9268	2209.91	0.84649	0.002613	-0.136734	2
18.0	48.6280	2217.66	0.85703	0.002627	-0.133403	2
19.0	48.2825	2223.95	0.86683	0.002637	-0.129907	2
20.0	47.8957	2228.90	0.87593	0.002642	-0.126254	2
21.0	47.4716	2232.63	0.88438	0.002643	-0.122449	2
22.0	47.0132	2235.22	0.89224	0.002640	-0.118500	2
23.0	46.5240	2236.78	0.89954	0.002633	-0.114412	2
24.0	46.0084	2237.39	0.90632	0.002622	-0.110192	2
25.0	45.4651	2237.09	0.91263	0.002608	-0.105849	2

26.0	44.9020	2235.99	0.91848	0.002590	-0.101388	2
27.0	44.3195	2234.15	0.92392	0.002570	-0.096816	2
28.0	43.7205	2231.62	0.92898	0.002547	-0.092140	2
29.0	43.1081	2228.47	0.93368	0.002521	-0.087367	2
30.0	42.4813	2224.65	0.93804	0.002494	-0.082503	2
31.0	41.8425	2220.18	0.94210	0.002464	-0.077555	2
32.0	41.1941	2215.10	0.94587	0.002432	-0.072531	2
33.0	40.5377	2209.50	0.94937	0.002398	-0.067436	2
34.0	39.8754	2203.41	0.95263	0.002364	-0.062277	2
35.0	39.2088	2196.87	0.95565	0.002328	-0.057059	2
36.0	38.5396	2189.92	0.95846	0.002291	-0.051789	2
37.0	37.8696	2182.55	0.96107	0.002253	-0.046474	2
38.0	37.1996	2174.87	0.96350	0.002215	-0.041117	2
39.0	36.5310	2166.88	0.96575	0.002176	-0.035725	2
40.0	35.8649	2158.61	0.96785	0.002137	-0.030302	2
41.0	35.2026	2150.07	0.96979	0.002099	-0.024855	2
42.0	34.5447	2141.32	0.97160	0.002060	-0.019387	2
43.0	33.8920	2132.38	0.97328	0.002022	-0.013903	2
44.0	33.2455	2123.25	0.97484	0.001983	-0.008407	2
45.0	32.6058	2113.96	0.97629	0.001945	-0.002904	2
46.0	31.9734	2104.54	0.97764	0.001908	0.002603	2
47.0	31.3490	2095.00	0.97889	0.001871	0.008109	2
48.0	30.7329	2085.35	0.98006	0.001835	0.013612	2
49.0	30.1256	2075.63	0.98114	0.001799	0.019108	2
50.0	29.5273	2065.83	0.98214	0.001764	0.024593	2
51.0	28.9387	2055.97	0.98308	0.001730	0.030065	2
52.0	28.3596	2046.08	0.98395	0.001696	0.035522	2
53.0	27.7907	2036.14	0.98475	0.001663	0.040959	2
54.0	27.2316	2026.20	0.98550	0.001630	0.046376	2
55.0	26.6827	2016.26	0.98620	0.001599	0.051769	2
56.0	26.1444	2006.29	0.98684	0.001568	0.057137	2
57.0	25.6162	1996.35	0.98745	0.001538	0.062477	2
58.0	25.0984	1986.44	0.98800	0.001508	0.067788	2
59.0	24.5913	1976.52	0.98852	0.001479	0.073068	2
60.0	24.0944	1966.66	0.98900	0.001451	0.078315	2
61.0	23.6081	1956.81	0.98945	0.001424	0.083528	2
62.0	23.1319	1947.03	0.98987	0.001397	0.088705	2
63.0	22.6660	1937.31	0.99026	0.001371	0.093845	2
64.0	22.2105	1927.60	0.99061	0.001345	0.098948	2
65.0	21.7648	1917.99	0.99095	0.001321	0.104012	2
66.0	21.3294	1908.41	0.99126	0.001296	0.109035	2
67.0	20.9035	1898.92	0.99155	0.001273	0.114019	2
68.0	20.4874	1889.51	0.99182	0.001250	0.118960	2
69.0	20.0809	1880.14	0.99206	0.001228	0.123859	2
70.0	19.6838	1870.88	0.99230	0.001206	0.128716	2
71.0	19.2958	1861.69	0.99251	0.001184	0.133529	2
72.0	18.9171	1852.56	0.99271	0.001164	0.138299	2
73.0	18.5472	1843.53	0.99290	0.001144	0.143024	2
74.0	18.1863	1834.55	0.99307	0.001124	0.147705	2
75.0	17.8337	1825.69	0.99323	0.001105	0.152341	2
76.0	17.4896	1816.92	0.99338	0.001086	0.156932	2
77.0	17.1539	1808.20	0.99352	0.001068	0.161477	2
78.0	16.8261	1799.60	0.99364	0.001050	0.165978	2
79.0	16.5063	1791.05	0.99376	0.001033	0.170432	2
80.0	16.1941	1782.62	0.99387	0.001016	0.174842	2
81.0	15.8895	1774.28	0.99398	0.000999	0.179206	2
82.0	15.5924	1766.00	0.99407	0.000983	0.183524	2
83.0	15.3023	1757.84	0.99416	0.000967	0.187797	2
84.0	15.0193	1749.76	0.99424	0.000952	0.192025	2

85.0	14.7433	1741.75	0.99432	0.000937	0.196207	2
86.0	14.4739	1733.85	0.99439	0.000923	0.200344	2
87.0	14.2111	1726.01	0.99446	0.000909	0.204436	2
88.0	13.9546	1718.28	0.99452	0.000895	0.208484	2
89.0	13.7043	1710.64	0.99458	0.000881	0.212487	2
90.0	13.4601	1703.07	0.99463	0.000868	0.216445	2
91.0	13.2218	1695.60	0.99468	0.000855	0.220360	2
92.0	12.9894	1688.20	0.99473	0.000842	0.224230	2
93.0	12.7625	1680.90	0.99477	0.000830	0.228058	2
94.0	12.5410	1673.68	0.99481	0.000818	0.231841	2
95.0	12.3250	1666.53	0.99485	0.000807	0.235582	2
96.0	12.1141	1659.48	0.99488	0.000795	0.239280	2
97.0	11.9082	1652.51	0.99491	0.000784	0.242936	2
98.0	11.7073	1645.61	0.99494	0.000773	0.246550	2
99.0	11.5112	1638.80	0.99497	0.000762	0.250122	2
100.0	11.3199	1632.05	0.99500	0.000752	0.253652	2
101.0	11.1330	1625.40	0.99502	0.000742	0.257142	2
102.0	10.9505	1618.82	0.99504	0.000732	0.260591	2
103.0	10.7723	1612.30	0.99505	0.000722	0.264000	2
104.0	10.5982	1605.86	0.99506	0.000713	0.267368	2
105.0	10.4283	1599.48	0.99506	0.000704	0.270698	2
106.0	10.2625	1593.21	0.99508	0.000694	0.273987	2
107.0	10.1006	1587.02	0.99510	0.000686	0.277238	2
108.0	9.9425	1580.89	0.99512	0.000677	0.280450	2
109.0	9.7879	1574.82	0.99512	0.000669	0.283624	2
110.0	9.6370	1568.81	0.99512	0.000660	0.286761	2
111.0	9.4895	1562.89	0.99513	0.000652	0.289860	2
112.0	9.3455	1557.05	0.99514	0.000644	0.292922	2
113.0	9.2049	1551.26	0.99515	0.000637	0.295947	2
114.0	9.0674	1545.55	0.99515	0.000629	0.298936	2
115.0	8.9330	1539.90	0.99516	0.000622	0.301890	2
116.0	8.8018	1534.32	0.99516	0.000614	0.304807	2
117.0	8.6735	1528.81	0.99517	0.000607	0.307690	2
118.0	8.5481	1523.36	0.99517	0.000600	0.310538	2
119.0	8.4256	1517.98	0.99518	0.000593	0.313351	2
120.0	8.3057	1512.65	0.99518	0.000587	0.316130	2
121.0	8.1886	1507.39	0.99519	0.000580	0.318875	2
122.0	8.0742	1502.20	0.99519	0.000574	0.321588	2
123.0	7.9622	1497.06	0.99519	0.000568	0.324267	2
124.0	7.8528	1491.98	0.99519	0.000562	0.326913	2
125.0	7.7457	1486.95	0.99520	0.000556	0.329527	2
126.0	7.6409	1481.98	0.99520	0.000550	0.332109	2
127.0	7.5385	1477.07	0.99520	0.000544	0.334660	2
128.0	7.4383	1472.21	0.99520	0.000538	0.337179	2
129.0	7.3403	1467.41	0.99521	0.000533	0.339667	2
130.0	7.2443	1462.66	0.99521	0.000527	0.342124	2
131.0	7.1505	1457.96	0.99521	0.000522	0.344552	2
132.0	7.0586	1453.31	0.99521	0.000517	0.346949	2
133.0	6.9688	1448.71	0.99521	0.000512	0.349316	2
134.0	6.8808	1444.17	0.99521	0.000507	0.351654	2
135.0	6.7947	1439.68	0.99522	0.000502	0.353963	2
136.0	6.7106	1435.24	0.99522	0.000497	0.356243	2
137.0	6.6281	1430.85	0.99522	0.000493	0.358495	2
138.0	6.5474	1426.50	0.99522	0.000488	0.360719	2
139.0	6.4683	1422.21	0.99522	0.000483	0.362915	2
140.0	6.3909	1417.96	0.99522	0.000479	0.365083	2
141.0	6.3152	1413.76	0.99522	0.000475	0.367224	2
142.0	6.2411	1409.61	0.99522	0.000470	0.369338	2
143.0	6.1684	1405.50	0.99522	0.000466	0.371425	2

