

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

by

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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

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Vol. I

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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. Unavailability 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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ACKNOWLEDGEMENTS

First of all, I would like to thank my advisor, Professor John Heywood, for his guidance during the course of my research. I feel fortunate to have had the opportunity to work with such a knowledgeable person.

A special thanks goes to my fellow students at Sloan Automotive Laboratory. I truly appreciate your encouragement--especially when things looked particularly bleak, and your friendship.

The two people largely responsible for my "hanging in there" are my parents, Dorothy and Louis. Mom and Dad thank you for your continued love and support. I Love You.

JMR 1985

This research has been sponsored by N.A.S.A. Grant# NAG 3-82.

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CHAPTER 1.0 INTRODUCTION

The direct-injection 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 plagued 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 shrouded 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 Yamamoto 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 °F at 2000 RPM decreases 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 °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 occurring 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:

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

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:

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

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:

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

where c_v is the specific heat at constant volume. The boundary work term is given by the expression $p dV$, 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

$$dm = dm_{inj} - dm_{cr} \quad (3.4)$$

and component mass balances for fuel vapor and products respectively

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

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

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

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

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

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

$$p dV + \delta Q_{ht} = 0 \quad (3.6)$$

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

$$u_p \sim u_f = (u_p \sim u_p^{\circ}) + (u_p^{\circ} \sim u_f^{\circ}) \sim (u_f \sim u_f^{\circ}) \quad (3.7)$$

where the superscript $^{\circ}$ 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:

$$\delta Q_{\text{gross}} = (u_p^{\circ} \sim u_f^{\circ}) dm_{R(f)} \quad (3.8)$$

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

$$\begin{aligned} \delta Q_{\text{gross}} = & \left[\left(\frac{\gamma}{\gamma-1} \right) pdV + \left(\frac{1}{\gamma-1} \right) Vdp \sim (h^* \sim u_f + c_v T) dm_{\text{inj}} + \right. \\ & \left. (h' \sim u_p + c_v T) dm_{\text{cr}} + \delta Q_{\text{ht}} \right] / [1 + \psi(T)] \end{aligned} \quad (3.9)$$

where,

$$\psi(T) = [(u_p \sim u_p^{\circ}) \sim (u_f \sim u_f^{\circ})] / [u_p^{\circ} \sim u_f^{\circ}]$$

and

$$u_p^{\circ} \sim u_f^{\circ} = -\text{LHV}_f$$

3.1.3 FUEL INJECTION MODEL

Using the definition of enthalpy for an ideal gas

$$h = u + pv,$$

the fuel injection term becomes:

$$(u_{f(1)}^* + p v_{f(1)} - u_f + c_v T) dm_{inj}$$

The superscript * indicates injection system conditions and the subscript f(1) denotes liquid fuel. The specific volume of fuel at any instance is very small. Hence, $p v_{f(1)}$ can be neglected. Also, the internal energy of liquid fuel can be expressed as $u_f^* - u_{1f}^*$; u_{1f}^* 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:

$$(c_{vf}(T^* - T) - u_{1f}^* + \frac{R}{\gamma - 1}) dm_{inj}$$

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,

$u_f \sim u_f^0$ in the denominator of $\Psi(T)$ may be expressed as $c_{vf}(T \sim T^0)$.

3.1.4 CREVICE FLOW MODEL

Proceeding in the same manner as the fuel injection term

$$h' \sim u_p = u' \sim u_p + pv_p = u' \sim u + RT'$$

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 positive 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:

$$\begin{aligned} \delta Q_{gross} = & \left\{ \frac{\gamma}{\gamma-1} p dV + \frac{1}{\gamma-1} V dp - [c_{vf}(T^* - T) - u_{lg}^* + \frac{R}{\gamma-1} T] dm_{inj} \right. \\ & + R \left[\frac{1}{B} \ln\left(\frac{A + BT'}{A + BT} \frac{\gamma-1}{\gamma-1}\right) + T' + \frac{T}{\gamma-1} \right] dm_{cr} + \delta Q_{ht} \left. \right\} / \\ & \left\{ 1 + \left[\frac{R}{B} \ln\left(\frac{A + BT^0}{A + BT} \frac{\gamma-1}{\gamma-1}\right) + c_{vf}(T - T^0) \right] / LHV_f \right\} \end{aligned} \quad (3.10)$$

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.

$$Nu = \frac{hL}{k} = C Re^a Pr^{0.3}$$

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 transfer 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:

$$h = C_1 131 R_r^{0.8} p^{0.8} T^{-0.53} (2.28 V_r + C_2 W_c)^{0.8}$$

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:

$$\frac{dQ}{d\theta} = \frac{dQ}{d\theta_m} \left[(\theta - \theta_s) / (\theta_m - \theta_s) \right] \quad (4.1)$$

For θ greater than θ_m , the rate of fuel burning is given by:

$$\frac{dQ}{d\theta} = \frac{dQ}{d\theta_m} \exp \left[- (\theta - \theta_m) / \tau \right] \quad (4.2)$$

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:

$$\dot{E} = \sum \dot{m}_j h_j - \dot{Q} - \dot{W} \quad (4.3)$$

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:

$$E = H - pV \quad (4.4)$$

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:

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

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

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

It is assumed that the ideal gas law is obeyed throughout the cycle.

Therefore, the rate of change of pressure is given by:

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

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

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

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

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

and

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

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

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:

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

where,

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

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

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

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

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

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:

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

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

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

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

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

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 correlation 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 analysis (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.

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TABLE 1

ADVANCED ROTARY ENGINE TECHNOLOGIES

Solid-State Ignition Trigger Vs. Mechanical Trigger	Retracting Apex Seals
Plasma Jet Ignition System	Thermostatically Controlled Rotor Oil Cooling
Eliminating Pilot Injector	Turbocharging with Variable Area Turbine
High Temperature Aluminum Castings	Spark Ignition Start/Auto-Ignition Run
Turbocharger	Aluminum Rotor (Reinforced Lands)
Thin Wall (Iron) Rotor	Insulated Rotor - Thermal Barrier Coating
Exhaust Port Thermal Liner (Metallic)	Independent Dual Ignition
Improved Lubricants	Variable Compression Ratio
Multiple Power Sources for Ignition	Insulated Rotor - Inserts on Metallic Pad Insulator
Induction Air Intercooler	Adiabatic Engine Ceramic End Walls
Variable Displacement Pressure Oil Pump	Composite Rotor (Reinforced Apex Seal Land)
Provision for Counter-Rotating Propellers	Electronic Injection (Fuel)
Total Diagnostics	Adiabatic Engine Ceramic Rotor Inserts
Electronic Ignition Schedule	Turbocompound
Computer vs. Mechanical Timing	Adiabatic Engine - Ceramic Rotor Housing Liner
Fiber Optics Data Bus	Pilot Nozzle Trigger for Ignition System
Low Pressure Drop Heat Exchangers	High Speed Propeller (No Reduction Gear)
NASVYTIS Traction Speed Reducer (Prop)	NASVYTIS Traction Speed Reducer (Turbocompound Drive - If Used)
Alternate Cooling Fluid	Adiabatic Engine - Ceramic Rolling Element Bearings
Composite Rotor Housing (Wear Resistant Liner)	
Wing Leading Edge with Integral Coolant Cooler	
Alternate Materials Seals	

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
Texasco TCP L-141	CITE [*] Heptane C7H16	2000 1000	1	9.84	7.62	580	10.2	Roosa-Master XM4-54 single-hole pencil, orifice dia. 0.635 mm, crack pressure 13.79 MPa	15° BTC Start	20° BTC
Texasco TCGS 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 XM4-1029 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 1.72-2.81 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 in- wardly 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 Std.	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).

<u>Heat Transfer:</u>		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
<u>Crevice Volume:</u>			
		% % Chemical Energy	
		0 97.1	
		2 99.0	
		4 101.0	
<u>$\gamma(T)$ Fit:</u>			
		1 st Fit 99.0	
		2nd Fit 99.3	
<u>Fuel Vaporization:</u>			
		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

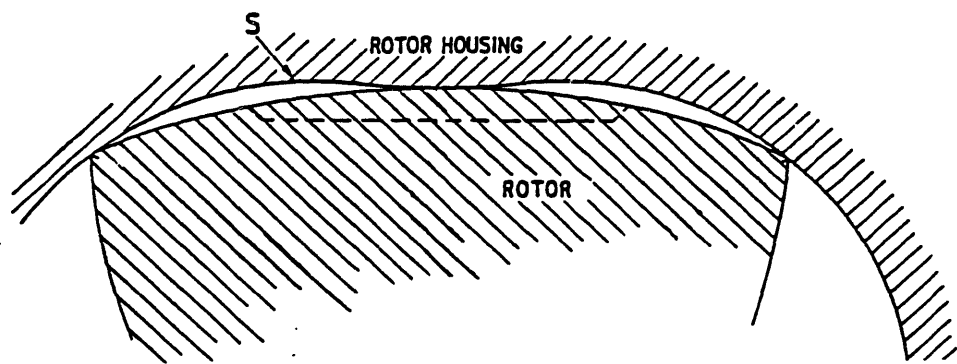


Figure 1. The Wankel engine rotor and epitrochoidal housing.

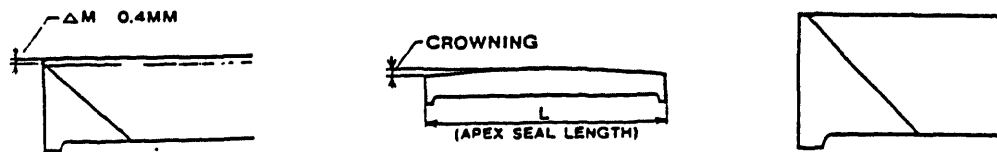


Figure 2a. Apex seal modifications.

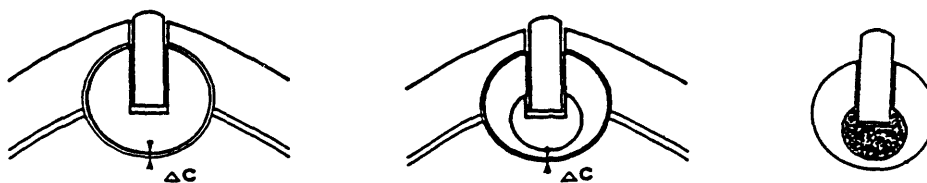


Figure 2b. Corner seal modifications.

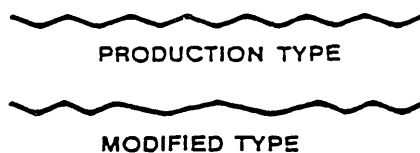


Figure 2c. Side seal spring modification.

Figure 2. Toyo Kogyo Wankel engine sealing modifications.

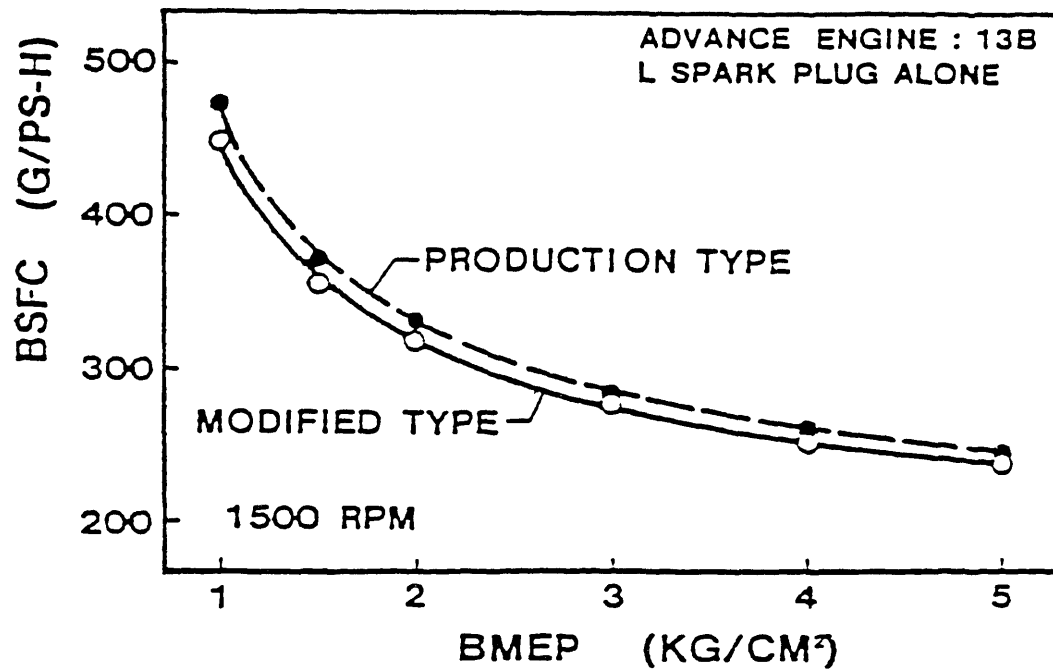


Figure 3. The affect of Toyo Kogyo sealing modifications on brake specific fuel consumption.

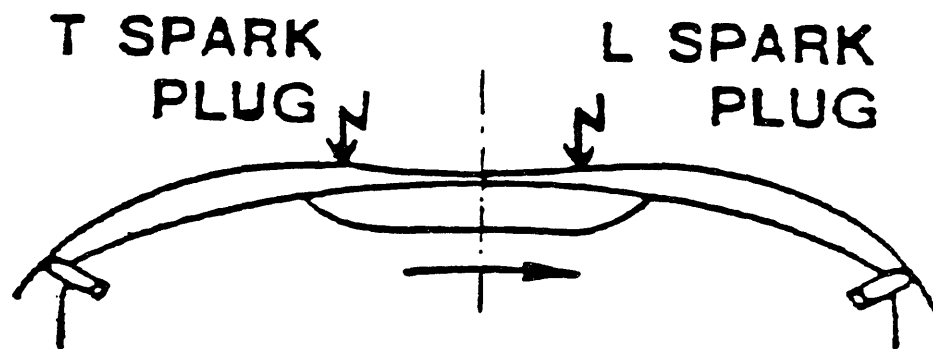


Figure 4. Leading and trailing spark plug placement about minor axis during high load and speed operation.