144.0	6.0973	1401.44	0.99522	0.000462	0.373486	2
145.0	6.0277	1397.43	0.99522	0.000458	0.375521	2
146.0	5.9594	1393.46	0.99523	0.000454	0.377530	2
147.0	5.8926	1389.54	0.99523	0.000450	0.379513	2
148.0	5.8271	1385.66	0.99523	0.000446	0.381471	2
149.0	5.7630	1381.82	0.99523	0.000443	0.383404	2
150.0	5.7002	1378.03	0.99523	0.000439	0.385312	2
151.0	5.6387	1374.28	0.99523	0.000435	0.387195	2
152.0	5.5784	1370.57	0.99523	0.000432	0.389054	2
153.0	5.5193	1366.90	0.99523	0.000428	0.390889	2
154.0	5.4614	1363.27	0.99523	0.000425	0.392701	2
155.0	5.4048	1359.69	0.99523	0.000422	0.394488	2
156.0	5.3492	1356.15	0.99523	0.000418	0.396253	2
157.0	5.2947	1352.65	0.99523	0.000415	0.397994	2
158.0	5.2413	1349.18	0.99523	0.000412	0.399712	2
159.0	5.1890	1345.76	0.99523	0.000409	0.401408	2
160.0	5.1378	1342.37	0.99523	0.000406	0.403081	2
161.0	5.0875	1339.03	0.99523	0.000403	0.404732	2
162.0	5.0382	1335.72	0.99523	0.000400	0.406361	2
163.0	4.9900	1332.45	0.99523	0.000397	0.407969	2
164.0	4.9427	1329.22	0.99523	0.000394	0.409554	2
165.0	4.8963	1326.02	0.99523	0.000391	0.411119	2
166.0	4.8508	1322.86	0.99523	0.000389	0.412662	2
167.0	4.8062	1319.74	0.99523	0.000386	0.414184	2
168.0	4.7625	1316.66	0.99523	0.000383	0.415686	2
169.0	4.7196	1313.61	0.99523	0.000381	0.417167	2
170.0	4.6776	1310.59	0.99523	0.000378	0.418627	2
171.0	4.6364	1307.61	0.99523	0.000376	0.420068	2
172.0	4.5960	1304.67	0.99523	0.000373	0.421488	2
173.0	4.5565	1301.76	0.99523	0.000371	0.422889	2
174.0	4.5176	1298.89	0.99523	0.000368	0.424269	2
175.0	4.4796	1296.05	0.99523	0.000366	0.425631	2
176.0	4.4422	1293.24	0.90523	0.000364	0.426973	2
177.0	4.4056	1290.46	0.99523	0.000361	0.428296	2
178.0	4.3697	1287.72	0.99523	0.000359	0.429600	2
179.0	4.3345	1285.01	0.99523	0.000357	0.430886	2
180.0	4.3000	1282.33	0.99523	0.000355	0.432153	2
181.0	4.2661	1279.69	0.99523	0.000353	0.433401	2
182.0	4.2329	1277.07	0.99523	0.000351	0.434631	2
183.0	4.2004	1274.50	0.99523	0.000349	0.435843	2
184.0	4.1685	1271.95	0.99523	0.000347	0.437037	2
185.0	4.1372	1269.43	0.99523	0.000345	0.438213	2
186.0	4.1065	1266.94	0.99523	0.000343	0.439372	2
187.0	4.0765	1264.48	0.99523	0.000341	0.440513	2
188.0	4.0470	1262.05	0.99523	0.000339	0.441636	2
189.0	4.0180	1259.65	0.99523	0.000337	0.442743	2
190.0	3.9897	1257.29	0.99523	0.000335	0.443832	2
191.0	3.9619	1254.95	0.99523	0.000334	0.444904	2
192.0	3.9347	1252.64	0.99523	0.000332	0.445959	2
193.0	3.9079	1250.36	0.99523	0.000330	0.446998	2
194.0	3.8817	1248.11	0.99523	0.000329	0.448020	2
195.0	3.8560	1245.89	0.99523	0.006327	0.449026	2
196.0	3.8309	1243.69	0.99523	0.000325	0.450015	2
197.0	3.8062	1241.53	0.99523	0.000324	0.450989	2
198.0	3.7820	1239.39	0.99523	0.000322	0.451946	2
199.0	3.7583	1237.28	0.99523	0.000321	0.452887	2

>>>>> START OF EXHAUST PROCESS

CA (DEG)	P (ATM)	TEMP (K)	MEX (G)	VEV (M/SEC)	Q DOT (KJ/DEG)	WORK (KJ)	IFG
199.0	3.7583	1237.28	-0.02281	0.0	0.000321	0.452887	2
200.0	3.7344	1235.23	-0.02268	258.3	0.000258	0.453812	2
210.0	3.4210	1208.60	-0.00858	255.6	0.000241	0.462130	2
220.0	3.0117	1172.24	0.02580	251.8	0.000214	0.468635	2
230.0	2.5580	1127.66	0.07506	247.2	0.000183	0.473350	2
240.0	2.1033	1076.48	0.13330	241.8	0.000150	0.476478	2
250.0	1.7227	1025.87	0.18782	235.3	0.000122	0.478333	2
260.0	1.4367	980.99	0.23272	216.3	0.000100	0.479264	2
270.0	1.2335	943.89	0.26746	179.3	0.000085	0.479531	2
280.0	1.1035	916.05	0.29169	124.6	0.000075	0.479307	2
290.0	1.0394	899.87	0.30571	63.5	0.000070	0.478684	2
300.0	1.0247	893.01	0.31199	31.7	0.000068	0.477688	2
310.0	1.0260	889.06	0.31680	35.7	0.000066	0.476317	2
320.0	1.0298	885.09	0.32273	45.1	0.000065	0.474583	2
330.0	1.0342	880.69	0.33005	54.0	0.000064	0.472503	2
340.0	1.0391	875.76	0.33873	62.2	0.000062	0.470101	2
350.0	1.0453	869.59	0.34876	70.8	0.000061	0.467407	2
360.0	1.0531	860.84	0.36033	80.0	0.000059	0.464447	2
370.0	1.0628	848.67	0.37360	89.5	0.000056	0.461256	2
380.0	1.0708	835.16	0.38845	95.9	0.000054	0.457872	2
390.0	1.0762	821.68	0.40442	99.5	0.000051	0.454346	2
400.0	1.0787	809.00	0.42109	100.6	0.000048	0.450734	2
410.0	1.0788	797.20	0.43809	100.0	0.000046	0.447093	2
420.0	1.0772	786.20	0.45507	98.1	0.000043	0.443479	2
430.0	1.0736	775.86	0.47181	94.7	0.000040	0.439947	2
440.0	1.0687	765.88	0.48803	90.1	0.000038	0.436549	2
450.0	1.0632	756.34	0.50343	84.8	0.000036	0.433335	2
460.0	1.0578	746.96	0.51782	79.2	0.000034	0.430347	2
470.0	1.0501	737.31	0.53114	70.8	0.000032	0.427623	2
480.0	1.0429	727.62	0.54306	61.8	0.000030	0.425200	2
490.0	1.0366	717.80	0.55344	52.7	0.000028	0.423104	2
500.0	1.0303	707.43	0.56223	41.3	0.000027	0.421359	2
510.0	1.0282	697.14	0.56914	36.7	0.000026	0.419984	2
520.0	1.0229	685.82	0.57433	21.6	0.000024	0.418992	2
530.0	1.0215	674.78	0.57747	15.8	0.000023	0.418393	2
540.0	1.0205	663.59	0.57858	9.2	0.000023	0.418193	2
550.0	1.0188	651.41	0.57755	14.0	0.000022	0.418393	2

CALCULATION RESULTS

```
—> VOLUMETRIC EFFICIENCY; (%)
   BASED ON: INTAKE / ATM                    ——>   81.2   79.6

—> PUMPING MEAN EFFECTIVE
   PRESSURE; (KPA) : PEMP                    ——>  -10.

—> GROSS INDICATED MEAN EFFECTIVE
   PRESSURE; (KPA) : IMEP                    ——>  740.

—> GROSS INDICATED SPECIFIC FUEL
   CONSUMPTION; (G/IKW-HR) : ISFC            ——>  247.

—> GROSS INDICATED THERMAL
   EFFICIENCY; (%)                           ——>   32.8

—> NET INDICATED THERMAL
   EFFICIENCY, (%)                           ——>   32.4

—> (HEAT TRANSFER PER CYCLE)/
   (MASS OF FUEL TIMES LHV); (%)             ——>   20.6

—> IGNITION DELAY (0 - 10%)
   (CRANK ANGLE) / (MS)                      ——>   11.43   0.63

—> BURN DURATION (10 - 90%)
   (CRANK ANGLE) / (MS)                      ——>   36.64   2.04

—> MEAN EXHAUST
   TEMPERATURE; (K)                          ——>  883.9
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MASS IN CYLINDER AT TIVO =  0.03811 G
MASS IN CYLINDER AT TIVC =  0.67234 G
MASS OF FUEL INDUCTED    =  0.02913 G
RESIDUAL FRACTION        =  0.15271
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```
HEATI  =  -0.000767 KJ  (TIPO   -   -270)
WORKI  =   0.055453 KJ

HEATC  =   0.007708 KJ  (-270   - TSPARK)
WORKC  =  -0.194128 KJ
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```
HEATCE =    0.253867 KJ  (TIPC   -   +270
WORKCE =    0.424078 KJ

HEATE  =    0.013010 KJ  (+270   -   TIPO)
WORKE  =   -0.061138 KJ
```

TOTAL ENTHALPY IN / CYCLE	=	0.16626 KJ
TOTAL ENTHALPY OUT / CYCLE	=	-0.82333 KJ
TOTAL HEAT LOSS / CYCLE	=	0.26611 KJ
TOTAL WORK OUTPUT / CYCLE	=	0.41839 KJ
HEAT LOSS TO CREVICE/CYCLE	=	0.24439 KJ
"LOST" FUEL ENERGY	=	0.02886 KJ
NET ENERGY GAIN / CYCLE	=	0.03096 KJ
(ENERGY GAIN)/(ENTHALPY IN)	=	18.61953 %
(ENERGY GAIN)/(MFUEL*LHV)	=	2.39426 %

HEAT TRANSFER DATA

CA (DEG)	VELHTX (CM/SEC)	HTPARO (KW/M**2)	HTPASI (KW/M**2)	HTPAHO (KW/M**2)	Q% ROTOR (%)	Q% SIDE (%)	Q% HOUSING (%)
-520.0	824.7	11.8	11.8	11.8	43.831	3.556	52.613
-510.0	824.7	11.2	11.2	11.2	43.160	4.320	52.520
-508.3	824.7	11.1	11.1	11.1	43.025	4.474	52.501
-503.8	824.7	2.4	2.4	2.4	42.628	4.927	52.445
-500.0	824.7	2.9	2.9	2.9	42.267	5.338	52.395
-490.0	824.7	2.7	2.7	2.7	41.191	6.564	52.245
-480.0	824.7	1.3	1.3	1.3	39.976	7.949	52.075
-470.0	824.7	0.3	0.3	0.3	38.665	9.443	51.892
-460.0	824.7	-0.5	-0.5	-0.5	37.299	10.999	51.702
-450.0	824.7	-1.0	-1.0	-1.0	35.916	12.576	51.508
-440.0	824.7	-1.5	-1.5	-1.5	34.546	14.137	51.317
-430.0	824.7	-1.8	-1.8	-1.8	33.213	15.656	51.131
-420.0	824.7	-2.1	-2.1	-2.1	31.937	17.110	50.953
-410.0	824.7	-2.3	-2.3	-2.3	30.732	18.483	50.785
-400.0	824.7	-2.5	-2.5	-2.5	29.608	19.764	50.628
-390.0	824.7	-2.6	-2.6	-2.6	28.569	20.948	50.483
-380.0	824.7	-2.7	-2.7	-2.7	27.620	22.029	50.350
-370.0	824.7	-2.8	-2.8	-2.8	26.762	23.008	50.231
-360.0	824.7	-2.8	-2.8	-2.8	25.993	23.883	50.123
-350.0	824.7	-2.9	-2.9	-2.9	25.314	24.658	50.029
-340.0	824.7	-2.9	-2.9	-2.9	24.721	25.333	49.946
-330.0	824.7	-2.9	-2.9	-2.9	24.214	25.911	49.875
-320.0	824.7	-2.9	-2.9	-2.9	23.789	26.396	49.816
-310.0	824.7	-2.9	-2.9	-2.9	23.444	26.789	49.768
-300.0	824.7	-2.9	-2.9	-2.9	23.178	27.092	49.730
-290.0	824.7	-2.9	-2.9	-2.9	22.989	27.307	49.704
-280.0	824.7	-2.9	-2.9	-2.9	22.876	27.436	49.688
-272.4	824.7	-2.9	-2.9	-2.9	22.841	27.476	49.683
-270.0	824.7	-2.8	-2.8	-2.8	22.839	27.478	49.683
-260.0	824.7	-2.8	-2.8	-2.8	22.876	27.436	49.688
-250.0	824.7	-2.8	-2.8	-2.8	22.989	27.307	49.704
-240.0	824.7	-2.7	-2.7	-2.7	23.178	27.092	49.730
-230.0	824.7	-2.5	-2.5	-2.5	23.444	26.789	49.768
-220.0	824.7	-2.4	-2.4	-2.4	23.789	26.396	49.816
-210.0	824.7	-2.1	-2.1	-2.1	24.214	25.911	49.875
-200.0	824.7	-1.8	-1.8	-1.8	24.721	25.333	49.946
-190.0	824.7	-1.4	-1.4	-1.4	25.314	24.658	50.029
-180.0	824.7	-0.8	-0.8	-0.8	25.993	23.883	50.123
-170.0	824.7	-0.2	-0.2	-0.2	26.762	23.008	50.231
-160.0	824.7	0.7	0.7	0.7	27.620	22.029	50.350
-150.0	824.7	1.8	1.8	1.8	28.569	20.948	50.483
-140.0	824.7	3.2	3.2	3.2	29.608	19.764	50.628
-130.0	824.7	5.0	5.0	5.0	30.732	18.483	50.785
-120.0	824.7	7.4	7.4	7.4	31.937	17.110	50.953
-110.0	824.7	10.4	10.4	10.4	33.213	15.656	51.131
-100.0	824.7	14.5	14.5	14.5	34.546	14.137	51.317
-90.0	824.7	19.8	19.8	19.8	35.916	12.576	51.508
-80.0	824.7	26.8	26.8	26.8	37.299	10.999	51.702
-70.0	824.7	36.1	36.1	36.1	38.665	9.443	51.892

-60.0	824.7	48.1	48.1	48.1	39.976	7.949	52.075
-50.0	824.7	63.2	63.2	63.2	41.191	6.564	52.245
-40.0	824.7	81.1	81.1	81.1	42.267	5.338	52.395
-30.0	824.7	100.6	100.6	100.6	43.160	4.320	52.520
-25.0	824.7	110.0	110.0	110.0	43.526	3.904	52.571
-24.0	824.9	112.5	112.5	112.5	43.592	3.829	52.580
-23.0	826.2	116.7	116.7	116.7	43.655	3.756	52.589
-22.0	828.7	122.4	122.4	122.4	43.716	3.687	52.597
-21.0	832.3	129.9	129.9	129.9	43.775	3.620	52.605
-20.0	836.9	139.1	139.1	139.1	43.831	3.556	52.613
-19.0	842.6	150.1	150.1	150.1	43.884	3.495	52.621
-18.0	849.4	163.1	163.1	163.1	43.935	3.437	52.628
-17.0	857.1	178.1	178.1	178.1	43.984	3.382	52.635
-16.0	865.7	195.3	195.3	195.3	44.029	3.330	52.641
-15.0	875.3	214.7	214.7	214.7	44.072	3.281	52.647
-14.0	885.7	236.4	236.4	236.4	44.113	3.235	52.653
-13.0	897.0	260.5	260.5	260.5	44.150	3.192	52.658
-12.0	909.0	287.3	287.3	287.3	44.185	3.152	52.663
-11.0	921.8	318.2	318.2	318.2	44.218	3.115	52.667
-10.0	935.3	352.7	352.7	352.7	44.247	3.082	52.671
-9.0	949.3	388.9	388.9	388.9	44.274	3.051	52.675
-8.0	964.0	427.5	427.5	427.5	44.298	3.024	52.678
-7.0	979.2	469.0	469.0	469.0	44.319	3.000	52.681
-6.0	995.0	513.7	513.7	513.7	44.337	2.979	52.684
-5.0	1011.3	561.4	561.4	561.4	44.353	2.961	52.686
-4.0	1028.0	612.3	612.3	612.3	44.366	2.946	52.688
-3.0	1045.2	666.5	666.5	666.5	44.376	2.935	52.689
-2.0	1062.8	723.8	723.8	723.8	44.383	2.927	52.690
-1.0	1080.8	784.4	784.4	784.4	44.387	2.922	52.691
0.0	1099.2	848.4	848.4	848.4	44.388	2.921	52.691
1.0	1116.8	912.0	912.0	912.0	44.387	2.922	52.691
2.0	1132.6	971.1	971.1	971.1	44.383	2.927	52.690
3.0	1146.9	1026.0	1026.0	1026.0	44.376	2.935	52.689
4.0	1159.7	1077.0	1077.0	1077.0	44.366	2.946	52.688
5.0	1171.3	1124.1	1124.1	1124.1	44.353	2.961	52.686
6.0	1181.7	1167.7	1167.7	1167.7	44.337	2.979	52.684
7.0	1191.1	1207.9	1207.9	1207.9	44.319	3.000	52.681
8.0	1199.5	1244.7	1244.7	1244.7	44.298	3.024	52.678
9.0	1207.0	1278.4	1278.4	1278.4	44.274	3.051	52.675
10.0	1213.8	1308.9	1308.9	1308.9	44.247	3.082	52.671
11.0	1219.8	1336.4	1336.4	1336.4	44.218	3.115	52.667
12.0	1225.2	1360.7	1360.7	1360.7	44.185	3.152	52.663
13.0	1230.0	1382.1	1382.1	1382.1	44.150	3.192	52.658
14.0	1234.3	1400.4	1400.4	1400.4	44.113	3.235	52.653
15.0	1238.1	1415.6	1415.6	1415.6	44.072	3.281	52.647
16.0	1241.5	1427.9	1427.9	1427.9	44.029	3.330	52.641
17.0	1244.4	1437.3	1437.3	1437.3	43.984	3.382	52.635
18.0	1247.0	1443.8	1443.8	1443.8	43.935	3.437	52.628
19.0	1249.2	1447.5	1447.5	1447.5	43.884	3.495	52.621
20.0	1251.2	1448.7	1448.7	1448.7	43.831	3.556	52.613
21.0	1252.0	1447.3	1447.3	1447.3	43.775	3.620	52.605
22.0	1254.3	1443.6	1443.6	1443.6	43.716	3.687	52.597
23.0	1255.5	1437.6	1437.6	1437.6	43.655	3.756	52.589
24.0	1256.4	1429.6	1429.6	1429.6	43.592	3.829	52.580
25.0	1257.2	1419.6	1419.6	1419.6	43.526	3.904	52.571
26.0	1257.8	1407.8	1407.8	1407.8	43.457	3.982	52.561
27.0	1258.2	1394.5	1394.5	1394.5	43.386	4.062	52.551
28.0	1258.5	1379.7	1379.7	1379.7	43.313	4.146	52.541