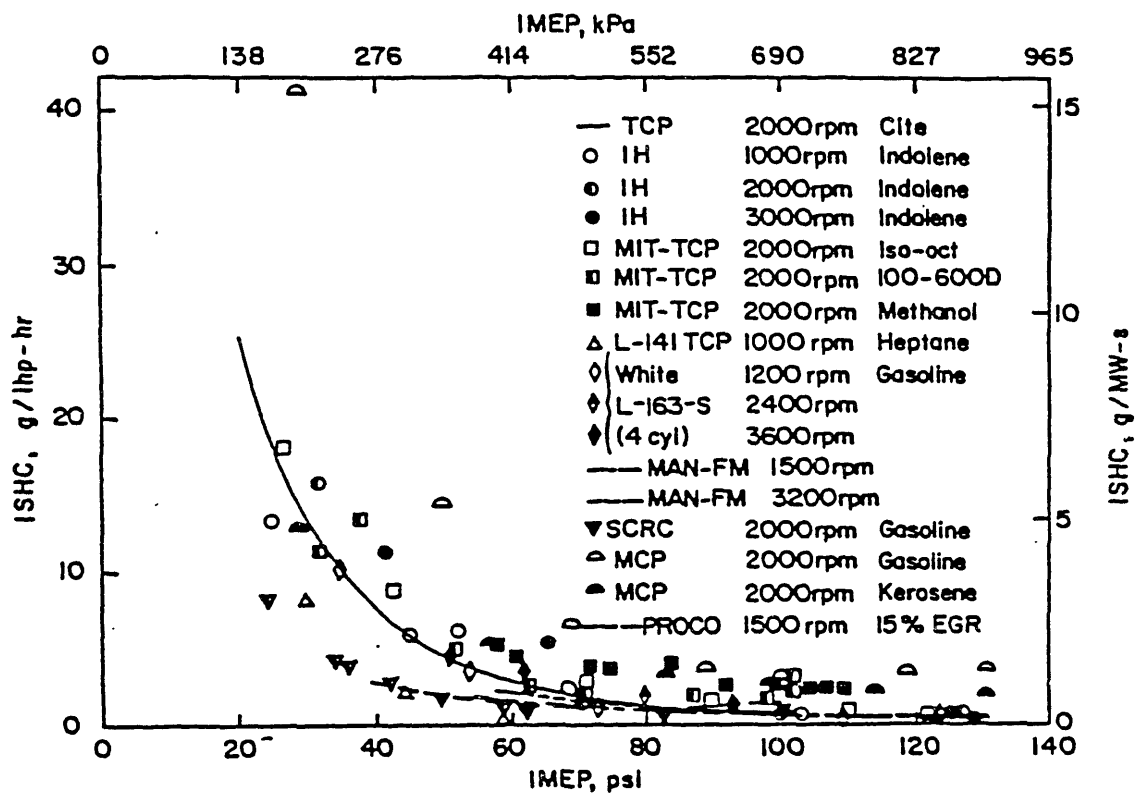


Figure 5. Indicated specific HC emissions versus load for stratified-charge engines.

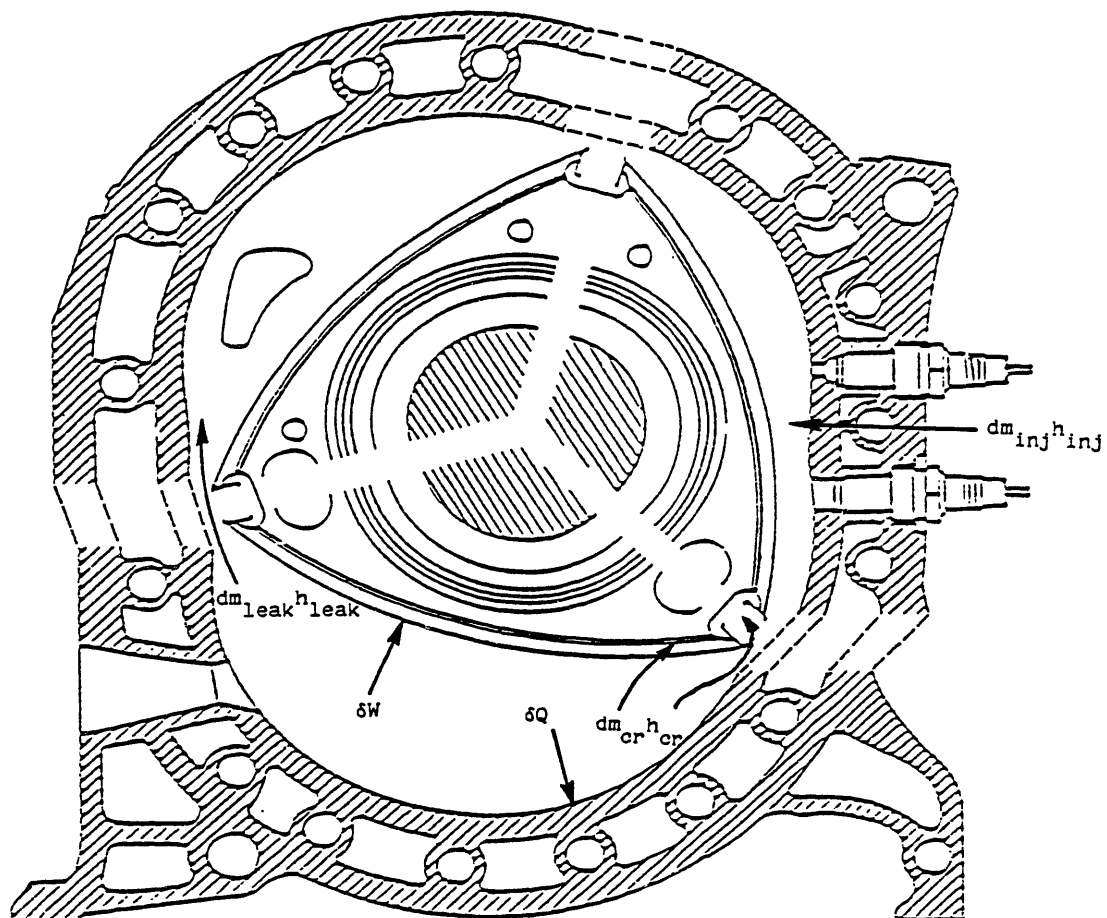
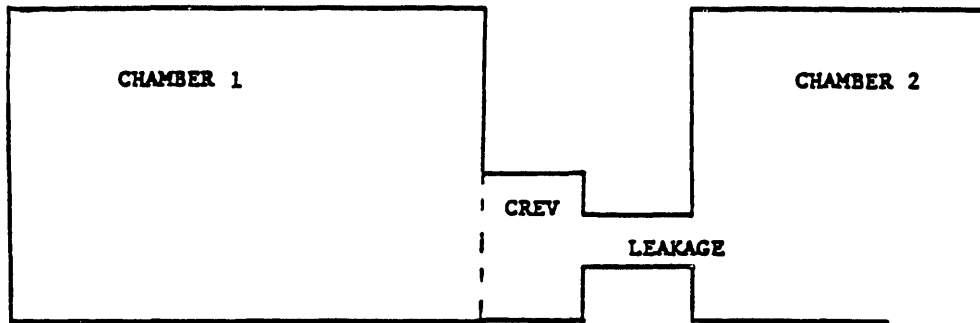


Figure 6. Energy transfer mechanisms across the Wankel engine combustion chamber boundary.



APPLY CONSERVATION OF MASS TO CREVICE VOLUME

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

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

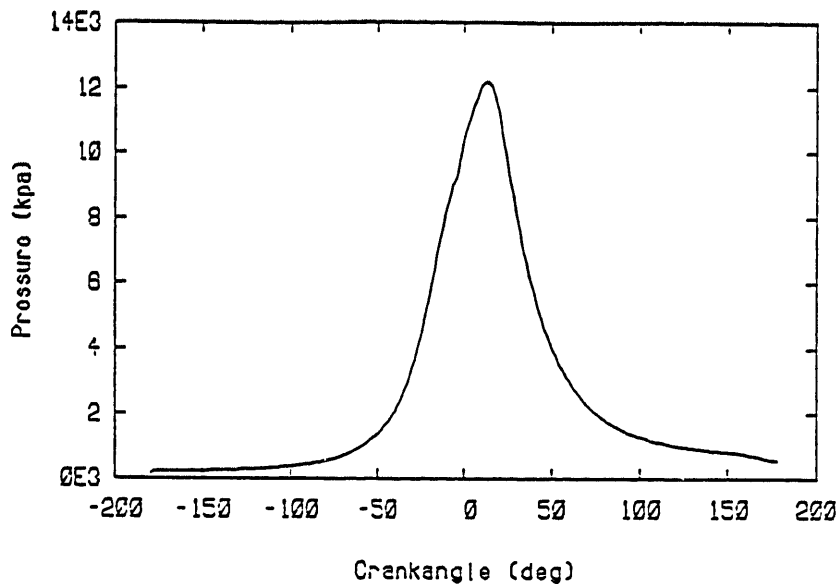


Figure 8a. Cylinder pressure.

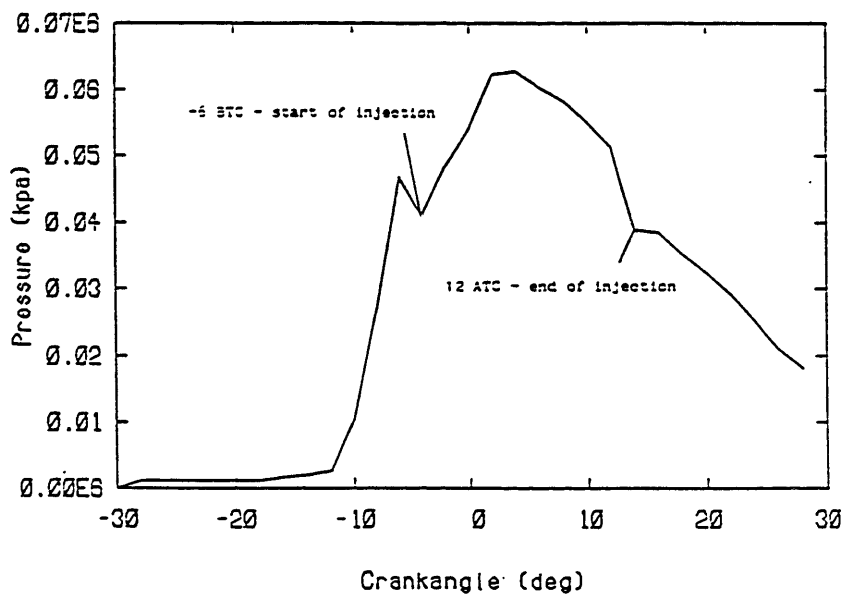


Figure 8b. Injection system pressure.

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

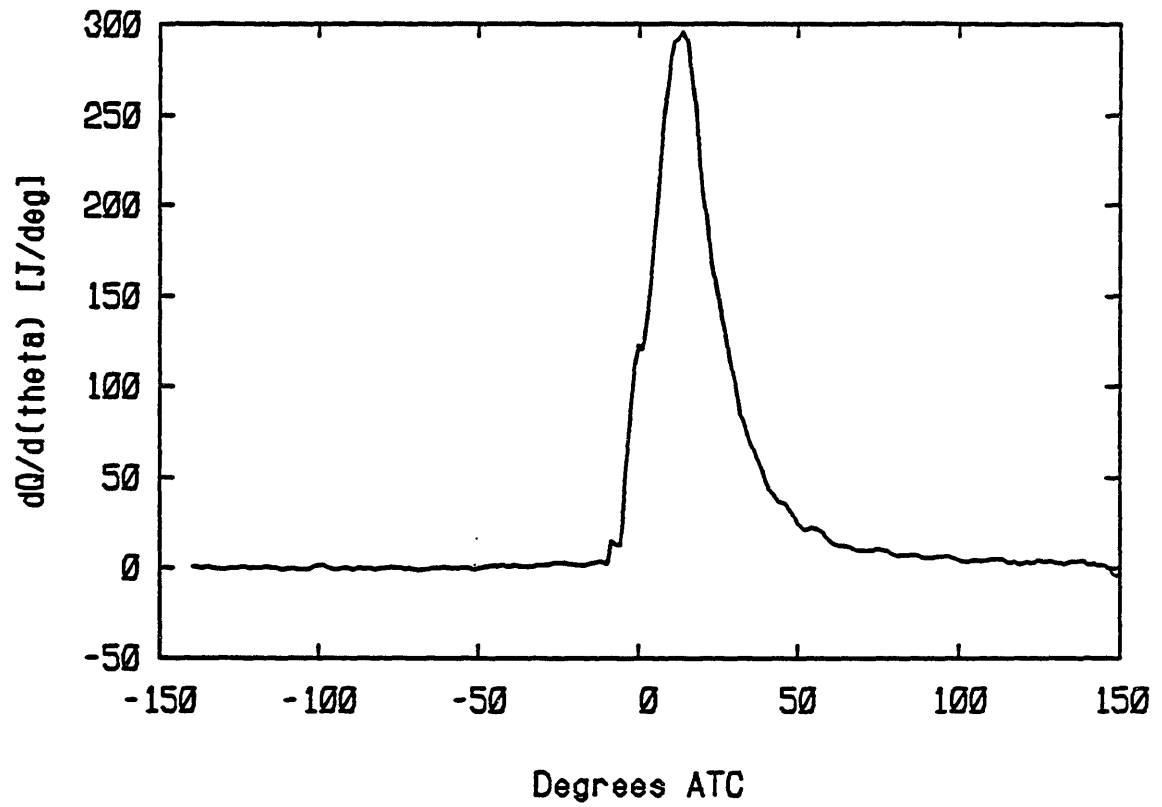


Figure 9. Rate of heat release for base case.