29.0	1258.6	1363.6	1363.6	1363.6	43.238	4.232	52.530
30.0	1258.6	1346.2	1346.2	1346.2	43.160	4.320	52.520
31.0	1258.5	1327.6	1327.6	1327.6	43.080	4.411	52.508
32.0	1258.2	1307.9	1307.9	1307.9	42.998	4.505	52.497
33.0	1257.7	1287.4	1287.4	1287.4	42.914	4.601	52.485
34.0	1257.2	1266.1	1266.1	1266.1	42.828	4.699	52.473
35.0	1256.5	1244.2	1244.2	1244.2	42.739	4.800	52.461
36.0	1255.7	1221.9	1221.9	1221.9	42.649	4.903	52.448
37.0	1254.9	1199.2	1199.2	1199.2	42.556	5.008	52.435
38.0	1253.9	1176.2	1176.2	1176.2	42.462	5.116	52.422
39.0	1252.9	1153.2	1153.2	1153.2	42.365	5.226	52.409
40.0	1251.8	1130.0	1130.0	1130.0	42.267	5.338	52.395
41.0	1250.7	1106.9	1106.9	1106.9	42.167	5.452	52.381
42.0	1249.5	1083.9	1083.9	1083.9	42.065	5.568	52.367
43.0	1248.2	1061.0	1061.0	1061.0	41.962	5.686	52.352
44.0	1246.8	1038.3	1038.3	1038.3	41.856	5.806	52.338
45.0	1245.5	1015.9	1015.9	1015.9	41.749	5.928	52.323
46.0	1244.0	993.8	993.8	993.8	41.641	6.052	52.308
47.0	1242.6	972.0	972.0	972.0	41.531	6.177	52.292
48.0	1241.1	950.6	950.6	950.6	41.419	6.304	52.277
49.0	1239.6	929.5	929.5	929.5	41.306	6.433	52.261
50.0	1238.0	908.8	908.8	908.8	41.191	6.564	52.245
51.0	1236.4	888.6	888.6	888.6	41.075	6.696	52.229
52.0	1234.8	868.8	868.8	868.8	40.958	6.830	52.212
53.0	1233.2	849.3	849.3	849.3	40.839	6.965	52.196
54.0	1231.5	830.4	830.4	830.4	40.719	7.102	52.179
55.0	1229.9	811.8	811.8	811.8	40.598	7.240	52.162
56.0	1228.2	793.7	793.7	793.7	40.476	7.379	52.145
57.0	1226.5	776.0	776.0	776.0	40.352	7.520	52.128
58.0	1224.8	758.8	758.8	758.8	40.228	7.662	52.110
59.0	1223.1	742.0	742.0	742.0	40.102	7.805	52.093
60.0	1221.4	725.6	725.6	725.6	39.976	7.949	52.075
61.0	1219.7	709.6	709.6	709.6	39.848	8.094	52.057
62.0	1218.0	694.0	694.0	694.0	39.720	8.241	52.039
63.0	1216.3	678.8	678.8	678.8	39.591	8.388	52.021
64.0	1214.5	664.1	664.1	664.1	39.461	8.536	52.003
65.0	1212.8	649.7	649.7	649.7	39.330	8.685	51.985
66.0	1211.1	635.6	635.6	635.6	39.198	8.835	51.967
67.0	1209.4	622.0	622.0	622.0	39.066	8.986	51.948
68.0	1207.7	608.7	608.7	608.7	38.933	9.138	51.930
69.0	1206.0	595.7	595.7	595.7	38.799	9.290	51.911
70.0	1204.3	583.1	583.1	583.1	38.665	9.443	51.892
71.0	1202.6	570.8	570.8	570.8	38.530	9.597	51.873
72.0	1200.9	558.9	558.9	558.9	38.395	9.751	51.854
73.0	1199.3	547.2	547.2	547.2	38.259	9.905	51.836
74.0	1197.6	535.9	535.9	535.9	38.123	10.060	51.817
75.0	1195.9	524.9	524.9	524.9	37.987	10.216	51.797
76.0	1194.3	514.1	514.1	514.1	37.850	10.372	51.778
77.0	1192.7	503.6	503.6	503.6	37.712	10.528	51.759
78.0	1191.0	493.5	493.5	493.5	37.575	10.685	51.740
79.0	1189.4	483.5	483.5	483.5	37.437	10.842	51.721
80.0	1187.8	473.9	473.9	473.9	37.299	10.999	51.702
81.0	1186.2	464.4	464.4	464.4	37.161	11.156	51.682
82.0	1184.7	455.3	455.3	455.3	37.023	11.314	51.663
83.0	1183.1	446.3	446.3	446.3	36.885	11.472	51.644
84.0	1181.5	437.6	437.6	437.6	36.746	11.629	51.624
85.0	1180.0	429.2	429.2	429.2	36.608	11.787	51.605
86.0	1178.5	420.9	420.9	420.9	36.469	11.945	51.586

87.0	1177.0	412.8	412.8	412.8	36.331	12.103	51.566
88.0	1175.5	405.0	405.0	405.0	36.193	12.260	51.547
89.0	1174.0	397.4	397.4	397.4	36.054	12.418	51.528
90.0	1172.5	389.9	389.9	389.9	35.916	12.576	51.508
91.0	1171.0	382.6	382.6	382.6	35.778	12.733	51.489
92.0	1169.6	375.6	375.6	375.6	35.640	12.890	51.470
93.0	1168.2	368.7	368.7	368.7	35.502	13.047	51.451
94.0	1166.7	361.9	361.9	361.9	35.365	13.204	51.432
95.0	1165.3	355.4	355.4	355.4	35.227	13.360	51.412
96.0	1163.9	349.0	349.0	349.0	35.090	13.516	51.393
97.0	1162.5	342.8	342.8	342.8	34.954	13.672	51.374
98.0	1161.2	336.7	336.7	336.7	34.817	13.828	51.355
99.0	1159.8	330.7	330.7	330.7	34.681	13.983	51.336
100.0	1158.5	325.0	325.0	325.0	34.546	14.137	51.317
101.0	1157.2	319.3	319.3	319.3	34.410	14.291	51.298
102.0	1155.8	313.8	313.8	313.8	34.275	14.445	51.279
103.0	1154.5	308.4	308.4	308.4	34.141	14.599	51.261
104.0	1153.2	303.2	303.2	303.2	34.007	14.751	51.242
105.0	1152.0	298.1	298.1	298.1	33.873	14.903	51.223
106.0	1150.7	293.1	293.1	293.1	33.740	15.055	51.205
107.0	1149.4	288.2	288.2	288.2	33.608	15.206	51.186
108.0	1148.2	283.5	283.5	283.5	33.475	15.357	51.168
109.0	1147.0	278.8	278.8	278.8	33.344	15.507	51.149
110.0	1145.8	274.3	274.3	274.3	33.213	15.656	51.131
111.0	1144.6	269.9	269.9	269.9	33.083	15.805	51.113
112.0	1143.4	265.5	265.5	265.5	32.953	15.952	51.095
113.0	1142.2	261.3	261.3	261.3	32.824	16.100	51.077
114.0	1141.0	257.2	257.2	257.2	32.695	16.246	51.059
115.0	1139.9	253.2	253.2	253.2	32.567	16.392	51.041
116.0	1138.7	249.2	249.2	249.2	32.440	16.537	51.023
117.0	1137.6	245.4	245.4	245.4	32.313	16.681	51.006
118.0	1136.5	241.7	241.7	241.7	32.187	16.825	50.988
119.0	1135.4	238.0	238.0	238.0	32.062	16.968	50.970
120.0	1134.3	234.4	234.4	234.4	31.937	17.110	50.953
121.0	1133.2	230.9	230.9	230.9	31.813	17.251	50.936
122.0	1132.1	227.5	227.5	227.5	31.690	17.391	50.919
123.0	1131.1	224.2	224.2	224.2	31.568	17.531	50.902
124.0	1130.0	220.9	220.9	220.9	31.446	17.669	50.885
125.0	1129.0	217.7	217.7	217.7	31.325	17.807	50.868
126.0	1127.9	214.6	214.6	214.6	31.205	17.944	50.851
127.0	1126.9	211.5	211.5	211.5	31.086	18.080	50.834
128.0	1125.9	208.5	208.5	208.5	30.967	18.215	50.818
129.0	1124.9	205.6	205.6	205.6	30.849	18.349	50.801
130.0	1123.9	202.8	202.8	202.8	30.732	18.483	50.785
131.0	1122.9	200.0	200.0	200.0	30.616	18.615	50.769
132.0	1121.9	197.2	197.2	197.2	30.501	18.747	50.753
133.0	1121.0	194.6	194.6	194.6	30.386	18.877	50.737
134.0	1120.0	191.9	191.9	191.9	30.272	19.007	50.721
135.0	1119.1	189.4	189.4	189.4	30.159	19.136	50.705
136.0	1118.2	186.9	186.9	186.9	30.047	19.263	50.689
137.0	1117.2	184.4	184.4	184.4	29.936	19.390	50.674
138.0	1116.3	182.0	182.0	182.0	29.826	19.516	50.658
139.0	1115.4	179.7	179.7	179.7	29.716	19.641	50.643
140.0	1114.5	177.4	177.4	177.4	29.608	19.764	50.628
141.0	1113.6	175.1	175.1	175.1	29.500	19.887	50.613
142.0	1112.7	172.9	172.9	172.9	29.393	20.009	50.598
143.0	1111.9	170.8	170.8	170.8	29.287	20.130	50.583
144.0	1111.0	168.6	168.6	168.6	29.182	20.250	50.568

145.0	1110.1	166.6	166.6	166.6	29.077	20.369	50.554
146.0	1109.3	164.6	164.6	164.6	28.974	20.487	50.539
147.0	1108.4	162.6	162.6	162.6	28.871	20.603	50.525
148.0	1107.6	160.6	160.6	160.6	28.770	20.719	50.511
149.0	1106.8	158.7	158.7	158.7	28.669	20.834	50.497
150.0	1106.0	156.9	156.9	156.9	28.569	20.948	50.483
151.0	1105.2	155.0	155.0	155.0	28.470	21.061	50.469
152.0	1104.4	153.2	153.2	153.2	28.372	21.172	50.455
153.0	1103.6	151.5	151.5	151.5	28.275	21.283	50.442
154.0	1102.8	149.8	149.8	149.8	28.179	21.393	50.428
155.0	1102.0	148.1	148.1	148.1	28.083	21.501	50.415
156.0	1101.3	146.5	146.5	146.5	27.989	21.609	50.402
157.0	1100.5	144.8	144.8	144.8	27.895	21.716	50.389
158.0	1099.7	143.3	143.3	143.3	27.803	21.821	50.376
159.0	1099.0	141.7	141.7	141.7	27.711	21.926	50.363
160.0	1098.3	140.2	140.2	140.2	27.620	22.029	50.350
161.0	1097.5	138.7	138.7	138.7	27.530	22.132	50.338
162.0	1096.8	137.2	137.2	137.2	27.441	22.233	50.326
163.0	1096.1	135.8	135.8	135.8	27.353	22.334	50.313
164.0	1095.4	134.4	134.4	134.4	27.266	22.433	50.301
165.0	1094.7	133.0	133.0	133.0	27.180	22.531	50.289
166.0	1094.0	131.7	131.7	131.7	27.094	22.629	50.277
167.0	1093.3	130.4	130.4	130.4	27.010	22.725	50.265
168.0	1092.6	129.1	129.1	129.1	26.926	22.820	50.254
169.0	1092.0	127.8	127.8	127.8	26.843	22.914	50.242
170.0	1091.3	126.6	126.6	126.6	26.762	23.008	50.231
171.0	1090.6	125.4	125.4	125.4	26.681	23.100	50.219
172.0	1090.0	124.2	124.2	124.2	26.601	23.191	50.208
173.0	1089.4	123.0	123.0	123.0	26.522	23.281	50.197
174.0	1088.7	121.8	121.8	121.8	26.444	23.370	50.186
175.0	1088.1	120.7	120.7	120.7	26.366	23.458	50.175
176.0	1087.5	119.6	119.6	119.6	26.290	23.545	50.165
177.0	1086.8	118.5	118.5	118.5	26.214	23.631	50.154
178.0	1086.2	117.5	117.5	117.5	26.140	23.716	50.144
179.0	1085.6	116.4	116.4	116.4	26.066	23.800	50.134
180.0	1085.0	115.4	115.4	115.4	25.993	23.883	50.123
181.0	1084.4	114.4	114.4	114.4	25.921	23.965	50.113
182.0	1083.8	113.4	113.4	113.4	25.850	24.046	50.103
183.0	1083.3	112.5	112.5	112.5	25.780	24.126	50.094
184.0	1082.7	111.5	111.5	111.5	25.711	24.205	50.084
185.0	1082.1	110.6	110.6	110.6	25.643	24.283	50.074
186.0	1081.5	109.7	109.7	109.7	25.575	24.360	50.065
187.0	1081.0	108.8	108.8	108.8	25.509	24.436	50.056
188.0	1080.4	107.9	107.9	107.9	25.443	24.511	50.047
189.0	1079.9	107.1	107.1	107.1	25.378	24.585	50.037
190.0	1079.4	106.2	106.2	106.2	25.314	24.658	50.029
191.0	1078.8	105.4	105.4	105.4	25.251	24.729	50.020
192.0	1078.3	104.6	104.6	104.6	25.188	24.800	50.011
193.0	1077.8	103.8	103.8	103.8	25.127	24.870	50.002
194.0	1077.3	103.0	103.0	103.0	25.067	24.939	49.994
195.0	1076.7	102.3	102.3	102.3	25.007	25.007	49.986
196.0	1076.2	101.5	101.5	101.5	24.948	25.074	49.978
197.0	1075.7	100.8	100.8	100.8	24.890	25.140	49.969
198.0	1075.2	100.1	100.1	100.1	24.833	25.206	49.961
199.0	1074.8	99.4	99.4	99.4	24.777	25.270	49.954
200.0	824.7	79.9	79.9	79.9	24.721	25.333	49.946
210.0	824.7	72.9	72.9	72.9	24.214	25.911	49.875
220.0	824.7	63.8	63.8	63.8	23.789	26.396	49.816

230.0	824.7	53.8	53.8	53.8	23.444	26.789	49.768
240.0	824.7	43.6	43.6	43.6	23.178	27.092	49.730
250.0	824.7	35.0	35.0	35.0	22.989	27.307	49.704
260.0	824.7	28.7	28.7	28.7	22.876	27.436	49.688
270.0	824.7	24.3	24.3	24.3	22.839	27.478	49.683
280.0	824.7	21.4	21.4	21.4	22.876	27.436	49.688
290.0	824.7	20.0	20.0	20.0	22.989	27.307	49.704
300.0	824.7	19.6	19.6	19.6	23.178	27.092	49.730
310.0	824.7	19.5	19.5	19.5	23.444	26.789	49.768
320.0	824.7	19.4	19.4	19.4	23.789	26.396	49.816
330.0	824.7	19.4	19.4	19.4	24.214	25.911	49.875
340.0	824.7	19.3	19.3	19.3	24.721	25.333	49.946
350.0	824.7	19.2	19.2	19.2	25.314	24.658	50.029
360.0	824.7	19.1	19.1	19.1	25.993	23.883	50.123
370.0	824.7	18.8	18.8	18.8	26.762	23.008	50.231
380.0	824.7	18.6	18.6	18.6	27.620	22.029	50.350
390.0	824.7	18.2	18.2	18.2	28.569	20.948	50.483
400.0	824.7	17.9	17.9	17.9	29.608	19.764	50.628
410.0	824.7	17.5	17.5	17.5	30.732	18.483	50.785
420.0	824.7	17.2	17.2	17.2	31.937	17.110	50.953
430.0	824.7	16.8	16.8	16.8	33.213	15.656	51.131
440.0	824.7	16.5	16.5	16.5	34.546	14.137	51.317
450.0	824.7	16.1	16.1	16.1	35.916	12.576	51.508
460.0	824.7	15.7	15.7	15.7	37.299	10.999	51.702
470.0	824.7	15.3	15.3	15.3	38.665	9.443	51.892
480.0	824.7	14.9	14.9	14.9	39.976	7.949	52.075
490.0	824.7	14.6	14.6	14.6	41.191	6.564	52.245
500.0	824.7	14.2	14.2	14.2	42.267	5.338	52.395
510.0	824.7	13.8	13.8	13.8	43.160	4.320	52.520
520.0	824.7	13.4	13.4	13.4	43.831	3.556	52.613
530.0	824.7	13.0	13.0	13.0	44.247	3.082	52.671
540.0	824.7	12.6	12.6	12.6	44.388	2.921	52.691
550.0	824.7	12.2	12.2	12.2	44.247	3.082	52.671

LEAKAGE AND CREVICE VOLUME DATA

CA (DEG)	CHAMBER MASS (G)	LEAD CREVICE MASS (G)	LAG CREVICE MASS (G)	LEAD LEAKAGE MASS (G)	LAG LEAKAGE MASS (G)	LEAD CREVICE COMPOSITION ( )	LAG CREVICE COMPOSITION ( )
-520.0	0.0415	0.000000	0.000000	-0.000181	-0.000442	0.007641	0.054094
-510.0	0.0463	0.000000	0.000000	-0.000386	-0.000853	0.007675	0.054094
-508.3	0.0473	0.000000	0.000000	-0.000423	-0.000918	0.007680	0.054094
-503.8	0.0560	0.000000	0.000000	-0.000527	-0.001089	0.007694	0.054094
-500.0	0.0694	0.000000	0.000000	-0.000617	-0.001222	0.007705	0.054094
-490.0	0.0894	0.000000	0.000000	-0.000878	-0.001542	0.007730	0.054087
-480.0	0.1119	0.000000	0.000000	-0.001177	-0.001809	0.007744	0.054067
-470.0	0.1385	0.000000	0.000000	-0.001524	-0.002027	0.007744	0.054023
-460.0	0.1679	0.000000	0.000000	-0.001929	-0.002205	0.007744	0.053969
-450.0	0.1997	0.000000	0.000000	-0.002410	-0.002344	0.007744	0.053896
-440.0	0.2336	0.000000	0.000000	-0.002986	-0.002449	0.007744	0.053789
-430.0	0.2693	0.000000	0.000000	-0.003685	-0.002525	0.007744	0.053668
-420.0	0.3061	0.000000	0.000000	-0.004539	-0.002588	0.007744	0.053517
-410.0	0.3440	0.000000	0.000000	-0.005585	-0.002648	0.007744	0.053330
-400.0	0.3813	0.000000	0.000000	-0.006864	-0.002709	0.007744	0.053100
-390.0	0.4186	0.000000	0.000000	-0.008405	-0.002771	0.007744	0.052816
-380.0	0.4550	0.000000	0.000000	-0.010229	-0.002835	0.008608	0.052482
-370.0	0.4903	0.000000	0.000000	-0.012768	-0.002900	0.015610	0.052053
-360.0	0.5240	0.000000	0.000000	-0.016723	-0.002968	0.029920	0.051550
-350.0	0.5552	0.000000	0.000000	-0.022080	-0.003038	0.042820	0.051199
-340.0	0.5831	0.000000	0.000000	-0.027723	-0.003112	0.049063	0.051064
-330.0	0.6077	0.000000	0.000000	-0.032932	-0.003188	0.052055	0.051055
-320.0	0.6292	0.000000	0.000000	-0.037429	-0.003264	0.053399	0.051100
-310.0	0.6472	0.000000	0.000000	-0.041172	-0.003342	0.053935	0.051160
-300.0	0.6618	0.000000	0.000000	-0.044237	-0.003418	0.054117	0.051219
-290.0	0.6726	0.000000	0.000000	-0.046738	-0.003493	0.054156	0.051273
-280.0	0.6793	0.000000	0.000000	-0.048786	-0.003566	0.054146	0.051321
-272.4	0.6812	0.000000	0.000000	-0.050095	-0.003619	0.054130	0.051355
-270.0	0.6814	0.000000	0.000000	-0.050480	-0.003636	0.054125	0.051365
-260.0	0.6801	0.000000	0.000000	-0.051895	-0.003703	0.054107	0.051405
-250.0	0.6768	0.000000	0.000000	-0.053092	-0.003765	0.054095	0.051444
-240.0	0.6729	0.000000	0.000000	-0.054118	-0.003819	0.054091	0.051481
-230.0	0.6708	0.000000	0.000000	-0.055007	-0.003855	0.054092	0.051520
-220.0	0.6708	0.000000	0.000886	-0.055786	-0.003827	0.054093	0.048573
-210.0	0.6712	0.000000	0.000932	-0.056478	-0.003762	0.054093	0.043933
-200.0	0.6717	0.000000	0.000988	-0.057098	-0.003672	0.054094	0.038837
-190.0	0.6720	0.000000	0.001057	-0.057659	-0.003560	0.054094	0.033793
-180.0	0.6723	0.000000	0.001142	-0.058173	-0.003426	0.054094	0.029102
-170.0	0.6726	0.000000	0.001246	-0.058647	-0.003270	0.054094	0.024939
-160.0	0.6727	0.000000	0.001372	-0.059089	-0.003090	0.054094	0.021366
-150.0	0.6727	0.000000	0.001528	-0.059500	-0.002885	0.054094	0.018400
-140.0	0.6727	0.000000	0.001720	-0.059862	-0.002656	0.054094	0.015996
-130.0	0.6724	0.000000	0.001958	-0.060112	-0.002396	0.054087	0.014077
-120.0	0.6715	0.002242	0.002253	-0.059978	-0.002099	0.046302	0.012565
-110.0	0.6701	0.002613	0.002622	-0.059648	-0.001754	0.036703	0.011384