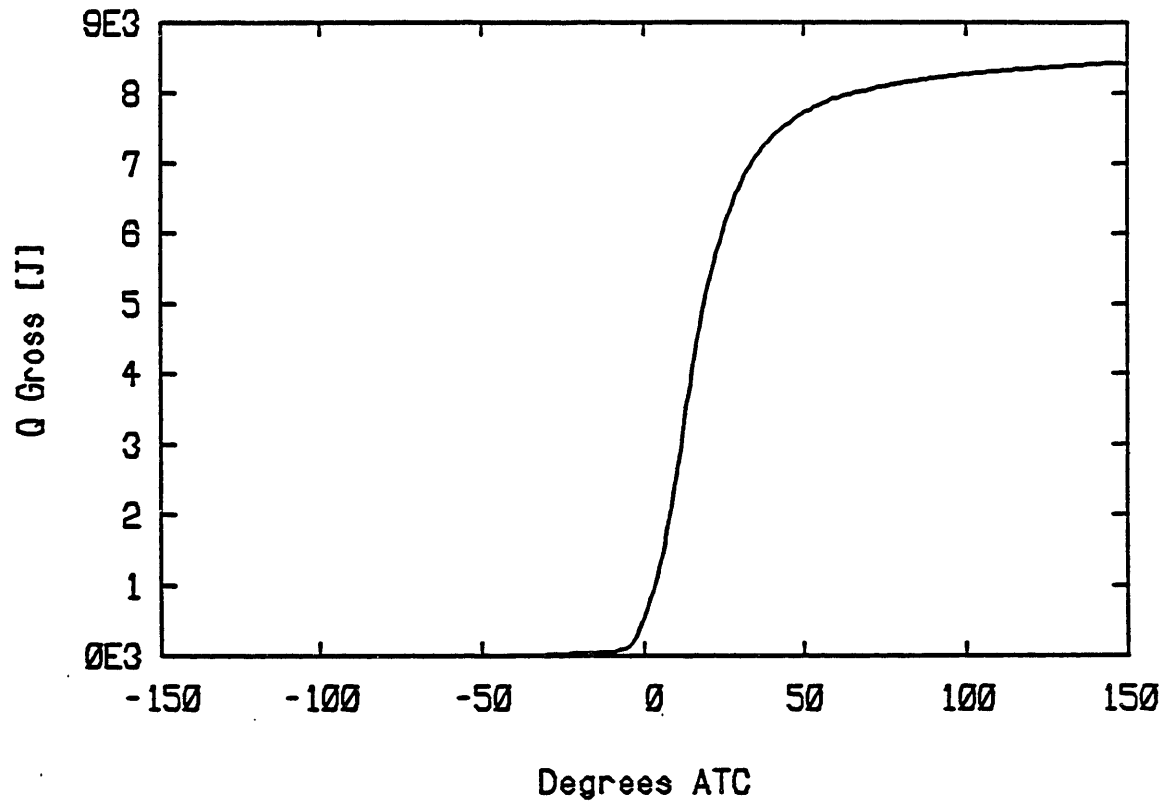


Figure 10. Integrated heat release for base case.

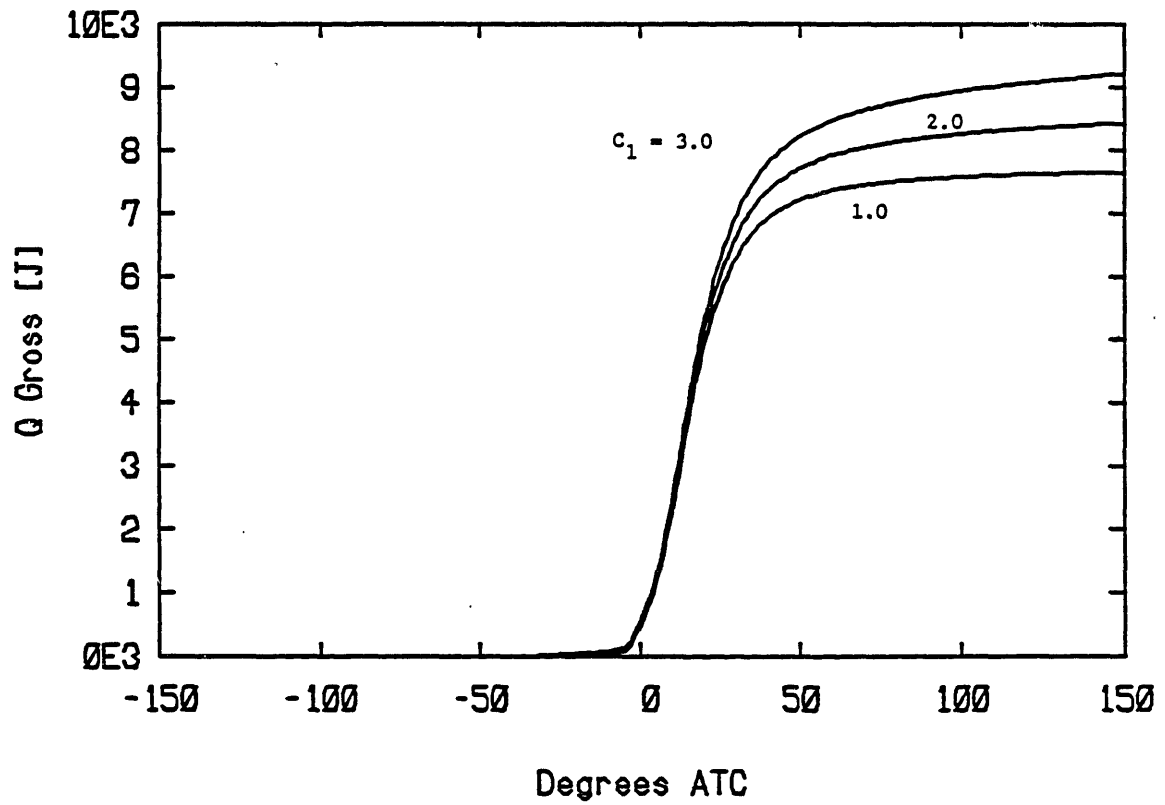


Figure 11. Integrated heat release curves illustrating sensitivity to C_1 .

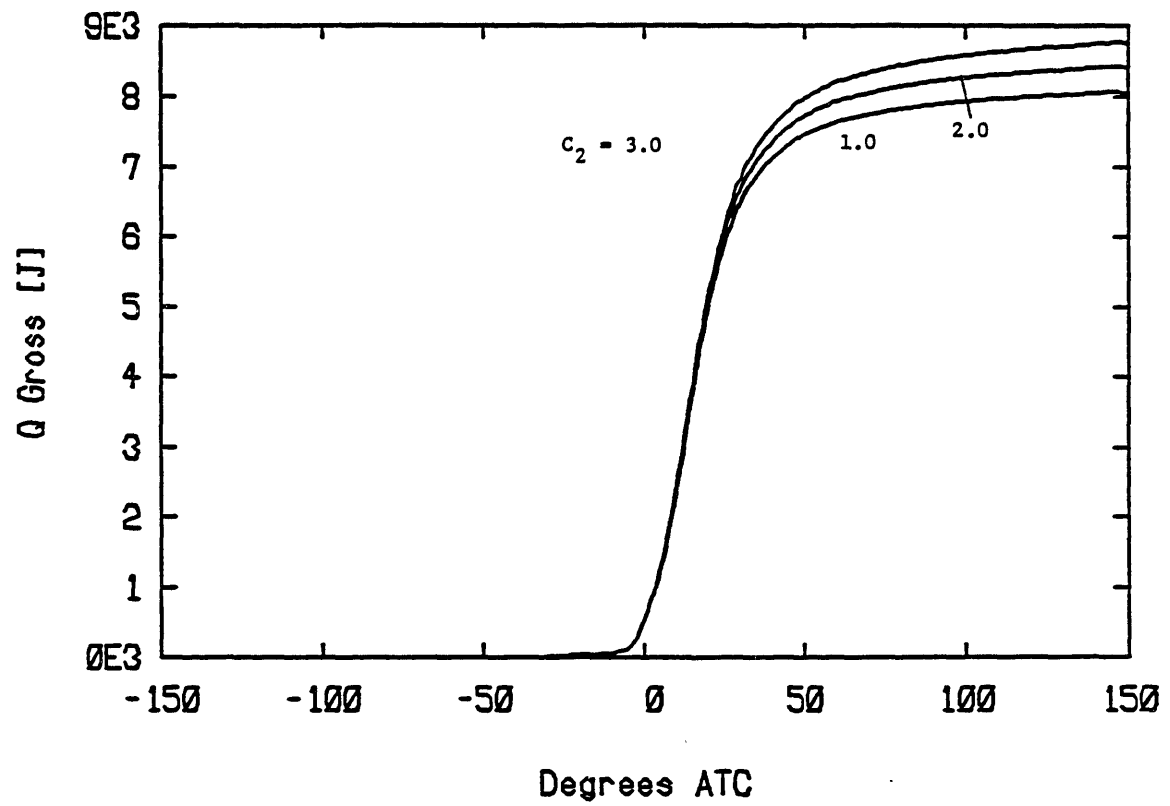


Figure 12. Integrated heat release curves illustrating sensitivity to C_2 .

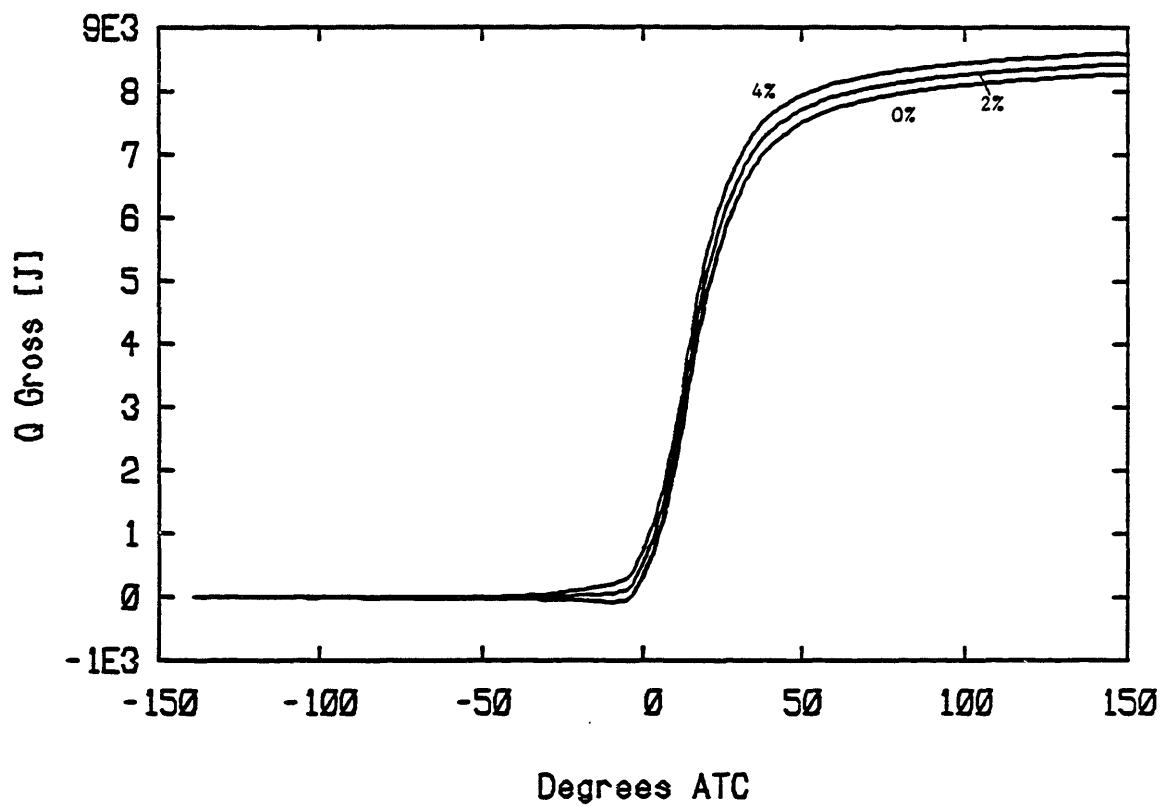


Figure 13. Integrated heat release curves illustrating sensitivity to crevice volume (expressed as percent of clearance volume).

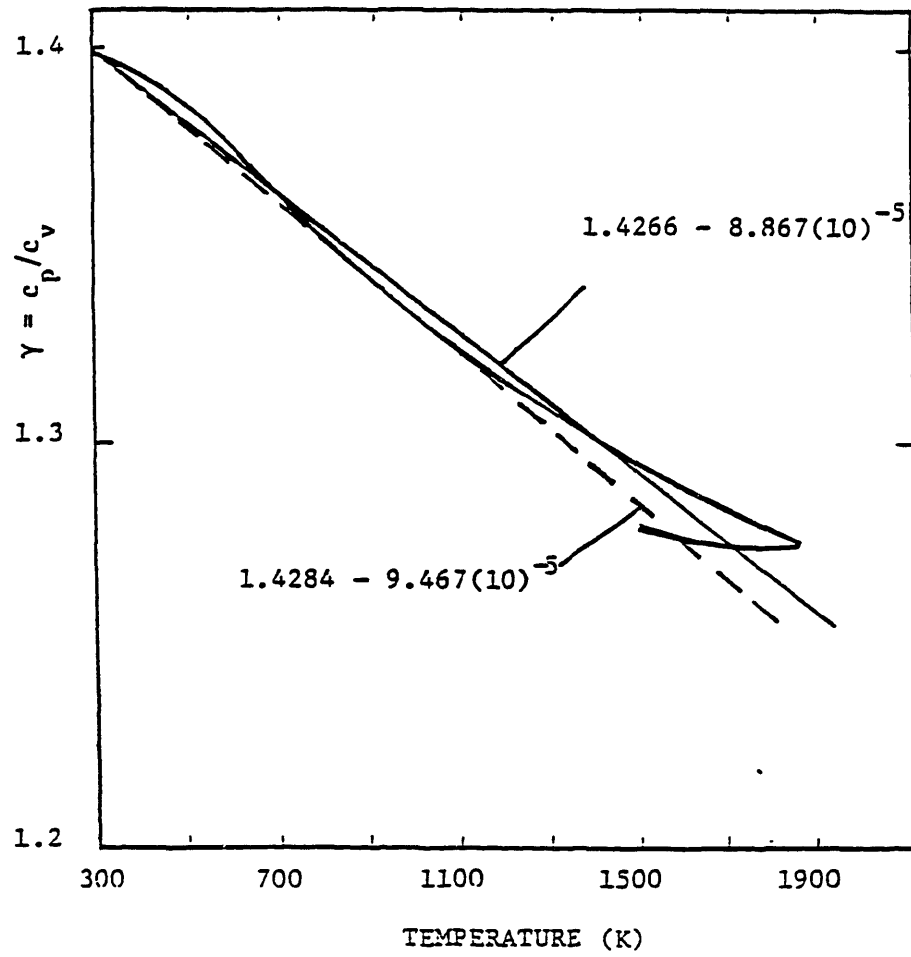


Figure 14. Selected linear functions of temperature for $\gamma(T)$.

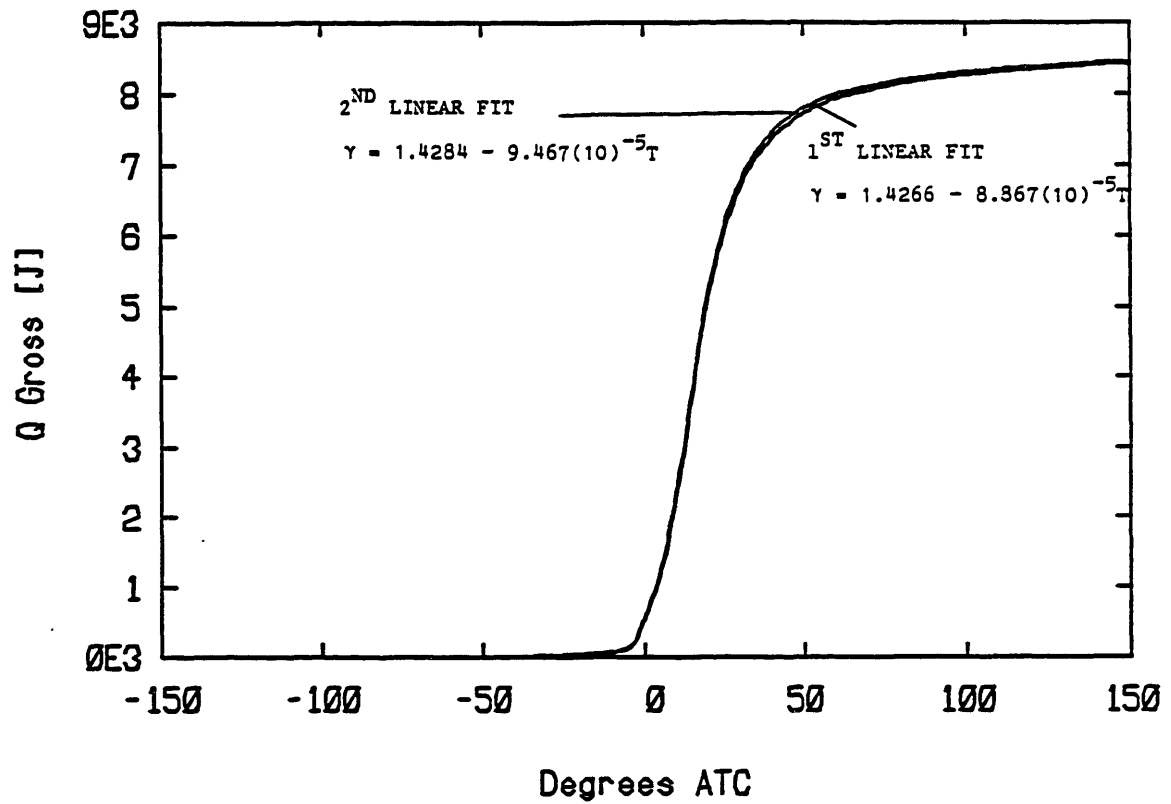


Figure 15. Integrated heat release curves for the two selected linear functions of $\gamma(T)$.

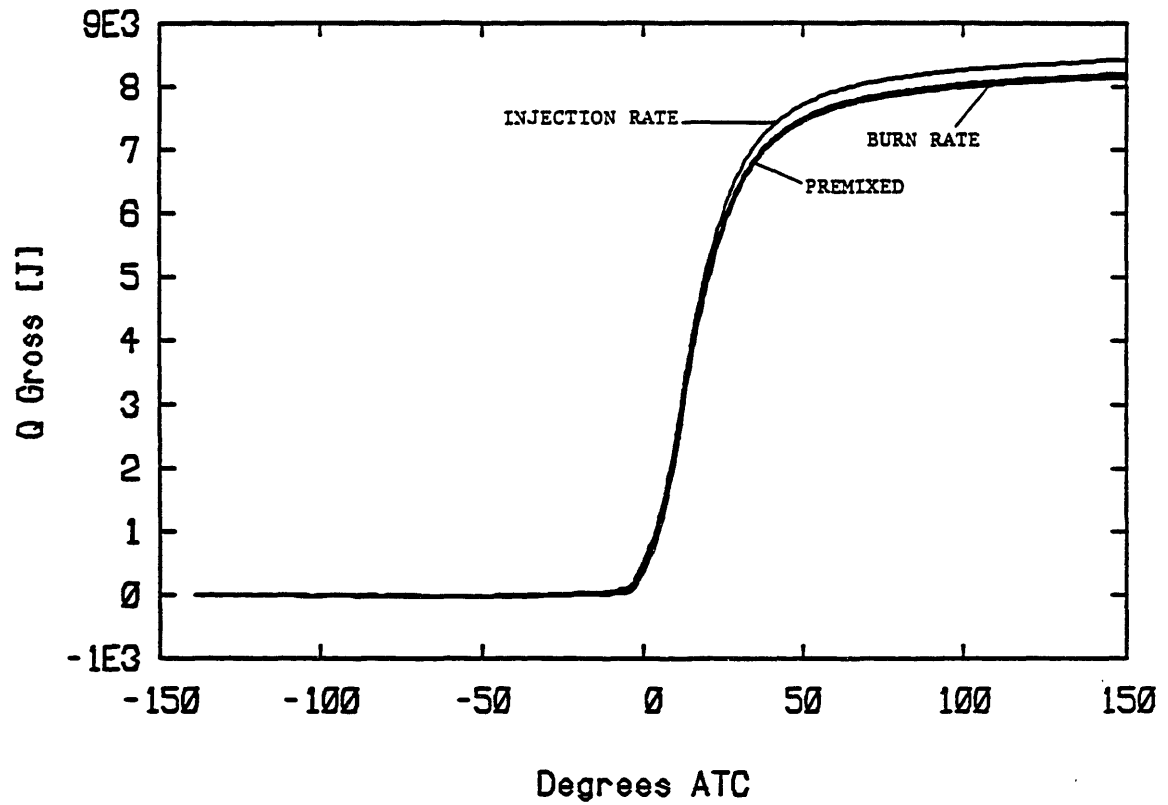


Figure 16. Integrated heat release curves for the two limiting vaporization rates and premixed charge combustion.

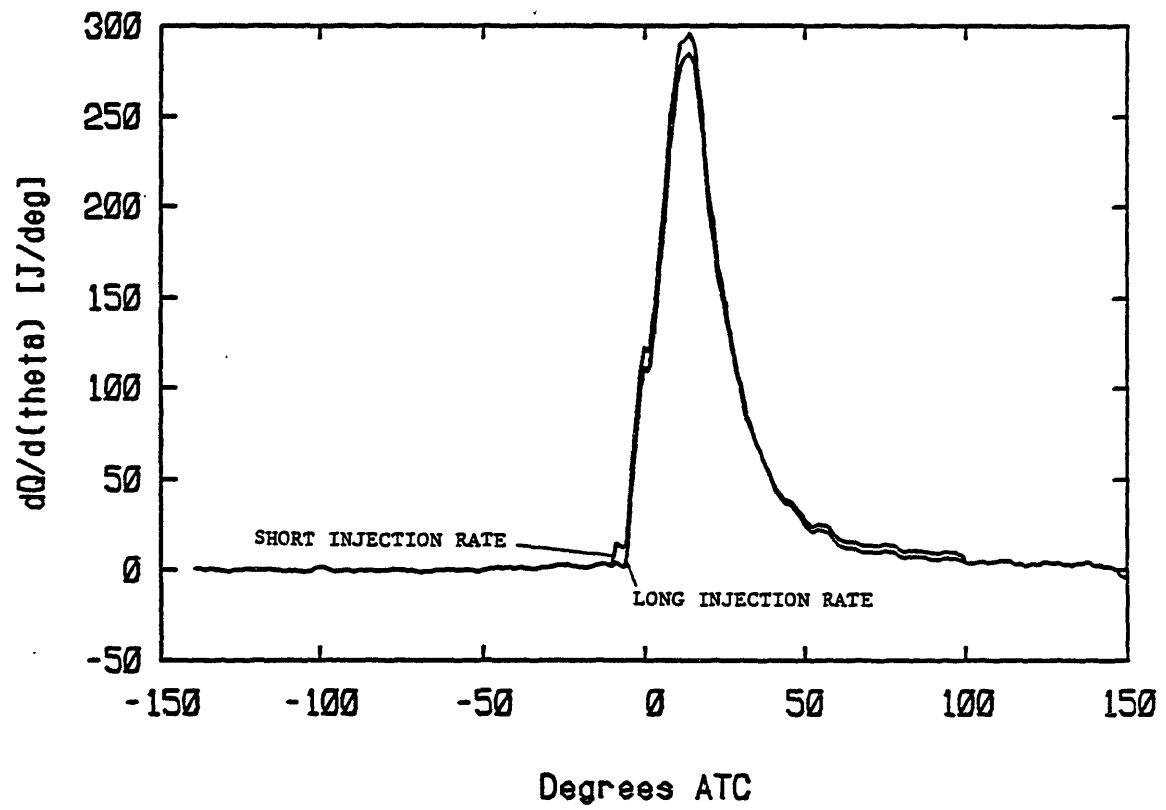


Figure 17. Rate of heat release curves comparing long and short injection duration rates.

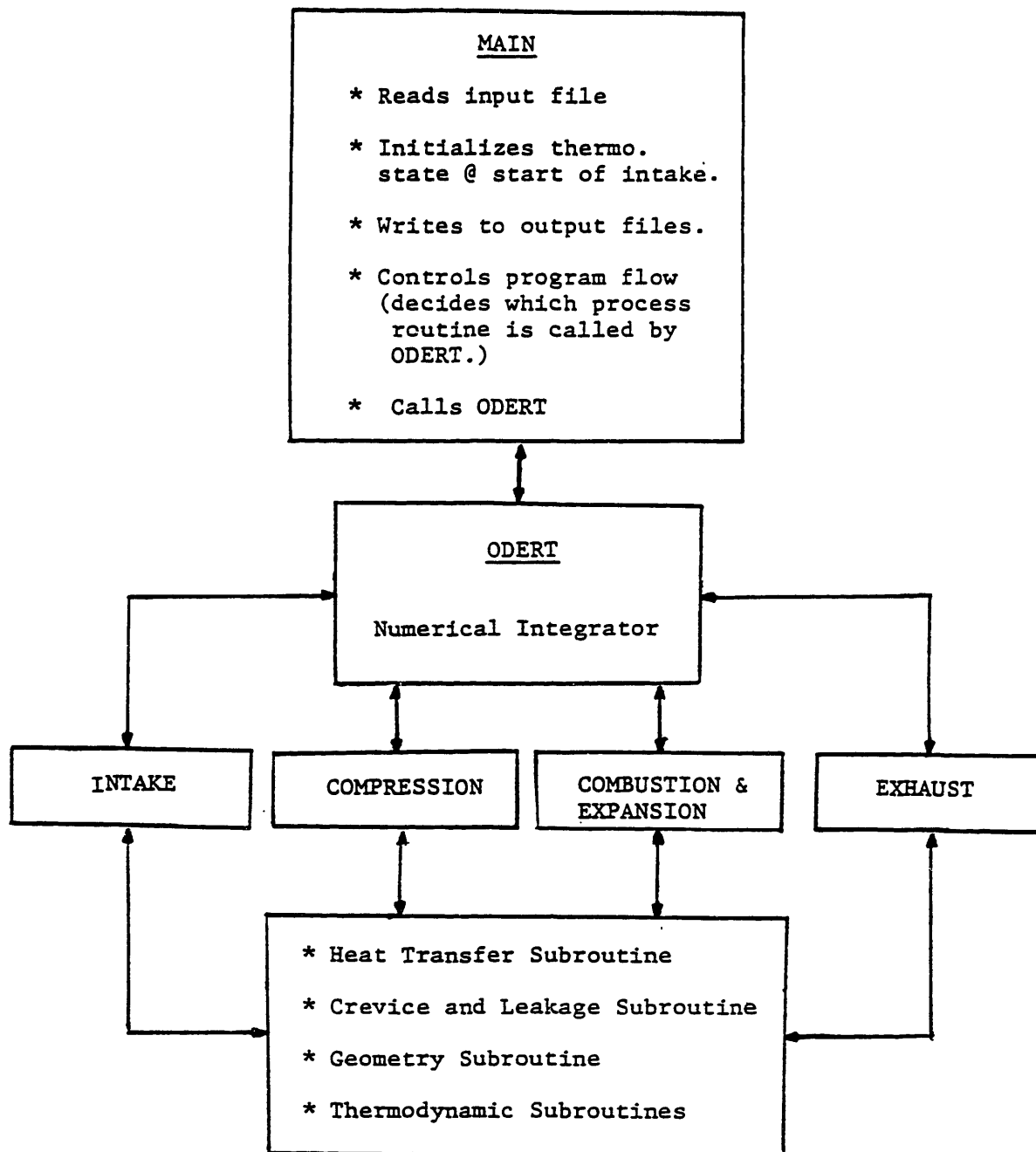


Figure 18. Flow chart of Wankel stratified-charge engine cycle simulation.