-100.0	0.6683	0.003082	0.003090	-0.059246	-0.001351	0.029129	0.010472
-90.0	0.6662	0.003678	0.003685	-0.058770	-0.000873	0.023359	0.009778
-80.0	0.6635	0.004442	0.004448	-0.058197	-0.000299	0.019024	0.009256
-70.0	0.6602	0.005412	0.005417	-0.057502	0.000397	0.015833	0.008872
-60.0	0.6560	0.006635	0.006639	-0.056652	0.001248	0.013524	0.008594
-50.0	0.6509	0.008143	0.008147	-0.055609	0.002292	0.011885	0.008397
-40.0	0.6449	0.009907	0.009910	-0.054334	0.003568	0.010749	0.008261
-30.0	0.6380	0.011811	0.011814	-0.052796	0.005107	0.009980	0.008168
-24.0	0.6336	0.012945	0.012948	-0.051744	0.006159	0.009647	0.008128
-23.0	0.6328	0.013221	0.013224	-0.051559	0.006344	0.009590	0.008124
-22.0	0.6318	0.013563	0.013566	-0.051369	0.006534	0.009533	0.008125
-21.0	0.6308	0.013972	0.013974	-0.051174	0.006729	0.009483	0.008134
-20.0	0.6296	0.014447	0.014450	-0.050973	0.006930	0.009443	0.008158
-19.0	0.6284	0.014988	0.014990	-0.050765	0.007139	0.009420	0.008199
-18.0	0.6270	0.015593	0.015595	-0.050548	0.007355	0.009419	0.008262
-17.0	0.6255	0.016261	0.016264	-0.050323	0.007581	0.009445	0.008351
-16.0	0.6240	0.016992	0.016994	-0.050087	0.007816	0.009502	0.008469
-15.0	0.6223	0.017781	0.017783	-0.049841	0.008063	0.009594	0.008621
-14.0	0.6206	0.018627	0.018629	-0.049583	0.008321	0.009724	0.008808
-13.0	0.6188	0.019526	0.019529	-0.049313	0.008591	0.009893	0.009032
-12.0	0.6169	0.020477	0.020480	-0.049029	0.008874	0.010104	0.009295
-11.0	0.6149	0.021479	0.021482	-0.048732	0.009171	0.010359	0.009598
-10.0	0.6128	0.022521	0.022523	-0.048421	0.009483	0.010656	0.009941
-9.0	0.6107	0.023598	0.023600	-0.048094	0.009810	0.010996	0.010323
-8.0	0.6085	0.024710	0.024713	-0.047752	0.010152	0.011380	0.010746
-7.0	0.6063	0.025855	0.025858	-0.047394	0.010510	0.011807	0.011210
-6.0	0.6040	0.027028	0.027030	-0.047019	0.010885	0.012277	0.011713
-5.0	0.6017	0.028225	0.028227	-0.046628	0.011276	0.012789	0.012257
-4.0	0.5993	0.029441	0.029443	-0.046219	0.011685	0.013342	0.012839
-3.0	0.5970	0.030674	0.030676	-0.045794	0.012110	0.013936	0.013460
-2.0	0.5946	0.031918	0.031920	-0.045350	0.012554	0.014570	0.014119
-1.0	0.5922	0.033170	0.033172	-0.044890	0.013015	0.015242	0.014814
0.0	0.5898	0.034427	0.034428	-0.044411	0.013493	0.015952	0.015546
1.0	0.5875	0.035607	0.035609	-0.043915	0.013989	0.016665	0.016279
2.0	0.5854	0.036643	0.036645	-0.043403	0.014501	0.017347	0.016976
3.0	0.5835	0.037547	0.037549	-0.042878	0.015027	0.017995	0.017639
4.0	0.5817	0.038328	0.038330	-0.042340	0.015564	0.018610	0.018265
5.0	0.5800	0.038995	0.038997	-0.041793	0.016112	0.019189	0.018855
6.0	0.5785	0.039555	0.039557	-0.041236	0.016668	0.019734	0.019410
7.0	0.5772	0.040017	0.040019	-0.040673	0.017232	0.020245	0.019929
8.0	0.5759	0.040386	0.040388	-0.040104	0.017801	0.020723	0.020414
9.0	0.5748	0.040670	0.040672	-0.039530	0.018375	0.021167	0.020865
10.0	0.5738	0.040875	0.040877	-0.038952	0.018952	0.021581	0.021284
11.0	0.5729	0.041007	0.041009	-0.038373	0.019532	0.021964	0.021672
12.0	0.5720	0.041070	0.041072	-0.037791	0.020113	0.022317	0.022030
13.0	0.5713	0.041072	0.041074	-0.037210	0.020695	0.022642	0.022360
14.0	0.5707	0.041014	0.041015	-0.036629	0.021276	0.022940	0.022660
15.0	0.5701	0.040901	0.040903	-0.036049	0.021856	0.023210	0.022934
16.0	0.5696	0.040740	0.040742	-0.035471	0.022434	0.023456	0.023183
17.0	0.5692	0.040534	0.040536	-0.034896	0.023009	0.023678	0.023408
18.0	0.5689	0.040286	0.040287	-0.034324	0.023581	0.023876	0.023608
19.0	0.5686	0.039999	0.040000	-0.033755	0.024149	0.024052	0.023785
20.0	0.5684	0.039677	0.039679	-0.033191	0.024713	0.024206	0.023941
21.0	0.5682	0.039325	0.039327	-0.032632	0.025273	0.024340	0.024077
22.0	0.5681	0.038945	0.038946	-0.032078	0.025827	0.024455	0.024193
23.0	0.5680	0.038539	0.038541	-0.031530	0.026375	0.024552	0.024290
24.0	0.5680	0.038112	0.038113	-0.030987	0.026918	0.024631	0.024370
25.0	0.5680	0.037661	0.037663	-0.030451	0.027454	0.024691	0.024431

26.0	0.5681	0.037194	0.037196	-0.029921	0.027984	0.024737	0.024477
27.0	0.5681	0.036712	0.036713	-0.029398	0.028507	0.024767	0.024507
28.0	0.5682	0.036216	0.036217	-0.028882	0.029023	0.024782	0.024522
29.0	0.5684	0.035708	0.035710	-0.028373	0.029532	0.024784	0.024525
30.0	0.5685	0.035189	0.035190	-0.027871	0.030034	0.024784	0.024525
31.0	0.5687	0.034660	0.034661	-0.027377	0.030529	0.024784	0.024525
32.0	0.5689	0.034123	0.034124	-0.026890	0.031015	0.024784	0.024525
33.0	0.5692	0.033579	0.033580	-0.026411	0.031495	0.024784	0.024525
34.0	0.5694	0.033030	0.033032	-0.025939	0.031966	0.024784	0.024525
35.0	0.5697	0.032478	0.032479	-0.025476	0.032430	0.024784	0.024525
36.0	0.5700	0.031924	0.031925	-0.025020	0.032885	0.024784	0.024525
37.0	0.5702	0.031369	0.031370	-0.024572	0.033333	0.024784	0.024525
38.0	0.5705	0.030814	0.030815	-0.024132	0.033774	0.024784	0.024525
39.0	0.5709	0.030260	0.030261	-0.023699	0.034206	0.024784	0.024525
40.0	0.5712	0.029708	0.029710	-0.023275	0.034630	0.024784	0.024525
41.0	0.5715	0.029160	0.029161	-0.022858	0.035047	0.024784	0.024525
42.0	0.5718	0.028615	0.028616	-0.022450	0.035456	0.024784	0.024525
43.0	0.5721	0.028074	0.028075	-0.022048	0.035857	0.024784	0.024525
44.0	0.5725	0.027539	0.027540	-0.021655	0.036251	0.024784	0.024525
45.0	0.5728	0.027009	0.027010	-0.021269	0.036637	0.024784	0.024525
46.0	0.5731	0.026485	0.026486	-0.020890	0.037015	0.024784	0.024525
47.0	0.5735	0.025968	0.025969	-0.020519	0.037387	0.024784	0.024525
48.0	0.5738	0.025457	0.025458	-0.020155	0.037751	0.024784	0.024525
49.0	0.5741	0.024954	0.024955	-0.019798	0.038107	0.024784	0.024525
50.0	0.5744	0.024459	0.024460	-0.019448	0.038457	0.024784	0.024525
51.0	0.5748	0.023971	0.023972	-0.019106	0.038800	0.024784	0.024525
52.0	0.5751	0.023492	0.023492	-0.018770	0.039136	0.024784	0.024525
53.0	0.5754	0.023020	0.023021	-0.018441	0.039465	0.024784	0.024525
54.0	0.5757	0.022557	0.022558	-0.018118	0.039788	0.024784	0.024525
55.0	0.5760	0.022102	0.022103	-0.017802	0.040104	0.024784	0.024525
56.0	0.5763	0.021657	0.021657	-0.017492	0.040413	0.024784	0.024525
57.0	0.5765	0.021219	0.021220	-0.017189	0.040717	0.024784	0.024525
58.0	0.5768	0.020790	0.020791	-0.016892	0.041014	0.024784	0.024525
59.0	0.5771	0.020370	0.020371	-0.016600	0.041305	0.024784	0.024525
60.0	0.5774	0.019958	0.019959	-0.016315	0.041591	0.024784	0.024525
61.0	0.5776	0.019556	0.019556	-0.016035	0.041871	0.024784	0.024525
62.0	0.5779	0.019161	0.019162	-0.015761	0.042145	0.024784	0.024525
63.0	0.5781	0.018775	0.018776	-0.015493	0.042413	0.024784	0.024525
64.0	0.5784	0.018398	0.018399	-0.015230	0.042676	0.024784	0.024525
65.0	0.5786	0.018029	0.018029	-0.014972	0.042934	0.024784	0.024525
66.0	0.5788	0.017668	0.017669	-0.014719	0.043187	0.024784	0.024525
67.0	0.5790	0.017315	0.017316	-0.014472	0.043434	0.024784	0.024525
68.0	0.5793	0.016971	0.016971	-0.014229	0.043677	0.024784	0.024525
69.0	0.5795	0.016634	0.016635	-0.013991	0.043915	0.024784	0.024525
70.0	0.5797	0.016305	0.016305	-0.013758	0.044148	0.024784	0.024525
71.0	0.5798	0.015984	0.015984	-0.013530	0.044376	0.024784	0.024525
72.0	0.5800	0.015670	0.015670	-0.013306	0.044600	0.024784	0.024525
73.0	0.5802	0.015363	0.015364	-0.013086	0.044820	0.024784	0.024525
74.0	0.5804	0.015064	0.015065	-0.012871	0.045035	0.024784	0.024525
75.0	0.5806	0.014772	0.014773	-0.012659	0.045246	0.024784	0.024525
76.0	0.5807	0.014487	0.014488	-0.012452	0.045454	0.024784	0.024525
77.0	0.5809	0.014209	0.014210	-0.012249	0.045657	0.024784	0.024525
78.0	0.5810	0.013938	0.013938	-0.012050	0.045858	0.024784	0.024525
79.0	0.5812	0.013673	0.013673	-0.011855	0.046051	0.024784	0.024525
80.0	0.5813	0.013414	0.013415	-0.011663	0.046243	0.024784	0.024525
81.0	0.5814	0.013162	0.013162	-0.011475	0.046431	0.024784	0.024525
82.0	0.5816	0.012916	0.012916	-0.011290	0.046616	0.024784	0.024525
83.0	0.5817	0.012676	0.012676	-0.011109	0.046797	0.024784	0.024525