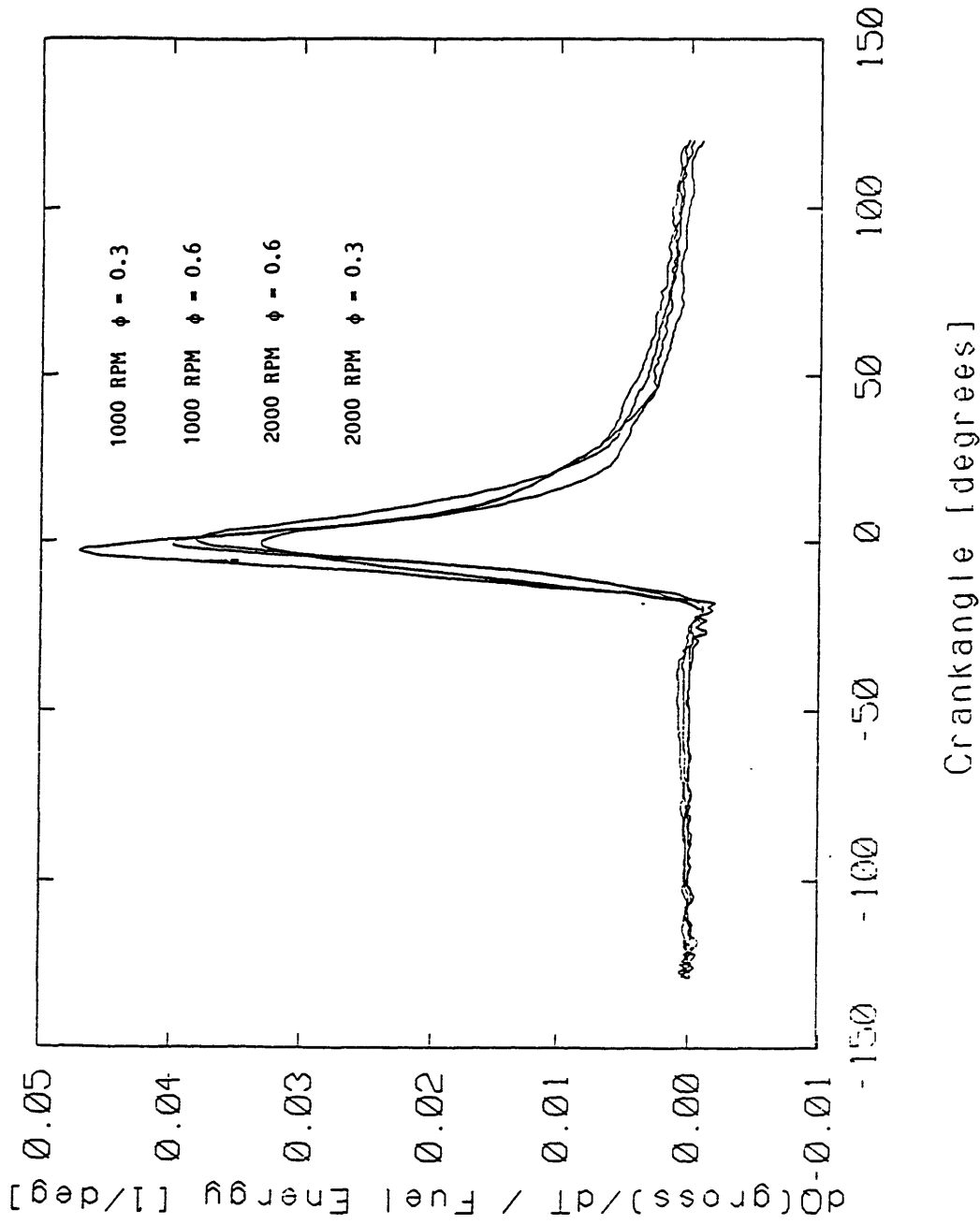


Figure 19. Normalized heat release rate curves for engine speeds of 1000 and 2000 RPM at $\phi = 0.3$ and $\phi = 0.6$.

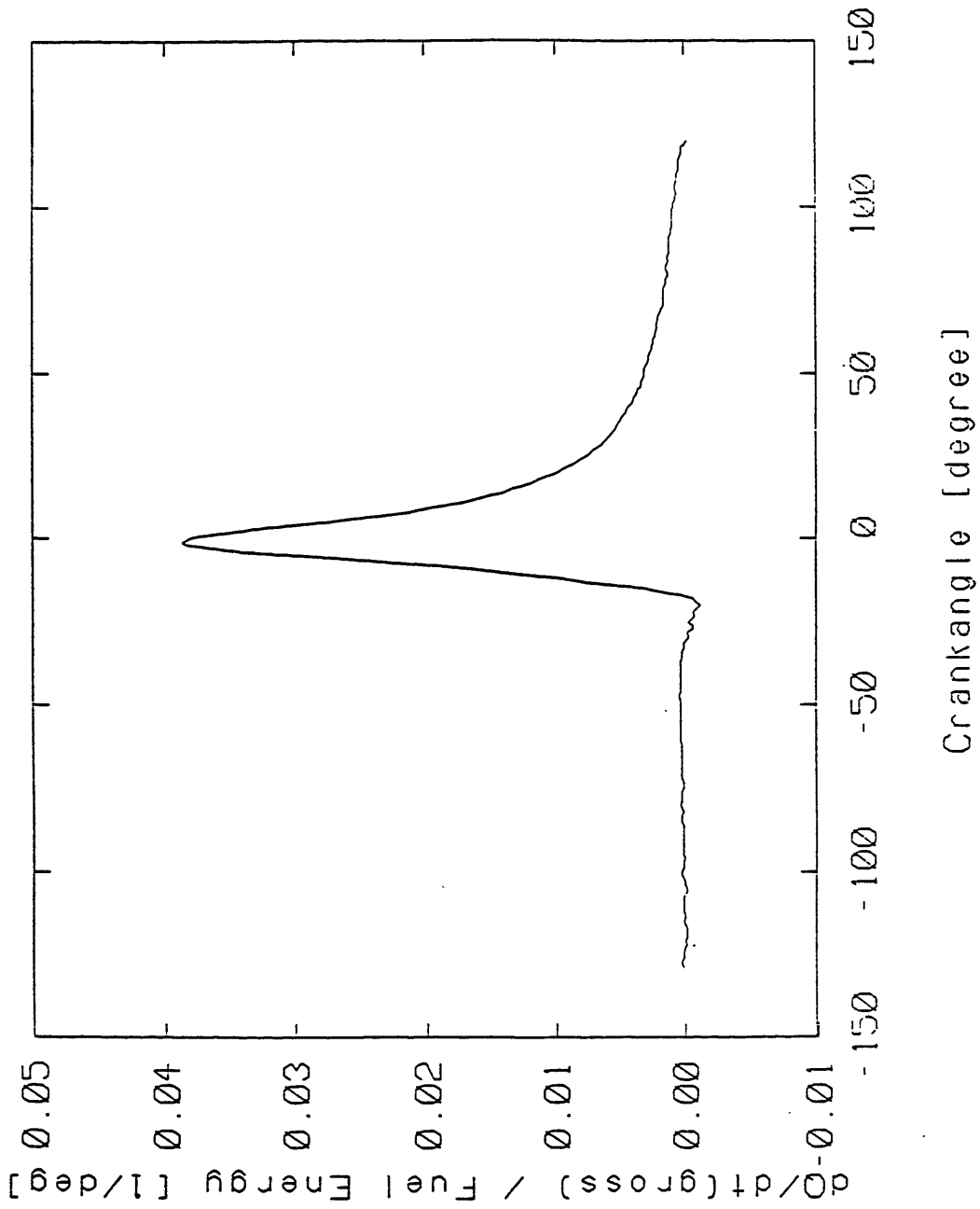


Figure 20. Average normalized heat release rate curve.

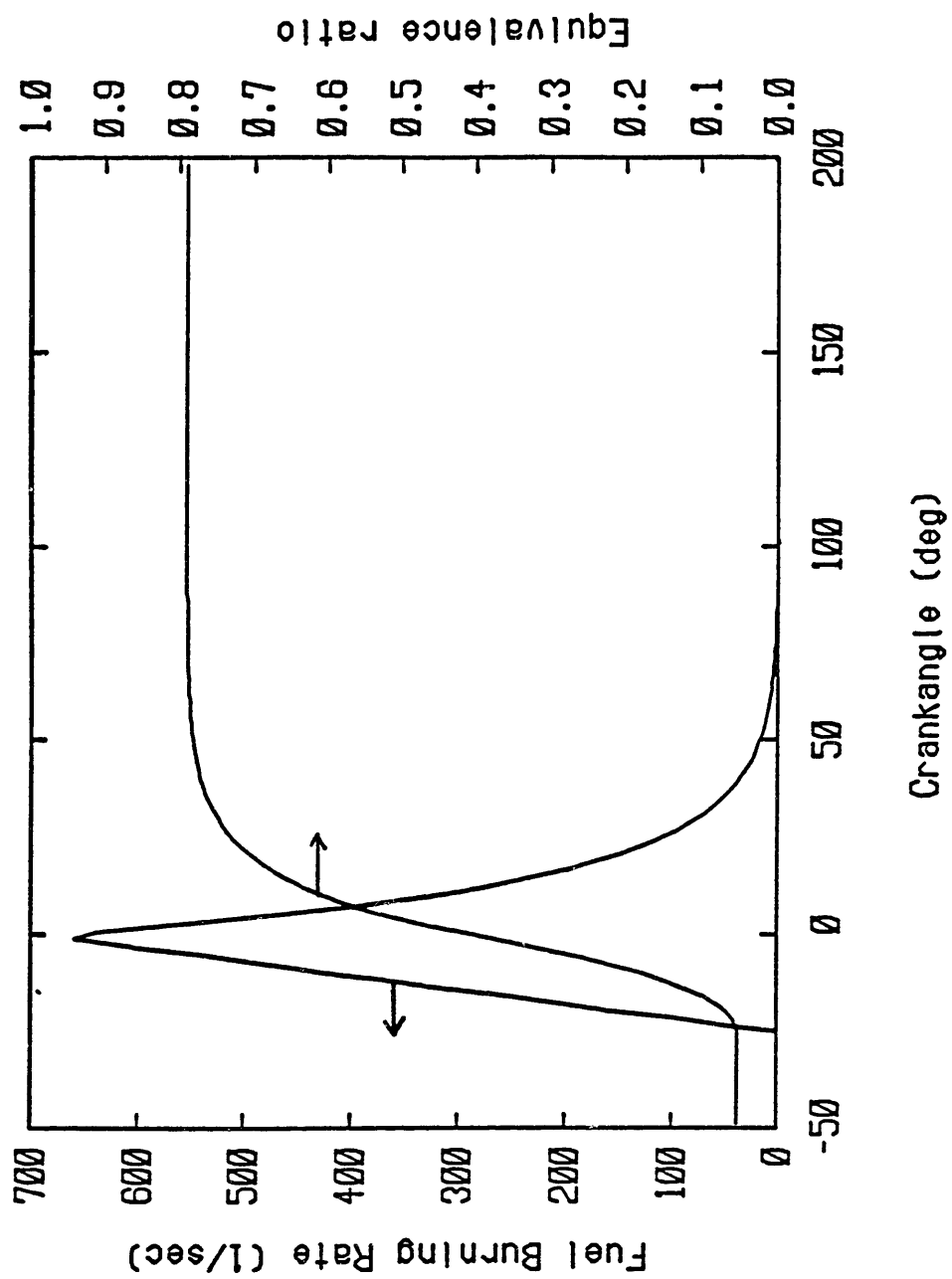


Figure 21. Chamber fuel mass burning rate and instantaneous average overall equivalence ratio.

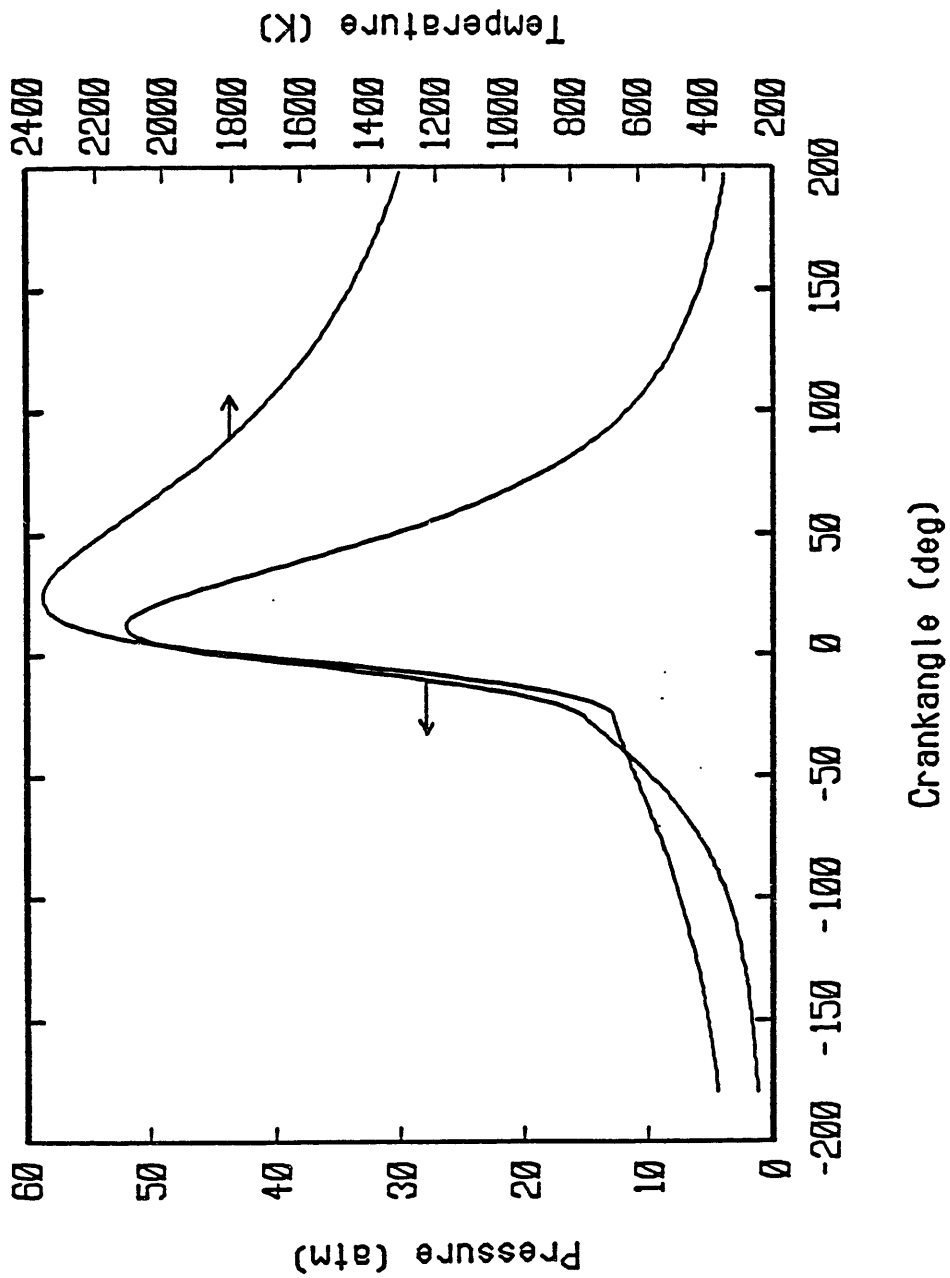


Figure 22. Chamber pressure and temperature for firing run at engine speed of 3000 RPM and equivalence ratio of 0.8 (includes all energy loss mechanisms).

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

by

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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

c Massachusetts Institute of Technology

Volume 2

MASSACHUSETTS INSTITUTE
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BY

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FEBRUARY 1983

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PURPOSE

THE PROGRAM IS A ZERO-DIMENSIONAL SIMULATION OF THE
DIRECT-INJECTION STRATIFIED-CHARGE WANKEL ENGINE OPERATING CYCLE.
THE PROGRAM CALCULATES TEMPERATURE AND PRESSURE IN THE
CHAMBER AND PREDICTS ENGINE PERFORMANCE AS A FUNCTION
OF ENGINE DESIGN AND OPERATING CONDITIONS.

DESCRIPTION OF PARAMETERS:

PARAMETER	INPUT	OUTPUT	DESCRIPTION
-----------	-------	--------	-------------

1 GEOMETRICAL AND DESIGN PARAMETERS

ECCEN	YES	NO	ECCENTRICITY OF ROTOR (CM)
ROTRAD	YES	NO	RADIUS OF ROTOR (CM)
DEPTH	YES	NO	HEIGHT OF CHAMBER (CM)
VFLANK	YES	NO	VOLUME OF ROTOR POCKET (CM**3)
TIPO	YES	NO	INTAKE PORT OPENS (DEG)
TIPC	YES	NO	INTAKE PORT CLOSES (DEG)
TEPO	YES	NO	EXHAUST PORT OPENS (DEG)
TEPC	YES	NO	EXHAUST PORT CLOSES (DEG)
THIPO	YES	NO	INTAKE PORT OPENING TIME (DEG)
THEPO	YES	NO	EXHAUST PORT OPENING TIME (DEG)
IPA	YES	NO	INTAKE PORT OPEN AREA (CM**2)
EPA	YES	NO	EXHAUST PORT OPEN AREA (CM**2)

2 OPERATING PARAMETERS

PATM	YES	NO	ATMOSPHERIC PRESSURE (ATM)
TATM	YES	NO	ATMOSPHERIC TEMPERATURE (K)
PIM	YES	NO	INTAKE PRESSURE (ATM)
PEM	YES	NO	EXHAUST PRESSURE (ATM)
TFRESH	YES	NO	FRESH CHARGE TEMPERATURE (K)
TEGR	YES	NO	EGR TEMPERATURE (K)
EGR	YES	NO	EXHAUST GAS RECIRCULATION (%)
TSPARK	YES	NO	IGNITION TIMING (DEG)
RPM	YES	NO	ENGINE SPEED (RPM)

3 LEAKAGE AND CREVICE VOLUME SUB-MODEL CONSTANTS

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

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

C 5 FUEL AND AIR SPECIFICATIONS

C
C

C	FUELTP	YES	NO	= 1 : ISOCTANE
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
C

C
C

C
C

C
C

C
C

C
C

C
C

C
C

C
C

C
C

C
C

C
C

C
C

C 7 INITIAL GUESSES AT THE START OF INTAKE PROCESS

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
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
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
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
C      REMARKS
C      NONE
C
C
C      SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED:
C
C      1  WORKING SUBROUTINES
C
C          INTAKE      CMPRES      CMBSTN      EXHAUST      CREVIC
C          GINT1       GINT2       GCMP       GEXH
C
C
C
C      2  SPECIAL UTILITY SUBROUTINES
C
C          IPACD       EPACD       CSAVDV      TABLE      BUILD
C
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

```

C
C
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C

METHOD
SEE REPORT

WRITTEN BY S. G. POULOS, S. H. MANSOURI, AND T. J. NORMAN
EDITED BY T. J. NORMAN
EDITED BY J. M. ROBERTS

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-----
C          FIRE   = .TRUE.
C          SPBURN = .TRUE.
C          FUELTP = 1
C          PHISTA = 1.00
C-----
C          ECCEN  = 1.50
C          ROTRAD = 10.5
C          DEPTH  = 7.00
C          VFLANK = 35.00
C          RPM    = 3000.
C-----
C          TIPO   = -530.0
C          TIPC   = -180.0
C          TEPO   = 199.0
C          TEPC   = 588.5
C          TSPARK = - 30.0
C          THIPO  = 120.0
C          THEPO  = 40.0
C          IPA    = 13.8
C          EPA    = 6.5
C-----
C          XBZERO = 0.0003
C          XBSTOP = 0.995
C          TMAX   = 0.0
C          DQDTMAX= 0.04
C-----
C          PATM   = 1.0
C          TATM   = 300.0
C          PIM    = 0.98
C          TFRESH = 300.0
C          TEGR   = 300.0
C          EGR    = 0.0
C          PEM    = 1.02
C-----
C          TROTOR = 370.0
C          TSIDE  = 370.0
C          THOUS  = 370.0
C          CONHT  = 0.0377
C          EXPHT  = 0.8
C-----
C          TPRINT = 10.0
C          TPRINX = 1.0
C-----
C          AREROT = .0002
C          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
C      READ (8,INPUT)
C
C      ESPDI  = 1./(6. * RPM)
C
C
C      TO ALLOW A NORMALIZED OUTPUT INTO DUMMY1 DATA FILE GIVE
C      ZMAST (MASS AT TIP) A VALUE OF UNITY UNTIL INTAKE PORT CLOSES
C
C      ZMAST = 1.
C
C      CALCULATE COMPRESSION RATIO
C
C      PI=3.1415926539
C      ROOT3 = SQRT(3.0)
C      DVOLUM = 3. * ROOT3 * ECCEN * ROTRAD * DEPTH
C      ALEAN  = ASIN( 3.*ECCEN/ROTRAD)
C      FH     = 1.5 * ROOT3 * ECCEN * ROTRAD
C      FC     = 2. * ECCEN * ROTRAD * COS( ALEAN ) +
&      ( 2/9.*ROTRAD*ROTRAD + 4.*ECCEN*ECCEN ) * ALEAN +
&      PI/3. * ECCEN*ECCEN
C      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
C      PSTART = 1.1
C      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)
      AEROT = AREROT
      REROT = 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) )
C      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),CRMASG,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
      I.E. REVERSE FLOW ACROSS INTAKE PORT.
C
      IF (IFLAG .NE. 2) GO TO 50
60 CONTINUE
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
      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 (EXHAUST, 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 (EXHAUST,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

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```

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,

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```

      &                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),

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```

      &          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, D1(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
C
C

NO CONVERGENCE CHECK IS PERFORMED AFTER THE FIRST ITERATION
BECAUSE THE CREVICE AND LEAKAGE MODEL IS NOT YET ACTIVATED

```

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

CAA

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

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882 FORMAT (1H ,2X,'CA = ',F8.2,10X,'P = ',F10.5,28X,'IFG = ',I2)

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C

```

883 FORMAT (1H ,2X,'CA = ',F6.2,10X,'P = ',F10.5,9X,'XB = ',F9.6,

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```

      &          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')//

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      &          ('      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      &      ' _____',
C      &      ' _____',/)
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,'>-----+-----<')/
C      &      (46X,'> _____<')/
C      &      (46X,'>      CALCULATION RESULTS      <')/
C      &      (46X,'> _____<')/
C      &      (46X,'>-----+-----<')///)
C
5920 FORMAT (/(33X,' -->  VOLUMETRIC EFFICIENCY; (%) ')/
C      & (33X,'      BASED ON: INTAKE / ATM      ----> ',2(F8.1))///
C      & (33X,' -->  PUMPING MEAN EFFECTIVE  ')/
C      & (33X,'      PRESSURE; (KPA) : PEMP      ----> ',1F6.0)///
C      & (33X,' -->  GROSS INDICATED MEAN EFFECTIVE ')/
C      & (33X,'      PRESSURE; (KPA) : IMEP      ----> ',1F6.0)///
C      & (33X,' -->  GROSS INDICATED SPECIFIC FUEL ')/
C      & (33X,'      CONSUMPTION; (G/IKW-HR) : ISFC ----> ',1F6.0)///
C      & (33X,' -->  GROSS INDICATED THERMAL      ')/
C      & (33X,'      EFFICIENCY; (%)      ----> ',1F7.1)///
C      & (33X,' -->  NET INDICATED THERMAL      ')/
C      & (33X,'      EFFICIENCY; (%)      ----> ',1F7.1)///
C      & (33X,' -->  (HEAT TRANSFER PER CYCLE)/  ')/
C      & (33X,'      (MASS OF FUEL TIMES LHV); (%) ----> ',1F7.1)///)

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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 ISOCTANE')
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,'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

```

SUBROUTINE INTAKE

PURPOSE

CALCULATES OR ASSISTS THE CREVICE AND HEAT TRANSFER SUBROUTINES
 CALCULATE THE TIME RATE OF CHANGE OF PRESSURE, TEMPERATURE,
 MASS, HEAT TRANSFER, AND WORK TRANSFER IN THE CHAMBER DURING
 INTAKE.