84.0	0.5818	0.012441	0.012442	-0.010931	0.046975	0.024784	0.024525
85.0	0.5819	0.012212	0.012213	-0.010757	0.047149	0.024784	0.024525
86.0	0.5820	0.011989	0.011990	-0.010586	0.047320	0.024784	0.024525
87.0	0.5821	0.011772	0.011772	-0.010418	0.047488	0.024784	0.024525
88.0	0.5822	0.011559	0.011560	-0.010252	0.047654	0.024784	0.024525
89.0	0.5823	0.011352	0.011352	-0.010090	0.047816	0.024784	0.024525
90.0	0.5824	0.011150	0.011150	-0.009931	0.047975	0.024784	0.024525
91.0	0.5825	0.010952	0.010953	-0.009775	0.048131	0.024784	0.024525
92.0	0.5825	0.010760	0.010760	-0.009621	0.048285	0.024784	0.024525
93.0	0.5826	0.010572	0.010572	-0.009470	0.048436	0.024784	0.024525
94.0	0.5827	0.010388	0.010389	-0.009322	0.048584	0.024784	0.024525
95.0	0.5828	0.010209	0.010210	-0.009176	0.048730	0.024784	0.024525
96.0	0.5828	0.010035	0.010035	-0.009033	0.048873	0.024784	0.024525
97.0	0.5829	0.009864	0.009864	-0.008892	0.049014	0.024784	0.024525
98.0	0.5829	0.009698	0.009698	-0.008753	0.049153	0.024784	0.024525
99.0	0.5830	0.009535	0.009536	-0.008617	0.049289	0.024784	0.024525
100.0	0.5830	0.009377	0.009377	-0.008483	0.049423	0.024784	0.024525
101.0	0.5831	0.009222	0.009222	-0.008352	0.049554	0.024784	0.024525
102.0	0.5831	0.009071	0.009071	-0.008222	0.049684	0.024784	0.024525
103.0	0.5832	0.008923	0.008923	-0.008095	0.049811	0.024784	0.024525
104.0	0.5832	0.008779	0.008779	-0.007970	0.049936	0.024784	0.024525
105.0	0.5832	0.008638	0.008639	-0.007846	0.050060	0.024784	0.024525
106.0	0.5833	0.008501	0.008501	-0.007725	0.050181	0.024784	0.024525
107.0	0.5833	0.008367	0.008367	-0.007606	0.050300	0.024784	0.024525
108.0	0.5833	0.008236	0.008236	-0.007488	0.050418	0.024784	0.024525
109.0	0.5834	0.008108	0.008108	-0.007373	0.050534	0.024784	0.024525
110.0	0.5834	0.007983	0.007983	-0.007259	0.050647	0.024784	0.024525
111.0	0.5834	0.007861	0.007861	-0.007147	0.050760	0.024784	0.024525
112.0	0.5834	0.007741	0.007742	-0.007036	0.050870	0.024784	0.024525
113.0	0.5834	0.007625	0.007625	-0.006927	0.050979	0.024784	0.024525
114.0	0.5835	0.007511	0.007511	-0.006820	0.051086	0.024784	0.024525
115.0	0.5835	0.007400	0.007400	-0.006715	0.051191	0.024784	0.024525
116.0	0.5835	0.007291	0.007291	-0.006611	0.051295	0.024784	0.024525
117.0	0.5835	0.007185	0.007185	-0.006508	0.051398	0.024784	0.024525
118.0	0.5835	0.007081	0.007081	-0.006407	0.051499	0.024784	0.024525
119.0	0.5835	0.006979	0.006980	-0.006308	0.051598	0.024784	0.024525
120.0	0.5835	0.006880	0.006880	-0.006210	0.051696	0.024784	0.024525
121.0	0.5835	0.006783	0.006783	-0.006113	0.051793	0.024785	0.024526
122.0	0.5835	0.006688	0.006688	-0.006018	0.051888	0.024787	0.024528
123.0	0.5835	0.006595	0.006596	-0.005924	0.051982	0.024792	0.024533
124.0	0.5835	0.006505	0.006505	-0.005831	0.052075	0.024801	0.024542
125.0	0.5835	0.006416	0.006416	-0.005740	0.052167	0.024814	0.024556
126.0	0.5835	0.006329	0.006329	-0.005649	0.052257	0.024832	0.024573
127.0	0.5835	0.006244	0.006245	-0.005560	0.052346	0.024851	0.024592
128.0	0.5835	0.006161	0.006162	-0.005473	0.052434	0.024872	0.024614
129.0	0.5834	0.006080	0.006080	-0.005386	0.052520	0.024898	0.024640
130.0	0.5834	0.006001	0.006001	-0.005301	0.052606	0.024928	0.024670
131.0	0.5834	0.005923	0.005923	-0.005216	0.052690	0.024962	0.024704
132.0	0.5834	0.005847	0.005847	-0.005133	0.052773	0.024998	0.024741
133.0	0.5834	0.005772	0.005773	-0.005051	0.052856	0.025038	0.024781
134.0	0.5834	0.005699	0.005700	-0.004969	0.052937	0.025081	0.024825
135.0	0.5834	0.005628	0.005628	-0.004889	0.053017	0.025128	0.024872
136.0	0.5833	0.005558	0.005559	-0.004810	0.053096	0.025177	0.024922
137.0	0.5833	0.005490	0.005490	-0.004732	0.053174	0.025230	0.024975
138.0	0.5833	0.005423	0.005423	-0.004655	0.053252	0.025286	0.025031
139.0	0.5833	0.005358	0.005358	-0.004578	0.053328	0.025345	0.025091
140.0	0.5833	0.005293	0.005294	-0.004503	0.053403	0.025407	0.025154
141.0	0.5832	0.005231	0.005231	-0.004429	0.053478	0.025473	0.025220

142.0	0.5832	0.005169	0.005169	-0.004355	0.053551	0.025541	0.025289
143.0	0.5832	0.005109	0.005109	-0.004282	0.053624	0.025612	0.025360
144.0	0.5832	0.005050	0.005050	-0.004210	0.053696	0.025686	0.025435
145.0	0.5831	0.004992	0.004992	-0.004139	0.053767	0.025764	0.025513
146.0	0.5831	0.004936	0.004936	-0.004069	0.053837	0.025844	0.025594
147.0	0.5831	0.004880	0.004880	-0.003999	0.053907	0.025927	0.025678
148.0	0.5830	0.004826	0.004826	-0.003931	0.053976	0.026012	0.025764
149.0	0.5830	0.004773	0.004773	-0.003863	0.054043	0.026101	0.025853
150.0	0.5830	0.004721	0.004721	-0.003796	0.054111	0.026192	0.025945
151.0	0.5830	0.004670	0.004670	-0.003729	0.054177	0.026286	0.026040
152.0	0.5829	0.004620	0.004620	-0.003663	0.054243	0.026383	0.026137
153.0	0.5829	0.004571	0.004571	-0.003598	0.054308	0.026482	0.026237
154.0	0.5829	0.004523	0.004523	-0.003534	0.054372	0.026583	0.026340
155.0	0.5828	0.004476	0.004476	-0.003470	0.054436	0.026688	0.026445
156.0	0.5828	0.004430	0.004430	-0.003407	0.054499	0.026794	0.026553
157.0	0.5828	0.004385	0.004385	-0.003345	0.054561	0.026904	0.026663
158.0	0.5827	0.004340	0.004340	-0.003283	0.054623	0.027015	0.026775
159.0	0.5827	0.004297	0.004297	-0.003222	0.054684	0.027129	0.026891
160.0	0.5826	0.004254	0.004255	-0.003162	0.054745	0.027245	0.027008
161.0	0.5826	0.004213	0.004213	-0.003102	0.054805	0.027364	0.027127
162.0	0.5826	0.004172	0.004172	-0.003042	0.054864	0.027484	0.027249
163.0	0.5825	0.004132	0.004132	-0.002984	0.054923	0.027607	0.027373
164.0	0.5825	0.004093	0.004093	-0.002925	0.054981	0.027732	0.027499
165.0	0.5825	0.004054	0.004054	-0.002868	0.055039	0.027859	0.027627
166.0	0.5824	0.004016	0.004016	-0.002811	0.055096	0.027988	0.027757
167.0	0.5824	0.003979	0.003979	-0.002754	0.055152	0.028119	0.027889
168.0	0.5823	0.003943	0.003943	-0.002698	0.055208	0.028252	0.028023
169.0	0.5823	0.003908	0.003908	-0.002643	0.055264	0.028387	0.028159
170.0	0.5823	0.003873	0.003873	-0.002587	0.055319	0.028524	0.028297
171.0	0.5822	0.003838	0.003839	-0.002533	0.055374	0.028662	0.028437
172.0	0.5822	0.003805	0.003805	-0.002479	0.055428	0.028802	0.028578
173.0	0.5821	0.003772	0.003772	-0.002425	0.055481	0.028945	0.028722
174.0	0.5821	0.003740	0.003740	-0.002372	0.055534	0.029088	0.028867
175.0	0.5821	0.003708	0.003708	-0.002319	0.055587	0.029234	0.029013
176.0	0.5820	0.003677	0.003677	-0.002267	0.055639	0.029380	0.029161
177.0	0.5820	0.003647	0.003647	-0.002215	0.055691	0.029529	0.029311
178.0	0.5819	0.003617	0.003617	-0.002164	0.055743	0.029678	0.029462
179.0	0.5819	0.003588	0.003588	-0.002113	0.055794	0.029830	0.029614
180.0	0.5818	0.003559	0.003559	-0.002062	0.055844	0.029982	0.029768
181.0	0.5818	0.003531	0.003531	-0.002012	0.055894	0.030136	0.029924
182.0	0.5817	0.003504	0.003504	-0.001962	0.055944	0.030291	0.030080
183.0	0.5817	0.003477	0.003477	-0.001913	0.055993	0.030448	0.030238
184.0	0.5817	0.003450	0.003450	-0.001864	0.056042	0.030606	0.030397
185.0	0.5816	0.003424	0.003424	-0.001815	0.056091	0.030765	0.030558
186.0	0.5816	0.003399	0.003399	-0.001767	0.056139	0.030924	0.030719
187.0	0.5815	0.003374	0.003374	-0.001719	0.056187	0.031085	0.030881
188.0	0.5815	0.003349	0.003349	-0.001672	0.056235	0.031248	0.031045
189.0	0.5814	0.003325	0.003325	-0.001624	0.056282	0.031411	0.031209
190.0	0.5814	0.003302	0.003302	-0.001578	0.056329	0.031574	0.031375
191.0	0.5813	0.003279	0.003279	-0.001531	0.056375	0.031740	0.031541
192.0	0.5813	0.003256	0.003256	-0.001485	0.056422	0.031905	0.031708
193.0	0.5812	0.003234	0.003234	-0.001439	0.056468	0.032072	0.031876
194.0	0.5812	0.003212	0.003212	-0.001393	0.056513	0.032239	0.032045
195.0	0.5811	0.003191	0.003191	-0.001348	0.056559	0.032407	0.032214
196.0	0.5811	0.003170	0.003170	-0.001303	0.056604	0.032576	0.032385
197.0	0.5810	0.003149	0.003149	-0.001258	0.056648	0.032745	0.032555
198.0	0.5810	0.003129	0.003129	-0.001214	0.056693	0.032915	0.032727
199.0	0.5809	0.003110	0.003110	-0.001170	0.056737	0.033086	0.032899