USAGE

CALL INTAKE (DT, DY, DYP)

DESCRIPTION OF PARAMETERS

PARAMETER	INPUT	OUTPUT	DESCRIPTION
DT	YES	NO	TIME (DEG)
DY(1)	NO	NO	MASS INDUCTED INTO CHAMBER THROUGH
-----	--	--	INTAKE PORT (G)
DY(2)	NO	NO	MASS EXHAUSTED FROM CHAMBER THROUGH
-----	--	--	EXHAUST PORT (G)
DY(5)	YES	NO	MASS FRACTION OF FRESH CHARGE (-)
DY(8)	NO	NO	HEAT TRANSFER TO ROTOR (KJ)
DY(9)	NO	NO	HEAT TRANSFER TO SIDE PLATES (KJ)
DY(10)	NO	NO	HEAT TRANSFER TO HOUSING (KJ)
DY(11)	YES	NO	CHAMBER TEMPERATURE (K)
DY(12)	YES	NO	CHAMBER PRESSURE (ATM)
DY(16)	NO	NO	TOTAL WORK TRANSFER (KJ)
DY(17)	NO	NO	TOTAL ENTHALPY EXHAUSTED (KJ)
DY(18)	NO	NO	TOTAL MASS LEAKED PAST LEAD
-----	--	--	APEX SEAL (G)
DY(19)	NO	NO	TOTAL MASS LEAKED PAST TRAILING
-----	--	--	APEX SEAL (G)
DY(20)	NO	NO	TOTAL HEAT LOSS TO CREVICE VOLUME
-----	--	--	WALLS (KJ)
DY(21)	NO	NO	MASS FRACTION OF FRESH CHARGE
-----	--	--	IN LEAD CREVICE (-)
DY(22)	NO	NO	MASS FRACTION OF FRESH CHARGE
-----	--	--	IN TRAILING CREVICE (-)
DY(23)	YES	NO	TOTAL MASS IN CHAMBER (G)
DY(24)	NO	NO	TOTAL MASS THAT HAS LEFT AND ENTERED
-----	--	--	LEADING CHAMBER OR CREVICE (G)
DY(25)	NO	NO	TOTAL MASS THAT HAS LEFT AND ENTERED
-----	--	--	TRAILING CHAMBER OR CREVICE (G)
DY(26)	YES	NO	CHAMBER FUEL FRACTION
DY(27)	YES	NO	INLET MANIFOLD FUEL FRACTION
DY(28)	YES	NO	EXHAUST MANIFOLD FUEL FRACTION
DY(29)	YES	NO	LEADING CREVICE FUEL MASS FRACTION
DY(30)	YES	NO	TRAILING CREVICE FUEL MASS FRACTION

DYP(1)	NO	YES	RATE AT WHICH MASS IS INDUCTED
-----	--	---	THROUGH THE INTAKE PORT (G/DEG)
DYP(2)	NO	YES	RATE AT WHICH MASS IS EXHAUSTED

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

REMARKS

NONE

SUBROUTINE AND FUNCTION SUBPROGRAMS REQUIRED

THERMO	IPACD	MFLRT	HEATTX
CSAVDV	EPACD	CREVIC	

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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
C      SUBROUTINE INTAKE (DT, DY, DYP)
C
C      REAL*8 DT, DY(30), DYP(30)
C      REAL MW, MWIM, MWIMM, MASS, MSTART,
C      &      MAXERR, IPA, MFUEL
C      DIMENSION Y(30), YP(30)
C      COMMON/EPARAM/ ECCEN, ROTRAD, DEPTH, VFLANK
C      COMMON/TEMPS/TROTOR,TSIDE,THOUS
C      COMMON/DTDTH/ ESPDI, RPM
C      COMMON/MANFP/ PIM, TIM, EGR, PEM, MSTART
C      COMMON/TIMES/ TIPO, TIPC, TEPO, TEPC, THIPO, THEPO, TSPARK
C      COMMON/IMTHP/ HIM, MWIM, GIM, RHOIM
C      COMMON/FIXX/ INFLAG
C      COMMON/HEATS/VELHTX, HTRCOE, HTPARO, HTPASI, HTPAHO, HTXRO,
C      &      HTXSI, HTXHO, QFRRO, QFRSI, QFRHO
C      COMMON/HTRAN/THTRAN
C      COMMON/YYYY1/ VIP, VEP
C      COMMON/RHMAS/ RHO, MASS, VOLUME, H, GAMMA
C      COMMON/CREV/DRHODP,CSUBT,MW,ITERAS,DVDT,CSUBP,DRHODT,HIMM,RESIDL,
C      &      RESFIM,CSUBF,DRHODF
C      COMMON/BURN/SPBURN,FIRE,FIREFL
C      COMMON/DUMMY/ADUMY,BDUMY,CDUMY
C      COMMON/FLOW/FMIN,MFUEL
C
C      VIP = 0.0
C      VEP = 0.0
C
C      DO 10 I = 1, 30
C          Y(I) = DY(I)
C 10 CONTINUE
C      T = DT
C      DO 20 I = 1, 30
C          YP(I) = 0.0
C 20 CONTINUE
C
C      FIND THERMODYNAMIC AND TRANSPORT PROPERTIES IN CHAMBER
C
C      RESFRK = 1. - Y(5)
C      FR = Y(26)
C      CALL THERMO (T, Y(11), Y(12), FR, H, CSUBP, CSUBT, CSUBF,
C      &      RHO, DRHODT, DRHODP, DRHODF, GAMMA, MW,
C      &      ADUMY, BDUMY, CDUMY, HDUMY)
C      MASS = Y(23)
C
C      FIND OUT IF INTAKE PORT IS OPEN.
C
C

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      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

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C      IS EXHAUST PORT STILL OPEN ?
C
50 IF ((T + 1080.) .GE. TEP) GO TO 80
C
C      YES IT IS.
C      ANY FLOW ACROSS IT ?
C
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.
CT      TEP = T + 1080.
CT
CT      CALL EPACD (TEP, AREA, CD)
C
C      FIND MASS FLOW RATE.
C
C      CALL MFLRT (CD, AREA, PEM, MW, Y(11), Y(12), GAMMA, FRAEV)
C
C      CALCULATE RATES DUE TO THIS FLOW.
C
C      YP(2) = -FRAEV
C      YP(26) = YP(26) + ( Y(28) - Y(26)) * FRAEV/MASS
C      IF (AREA .LE. 0.0) GO TO 80
C      VEP = -FRAEV/(RHO * AREA)*1000.
C      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
C      TEP = T + 1080.
C      CALL EPACD (TEP, AREA, CD)
C
C      FIND MASS FLOW RATE.
C
C      CALL MFLRT (CD, AREA, Y(12), MW, Y(11), PEM, GAMMA, FRAEV)
C
C      CALCULATE RATES DUE TO THIS FLOW.
C
C      YP(2) = FRAEV
C      IF (AREA .LE. 0.0) GO TO 75
C      VEP = FRAEV/(RHO * AREA)*1000.
75 CONTINUE
C

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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
C      CALL HEATTX (T,Y,YP,THTRAN)
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

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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

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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

REMARKS

NONE

SUBROUTINE AND FUNCTION SUBPROGRAMS REQUIRED

THERMO CSAVDV CREVIC HEATTX

METHOD

SEE REPORT

WRITTEN BY S. H. MANSOURI, S. G. POULOS, AND T. J. NORMAN

EDITED BY T. J. NORMAN

SUBROUTINE CMPRES (DT,DY,DYP)

```

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

```

```

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
C

```

      FIND THERMODYNAMIC AND TRANSPORT PROPERTIES IN CHAMBER

      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
C

```

      FIND SURFACE AREAS AND VOLUME OF CHAMBER

      CALL CSAVDV (T, VOLUME, DVDT)

```

C
C
C
C

```

      CALCULATE HEAT TRANSFER RATES

```

C
C
C

```

      CALL HEATTX (T,Y,YP,THTRAN)

```

C
C
C
C

```

      CALCULATE RATES OF CHANGE OF TEMPERATURE AND PRESSURE IN
      THE CHAMBER. THEN CALCULATE RATE OF DOING WORK.

```

```

30 CALL CREVIC (T,Y,YP)
      YP(16) = Y(12) * DVDT * .101325E-3

```

C
C
C

```

      CONVERT THE HEAT TRANSFER RATES TO KILO JOULES

```

```

      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
C
C

```

      CONVERT ALL TIME DERIVATIVES TO RATE PER CRANK
      ANGLE DEGREE.

```

```
      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
```

SUBROUTINE CMBSTN

PURPOSE

CALCULATES OR ASSISTS THE CREVICE AND HEAT TRANSFER SUBROUTINES
 CALCULATE THE TIME RATE OF CHANGE OF PRESSURE, TEMPERATURE,
 MASS, HEAT TRANSFER, AND WORK TRANSFER IN THE CHAMBER DURING
 COMBUSTION.

USAGE

CALL CMBSTN (DT, DY, DYP)

DESCRIPTION OF PARAMETERS

PARAMETER	INPUT	OUTPUT	DESCRIPTION
DT	YES	NO	TIME (DEG)
DY(3)	NO	NO	FUEL ENERGY THAT ENTERS EXHAUST CHAMBER (KJ)
-----	--	--	
DY(4)	YES	NO	MASS FRACTION BURNED (-)
DY(8)	NO	NO	HEAT TRANSFER TO ROTOR (KJ)
DY(9)	NO	NO	HEAT TRANSFER TO SIDE PLATES (KJ)
DY(10)	NO	NO	HEAT TRANSFER TO HOUSING (KJ)
DY(12)	YES	NO	CYLINDER PRESSURE (ATM)
DY(16)	NO	NO	TOTAL WORK TRANSFER (KJ)
DY(18)	NO	NO	TOTAL MASS LEAKED PAST LEAD APEX SEAL (G)
-----	--	--	
DY(19)	NO	NO	TOTAL MASS LEAKED PAST TRAILING APEX SEAL (G)
-----	--	--	
DY(20)	NO	NO	TOTAL HEAT LOSS TO CREVICE VOLUME WALLS (KJ)
-----	--	--	
DY(21)	NO	NO	MASS FRACTION OF FRESH CHARGE IN LEAD CREVICE (-)
-----	--	--	
DY(22)	NO	NO	MASS FRACTION OF FRESH CHARGE IN TRAILING CREVICE (-)
-----	--	--	
DY(23)	YES	NO	TOTAL MASS IN CHAMBER (G)
DY(24)	NO	NO	TOTAL MASS THAT HAS LEFT AND ENTERED LEADING CHAMBER OR CREVICE (G)
-----	--	--	
DY(25)	NO	NO	TOTAL MASS THAT HAS LEFT AND ENTERED TRAILING CHAMBER OR CREVICE (G)
-----	--	--	
DY(26)	YES	NO	CHAMBER FUEL FRACTION
DY(29)	YES	NO	LEADING CREVICE FUEL MASS FRACTION
DY(30)	YES	NO	TRAILING CREVICE FUEL MASS FRACTION

DYP(3)	NO	YES	RATE OF FUEL ENTERING EXHAUST CHAMBER.
-----	--	---	
DYP(4)	NO	YES	RATE OF CHANGE OF MASS FRACTION BURNED (1/DEG)
-----	--	---	
DYP(8)	NO	YES	RATE OF HEAT TRANSFER THROUGH ROTOR WALL (KJ/DEG)
-----	--	---	
DYP(9)	NO	YES	RATE OF HEAT TRANSFER THROUGH SIDE PLATES (KJ/DEG)
-----	--	---	
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

REMARKS

NONE

SUBROUTINE AND FUNCTION SUBPROGRAMS REQUIRED

THERMO CSAVDV CREVIC HEATTX

METHOD

SEE REPORT

WRITTEN BY S. H. MANSOURI, K. RADHAKRISHNAN, S. G. POULOS, AND

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SUBROUTINE CMBSTN (DT,DY,DYP)

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
      CALCULATE RATES OF CHANGE OF TEMPERATURE AND PRESSURE IN
      THE CYLINDER. THEN CALCULATE RATE OF DOING WORK.
C
      CALL CREVIC (T,Y,YP)
C
      YP(16) = Y(12) * DVDT * .101325E-3
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
      CONVERT ALL TIME DERIVATIVES TO RATE PER CRANK
      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

```

SUBROUTINE EXAUST

PURPOSE

CALCULATES OR ASSISTS THE CREVICE AND HEAT TRANSFER SUBROUTINES
 CALCULATE THE TIME RATE OF CHANGE OF PRESSURE, TEMPERATURE,
 MASS, HEAT TRANSFER, AND WORK TRANSFER IN THE CHAMBER DURING
 EXAUST.

USAGE

CALL EXAUST (DT, DY, DYP)

DESCRIPTION OF PARAMETERS

PARAMETER	INPUT	OUTPUT	DESCRIPTION
DT	YES	NO	TIME (DEG)
DY(2)	NO	NO	MASS EXHAUSTED FROM CHAMBER THROUGH EXHAUST PORT (G)
-----	---	---	
DY(3)	NO	NO	FUEL ENERGY THAT ENTERS EXHAUST (KJ)
DY(8)	NO	NO	HEAT TRANSFER TO ROTOR (KJ)
DY(9)	NO	NO	HEAT TRANSFER TO SIDE PLATES (KJ)
DY(10)	NO	NO	HEAT TRANSFER TO HOUSING (KJ)
DY(11)	YES	NO	CHAMBER TEMPERATURE (K)
DY(12)	YES	NO	CHAMBER PRESSURE (ATM)
DY(16)	NO	NO	TOTAL WORK TRANSFER (KJ)
DY(17)	NO	NO	TOTAL ENTHALPY EXHAUSTED (KJ)
DY(18)	NO	NO	TOTAL MASS LEAKED PAST LEAD APEX SEAL (G)
-----	---	---	
DY(19)	NO	NO	TOTAL MASS LEAKED PAST TRAILING APEX SEAL (G)
-----	---	---	
DY(20)	NO	NO	TOTAL HEAT LOSS TO CREVICE VOLUME WALLS (KJ)
-----	---	---	
DY(21)	NO	NO	MASS FRACTION OF FRESH CHARGE IN LEAD CREVICE (-)
-----	---	---	
DY(22)	NO	NO	MASS FRACTION OF FRESH CHARGE IN TRAILING CREVICE (-)
-----	---	---	
DY(23)	YES	NO	TOTAL MASS IN CHAMBER (G)
DY(24)	NO	NO	TOTAL MASS THAT HAS LEFT AND ENTERED LEADING CHAMBER OR CREVICE (G)
-----	---	---	
DY(25)	NO	NO	TOTAL MASS THAT HAS LEFT AND ENTERED TRAILING CHAMBER OR CREVICE (G)
-----	---	---	
DY(26)	YES	NO	CHAMBER FUEL MASS FRACTION
DY(28)	YES	NO	EXHAUST MANIFOLD FUEL MASS FRACTION
DY(29)	YES	NO	LEADING CREVICE FUEL MASS FRACTION
DY(30)	YES	NO	TRAILING CREVICE FUEL MASS FRACTION
-----	---	---	
DYP(2)	NO	YES	RATE AT WHICH MASS IS EXHAUSTED THROUGH THE EXHAUST PORT (G/DEG)
-----	---	---	
DYP(3)	NO	YES	RATE OF FUEL ENERGY ENTERING EXHAUST CHAMBER (KJ/DEG)
-----	---	---	
DYP(8)	NO	YES	RATE OF HEAT TRANSFER THROUGH 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 (/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