200.0	0.5808	0.003090	0.003090	-0.001126	0.056781	0.033253	0.033067
210.0	0.5664	0.002830	0.002830	-0.000706	0.057201	0.034377	0.034201
220.0	0.5319	0.002491	0.002491	-0.000329	0.057571	0.034671	0.034476
230.0	0.4828	0.002116	0.002124	-0.000003	0.057836	0.034666	0.007919
240.0	0.4248	0.001740	0.000000	0.000270	0.057713	0.034666	0.007920
250.0	0.3707	0.001425	0.000000	0.000493	0.057384	0.034666	0.007920
260.0	0.3263	0.001188	0.000000	0.000674	0.056980	0.034666	0.007920
270.0	0.2921	0.001020	0.000000	0.000818	0.056502	0.034666	0.007920
280.0	0.2684	0.000913	0.000000	0.000925	0.055928	0.034728	0.007920
290.0	0.2551	0.000860	0.000000	0.001005	0.055231	0.035302	0.007920
300.0	0.2496	0.000847	0.000000	0.001068	0.054380	0.036414	0.007920
310.0	0.2457	0.000848	0.000000	0.001129	0.053336	0.037648	0.007920
320.0	0.2410	0.000851	0.000000	0.001190	0.052059	0.038818	0.007920
330.0	0.2352	0.000855	0.000000	0.001252	0.050521	0.039913	0.007920
340.0	0.2283	0.000859	0.000000	0.001316	0.048696	0.040933	0.008792
350.0	0.2207	0.000864	0.000000	0.001382	0.046143	0.041874	0.015857
360.0	0.2131	0.000870	0.000000	0.001450	0.042141	0.042738	0.030299
370.0	0.2052	0.000878	0.000000	0.001520	0.036707	0.043528	0.043318
380.0	0.1960	0.000885	0.000000	0.001594	0.030970	0.044236	0.049618
390.0	0.1852	0.000889	0.000000	0.001670	0.025678	0.044874	0.052639
400.0	0.1730	0.000891	0.000000	0.001747	0.021108	0.045449	0.053997
410.0	0.1598	0.000891	0.000000	0.001824	0.017303	0.045969	0.054538
420.0	0.1458	0.000890	0.000000	0.001900	0.014188	0.046438	0.054721
430.0	0.1315	0.000887	0.000000	0.001975	0.011646	0.046857	0.054761
440.0	0.1173	0.000882	0.000000	0.002048	0.009563	0.047232	0.054750
450.0	0.1036	0.000878	0.000000	0.002118	0.007841	0.047569	0.054729
460.0	0.0906	0.000873	0.000000	0.002185	0.006401	0.047871	0.054711
470.0	0.0784	0.000867	0.000000	0.002248	0.005184	0.048129	0.054699
480.0	0.0675	0.000861	0.000000	0.002302	0.004141	0.048340	0.054695
490.0	0.0580	0.000861	0.000000	0.002338	0.003237	0.007559	0.054696
500.0	0.0500	0.000000	0.000000	0.002309	0.002444	0.007614	0.054697
510.0	0.0439	0.000000	0.000000	0.002244	0.001741	0.007662	0.054697
520.0	0.0394	0.000000	0.000000	0.002154	0.001110	0.007705	0.054697
530.0	0.0369	0.000000	0.000000	0.002041	0.000539	0.007745	0.054697
540.0	0.0365	0.000000	0.000000	0.001907	0.000016	0.007781	0.054697
550.0	0.0382	0.000000	0.000000	0.001750	-0.000466	0.007814	0.054697

```
START OF ITERATION # 3  OF  3 ALLOWED

CA =  -520.00      P =   1.00800     INFLAG =  0     IFG =  2
CA =  -510.00      P =   0.98408     INFLAG =  0     IFG =  2
CA =  -508.32      P =   0.98052     INFLAG =  0     IFG =  8
CA =  -503.77      P =   0.73691     INFLAG =  0     IFG =  8
CA =  -500.00      P =   0.86771     INFLAG =  1     IFG =  2
CA =  -490.00      P =   0.93820     INFLAG =  1     IFG =  2
CA =  -480.00      P =   0.93283     INFLAG =  1     IFG =  2
CA =  -470.00      P =   0.93867     INFLAG =  1     IFG =  2
CA =  -460.00      P =   0.94404     INFLAG =  1     IFG =  2
CA =  -450.00      P =   0.94830     INFLAG =  1     IFG =  2
CA =  -440.00      P =   0.95207     INFLAG =  1     IFG =  2
CA =  -430.00      P =   0.95546     INFLAG =  1     IFG =  2
CA =  -420.00      P =   0.95830     INFLAG =  1     IFG =  2
CA =  -410.00      P =   0.96206     INFLAG =  1     IFG =  2
CA =  -400.00      P =   0.96246     INFLAG =  1     IFG =  2
CA =  -390.00      P =   0.96403     INFLAG =  1     IFG =  2
CA =  -380.00      P =   0.96521     INFLAG =  1     IFG =  2
CA =  -370.00      P =   0.96684     INFLAG =  1     IFG =  2
CA =  -360.00      P =   0.96903     INFLAG =  1     IFG =  2
CA =  -350.00      P =   0.97139     INFLAG =  1     IFG =  2
CA =  -340.00      P =   0.97249     INFLAG =  1     IFG =  2
CA =  -330.00      P =   0.97310     INFLAG =  1     IFG =  2
CA =  -320.00      P =   0.97377     INFLAG =  1     IFG =  2
CA =  -310.00      P =   0.97455     INFLAG =  1     IFG =  2
CA =  -300.00      P =   0.97587     INFLAG =  1     IFG =  2
CA =  -290.00      P =   0.97764     INFLAG =  1     IFG =  2
CA =  -280.00      P =   0.97940     INFLAG =  1     IFG =  2
CA =  -272.44      P =   0.98004     INFLAG =  1     IFG =  8
CA =  -270.00      P =   0.98043     INFLAG =  0     IFG =  2
CA =  -260.00      P =   0.98302     INFLAG =  0     IFG =  2
CA =  -250.00      P =   0.98994     INFLAG =  0     IFG =  2
CA =  -240.00      P =   1.00400     INFLAG =  0     IFG =  2
CA =  -230.00      P =   1.03241     INFLAG =  0     IFG =  2
CA =  -220.00      P =   1.07373     INFLAG =  0     IFG =  2
CA =  -210.00      P =   1.12754     INFLAG =  0     IFG =  2
CA =  -200.00      P =   1.19486     INFLAG =  0     IFG =  2
CA =  -190.00      P =   1.27788     INFLAG =  0     IFG =  2
CA =  -180.00      P =   1.37954     INFLAG =  0     IFG =  2

VOLUMETRIC EFFICIENCY =  81.2 %

CA =  -170.00      P =   1.50387                     IFG =  2
CA =  -160.00      P =   1.65613                     IFG =  2
CA =  -150.00      P =   1.84322                     IFG =  2
CA =  -140.00      P =   2.07409                     IFG =  2
CA =  -130.00      P =   2.36048                     IFG =  2
CA =  -120.00      P =   2.71527                     IFG =  2
CA =  -110.00      P =   3.16007                     IFG =  2
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CA = -100.00      P =  3.72293                        IFG = 2
CA =  -90.00      P =  4.43932                        IFG = 2
CA =  -80.00      P =  5.35773                        IFG = 2
CA =  -70.00      P =  6.52561                        IFG = 2
CA =  -60.00      P =  7.99727                        IFG = 2
CA =  -50.00      P =  9.81260                        IFG = 2
CA =  -40.00      P = 11.93651                        IFG = 2
CA =  -30.00      P = 14.22880                        IFG = 2
CA = -24.00       P = 15.59461     XB = 0.001062     IFG = 2
CA = -23.00       P = 15.92721     XB = 0.003348     IFG = 2
CA = -22.00       P = 16.33923     XB = 0.007158     IFG = 2
CA = -21.00       P = 16.83146     XB = 0.012492     IFG = 2
CA = -20.00       P = 17.40388     XB = 0.019350     IFG = 2
CA = -19.00       P = 18.05502     XB = 0.027732     IFG = 2
CA = -18.00       P = 18.78402     XB = 0.037638     IFG = 2
CA = -17.00       P = 19.58952     XB = 0.049068     IFG = 2
CA = -16.00       P = 20.46925     XB = 0.062022     IFG = 2
CA = -15.00       P = 21.42054     XB = 0.076500     IFG = 2
CA = -14.00       P = 22.43974     XB = 0.092502     IFG = 2
CA = -13.00       P = 23.52410     XB = 0.110028     IFG = 2
CA = -12.00       P = 24.67047     XB = 0.129078     IFG = 2
CA = -11.00       P = 25.87882     XB = 0.149652     IFG = 2
CA = -10.00       P = 27.13466     XB = 0.171750     IFG = 2
CA =  -9.00       P = 28.43349     XB = 0.195372     IFG = 2
CA =  -8.00       P = 29.77585     XB = 0.220518     IFG = 2
CA =  -7.00       P = 31.15735     XB = 0.247188     IFG = 2
CA =  -6.00       P = 32.57247     XB = 0.275382     IFG = 2
CA =  -5.00       P = 34.01712     XB = 0.305100     IFG = 2
CA =  -4.00       P = 35.48591     XB = 0.336342     IFG = 2
CA =  -3.00       P = 36.97444     XB = 0.369108     IFG = 2
CA =  -2.00       P = 38.47746     XB = 0.403398     IFG = 2
CA =  -1.00       P = 39.99060     XB = 0.439212     IFG = 2
CA =   0.00       P = 41.50986     XB = 0.476549     IFG = 2
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CA =   2.00       P = 44.19087     XB = 0.547448     IFG = 2
CA =   3.00       P = 45.28512     XB = 0.579164     IFG = 2
CA =   4.00       P = 46.23141     XB = 0.608634     IFG = 2
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CA =   6.00       P = 47.71912     XB = 0.661462     IFG = 2
CA =   7.00       P = 48.27980     XB = 0.685104     IFG = 2
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