REMARKS

NONE

SUBROUTINE AND FUNCTION SUBPROGRAMS REQUIRED

THERMO	MFLRT	CREVIC
CSAVDV	EPACD	HEATTX

METHOD

SEE REPORT

WRITTEN BY S. H. MANSOURI, S. G. POULOS, AND T. J. NORMAN

EDITED BY T. J. NORMAN

EDITED BY J. M. ROBERTS

SUBROUTINE EXAUST (DT, DY, DYP)

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

C

```

    FIND THERMODYNAMIC AND TRANSPORT PROPERTIES IN CHAMBER

```

```

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

C

```

    IS EXHAUST PORT STILL OPEN ?

```

C

C

C

C

```

IF (T .GE. TEPC) GO TO 50

```

```

    YES IT IS.

```

```

    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
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

```

```
      YP(10) = YP(10) * 1.E-10
      THTRAN = THTRAN * 1.E-10 * ESPDI
C
      YP(17) = YP(2) * H/1.E+6
C
      CONVERT ALL TIME DERIVATIVES TO RATE PER CRANK
      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
```

SUBROUTINE CREVIC

PURPOSE

TO CALCULATE THE LEAKAGE AND CREVICE VOLUME MASS FLOW RATES AND COMPOSITIONS. BECAUSE AN ASSUMPTION FOR NET FLOW DIRECTION AT EACH APEX MUST BE MADE, AND THEN CHECKED, SEVERAL OF THE INTEGRATION VARIABLES ARE EVALUATED IN THIS SUBROUTINE RATHER THAN THE PROCESS SUBROUTINES.

USAGE

CALL CREVIC (T,Y,YP)

DESCRIPTION OF PARAMETERS

PARAMETER	INPUT	OUTPUT	DESCRIPTION
DT	YES	NO	TIME (DEG)
DY(3)	NO	NO	FUEL ENERGY THAT ENTERS EXHAUST CHAMBER (KJ)
-----	--	--	
DY(4)	NO	NO	MASS FRACTION BURNED (-)
DY(5)	YES	NO	MASS FRACTION OF FRESH CHARGE (-)
DY(11)	YES	NO	CHAMBER TEMPERATURE (K)
DY(12)	YES	NO	CHAMBER PRESSURE (ATM)
DY(18)	NO	NO	TOTAL MASS LEAKED PAST LEAD APEX SEAL (G)
-----	--	--	
DY(19)	NO	NO	TOTAL MASS LEAKED PAST TRAILING APEX SEAL (G)
-----	--	--	
DY(20)	NO	NO	TOTAL HEAT LOSS TO CREVICE VOLUME WALLS (KJ)
-----	--	--	
DY(21)	YES	NO	MASS FRACTION OF FRESH CHARGE IN LEAD CREVICE (-)
-----	---	---	
DY(22)	YES	NO	MASS FRACTION OF FRESH CHARGE IN TRAILING CREVICE (-)
-----	---	---	
DY(23)	YES	NO	TOTAL MASS IN CHAMBER (G)
DY(24)	NO	NO	TOTAL MASS IN LEADING CREVICE (G)
DY(25)	NO	NO	TOTAL MASS IN TRAILING CREVICE (G)
DY(26)	YES	NO	CHAMBER FUEL MASS FRACTION
DY(29)	YES	NO	LEADING CREVICE FUEL MASS FRACTION
DY(30)	YES	NO	TRAILING CREVICE FUEL MASS FRACTION
-----	-----	-----	-----
DYP(1)	YES	NO	RATE AT WHICH MASS IS INDUCTED THROUGH THE INTAKE PORT
-----	--	--	
DYP(2)	YES	NO	RATE AT WHICH MASS IS EXHAUSTED THROUGH THE EXHAUST PORT
-----	--	--	
DYP(3)	NO	YES	RATE OF FUEL ENTERING EXHAUST CHAMBER.
-----	--	---	
DYP(4)	YES	NO	RATE OF CHANGE OF MASS FRACTION BURNED
-----	--	---	
DYP(5)	NO	YES	RATE OF CHANGE OF MASS FRACTION OF FRESH CHARGE IN CHAMBER
-----	--	---	
DYP(11)	NO	YES	RATE OF CHANGE OF CHAMBER TEMPERATURE
-----	--	---	
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

REMARKS

- LEAD CHAMBER REFERS TO THE CHAMBER AHEAD (IN THE DIRECTION OF ROTATION) OF THE THERMODYNAMIC SYSTEM.
- LAG (OR TRAILING) CHAMBER REFERS TO THE CHAMBER BEHIND.
- REFER TO PROCESS ROUTINES FOR UNITS OF INTEGRATION VARIABLES.

SUBROUTINE AND FUNCTION SUBPROGRAMS REQUIRED

THERMO	MFLRT	TABLE
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METHOD

SEE REPORT

WRITTEN BY T. J. NORMAN

SUBROUTINE CREVIC(T,Y,YP)

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
 C
 C

DETERMINE THE PRESSURE DIFFERENCE ACROSS EACH APEX SEAL

C
 C
 C
 C
 C
 C
 C

IF (PLEAD .GE. Y(12)) GO TO 40

THE CHAMBER HAS A HIGHER PRESSURE THAN THE LEAD CHAMBER
 SO THE LEAD CREVICE IS ASSOCIATED WITH THE CHAMBER AND
 LEAKAGE FLOWS FROM THE LEAD CREVICE TO THE LEAD CHAMBER.

C
 C
 C
 C
 C
 C
 C

PLEADC = Y(12)

C
 C
 C
 C
 C
 C
 C

THERE IS A LEADING CREVICE VOLUME AND IT IS ATTACHED TO THE
 CHAMBER OF INTEREST. SINCE THE CREVICE VOLUME MASS IS NOT
 FELT UNTIL THE SUBSEQUENT CALL TO ODERT, CHECK TO SEE IF A
 MASS HAS YET BEEN CALCULATED. I.E. IS THIS THE SWITCHOVER POINT?

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
 C

OBTAIN THE THERMODYNAMIC STATE OF THE CREVICE VOLUME

C
 C
 C
 C

CALL THERMO(T,TCR,PLEADC,FRLDCR,HLEADC,XXA,XXB,XXC,
 & RHOLDC,XXD,XXE,XXF,GAMLDC,MWLDC,XXG,
 & XXH,XXI,XXJ)

C
 C

MASLDC = RHOLDC*VOLLLDC/1.E+3

C
 C
 C
 C

WHAT ABOUT LEAKAGE?

```

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,GAMLG, MWLGC,XXH,XXI,
&                XXJ,XXK)
C
C WHAT ABOUT LEAKAGE?
C
      CALL MFLRT(1.0,AREA,PLAGC,MWLGC,TCR,Y(12),GAMLG, LGLEAK)
      LGLEAK = -LGLGCR
      IF(AREALK.LE.0.0) LGLGCR=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
C
C

```

```

120 Y(12) = Y(12) * 1.01325E+5

```

```

      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
C
C

```

```

      NOTE FACTOR OF 1000.

```

```

      CALCULATE PHIDOT FOR USE IN YP(11) AND YP(12) EQUATIONS

```

```

      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

```

```

C

```

```

C

```

```

C

```

```

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) = (FRLD - 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
      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 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 USAGE

C CALL TABLE (T,Y,PLEAD,PLAG,X1LD,X1LG,FRLD,FRLG)

C DESCRIPTION OF PARAMETERS

PARAMETER	INPUT	OUTPUT	DESCRIPTION
DT	YES	NO	TIME (DEG)
PLEAD	NO	YES	LEADING CHAMBER PRESSURE (ATM)
PLAG	NO	YES	TRAILING CHAMBER PRESSURE (ATM)
X1LD	NO	YES	LEAD CREVICE COMPOSITION ()
X1LG	NO	YES	LAG CREVICE COMPOSITION ()
FRLD	NO	YES	LEAD CREVICE FUEL FRACTION COMP.
FRLG	NO	YES	LAG CREVICE FUEL FRACTION COMP.

C REMARKS

C NONE

C METHOD

C SEE REPORT

C WRITTEN BY T. J. NORMAN

C EDITED BY J. M. ROBERTS

C SUBROUTINE TABLE (T,Y,PLEAD,PLAG,X1LD,X1LG,FRLD,FRLG)

C LOGICAL FIREFL, FIRE

C DIMENSION Y(30)

C COMMON/TABLES/ PRES(0:1080), X1(0:1080), FUELFR(0:1080)

C COMMON/TIMES/ TIPO, TIPC, TEPO, TEPC, THIPO, THEPO, TSPARK

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 ABST = T + ABS(TIPO)

C TLEAD = ABST + 360.

C IF (TLEAD .GE. 1080.) TLEAD = TLEAD - 1080.

C TLAG = ABST - 360.

C IF (TLAG .LT. 0.0) TLAG = TLAG + 1080.

C ITLEAD = INT(TLEAD)

C 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      METHOD
C          SEE REPORT
C
C      WRITTEN BY T. J. NORMAN
C      EDITED BY J. M. ROBERTS
C
C      SUBROUTINE BUILD (DT,DY)
C
C      LOGICAL FIREFL, FIRE
C      REAL*8 DT,DY(30)
C      DIMENSION Y(30)
C      COMMON/TABLES/ PRES(0:1080), X1(0:1080), FUELFR(0:1080)
C      COMMON/TIMES/ TIPO, TIPC, TEPO, TEPC, THIPO, THEPO, TSPARK
C      COMMON/BURN/SPBURN,FIRE,FIREFL
C
C      T = DT
C      DO 10 I = 1,30
C          Y(I) = DY(I)
C 10 CONTINUE
C      ABST = T + ABS(TIPO)
C      IABST = INT(ABST)
C      IF ( IABST .NE. ABST ) GO TO 30
C      PRES(IABST) = Y(12)
C      X1(IABST) = Y(5)
C      IF( FIREFL ) X1(IABST) = 1. - Y(4)
C      FUELFR(IABST) = Y(26)
C
C 30 RETURN
C      END

```

C SUBROUTINE IPACD

C

C

PURPOSE

C

C

CALCULATES AREA AND DISCHARGE COEFFICIENT
OF THE INTAKE PORTS.

C

C

USAGE

C

C

CALL IPACD (T, AREA, CD)

C

C

DESCRIPTION OF PARAMETERS

C

C

PARAMETER	INPUT	OUTPUT	DESCRIPTION
T	YES	NO	TIME (DEG)
AREA	NO	YES	EFFECTIVE AREA OF INTAKE
----	--	---	PORT (CM**2)
CD	NO	YES	DISCHARGE COEFFICIENT

C

C

C

C

C

C

C

REMARKS

C

C

THIPO = NUMBER OF CRANK ANGLES REQUIRED TO FULLY OPEN
OR CLOSE THE PORT.

C

C

C

C

C

C

C

C

C

SUBROUTINE AND FUNCTION SUBPROGRAMS REQUIRED

C

C

NONE

C

C

METHOD

C

C

SEE REPORT

C

C

WRITTEN BY T. J. NORMAN

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

CJ

CJ

CJ

CJ

CJ

CJ

!!
THIS ROUTINE HAS BEEN CHANGED SUBSTANTIALY IN ORDER TO MODEL
THE ENLARGED INTAKE PORT INSTALLED IN THE NASA TEST ENGINE.
ANY CHANGES WHATSOEVER TO THE PORT CONFIGURATION MUST BE
REFLECTED IN THIS ROUTINE

!!
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.))-0.000073)
   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
C   IF (AREA .EQ. 0.0) AREA=1.E-6
C
C   RETURN
C   END

```

C SUBROUTINE EPACD

C PURPOSE

C CALCULATES AREA AND DISCHARGE COEFFICIENT
C OF EXHAUST VALVE

C USAGE

C CALL EPACD (T, AREA, CD)

C DESCRIPTION OF PARAMETERS

PARAMETER	INPUT	OUTPUT	DESCRIPTION
T	YES	NO	TIME (DEG)
AREA	NO	YES	EFFECTIVE AREA OF EXHAUST
----	--	---	PORT (CM**2)
CD	NO	YES	DISCHARGE COEFFICIENT

C REMARKS

C THEVO = NUMBER OF CRANK ANGLES REQUIRED TO OPEN OR CLOSE
C THE EXHAUST PORT

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 METHOD

C SEE REPORT

C WRITTEN BY T. J. NORMAN

C EDITED BY T. J. NORMAN

C SUBROUTINE EPACD (T, AREA, CD)

C REAL IPA

C COMMON/TIMES/ TIPO, TIPC, TEPO, TEPC, THIPO, THEPO, TSPARK

C COMMON/PORTS/ IPA, EPA

C IF (T .GT. (TEPO + THEPO)) GO TO 20

C AREA = EPA *(T - TEPO)/THEPO

C GO TO 40

20 IF (T .LT. (TEPC - THEPO)) GO TO 30

C AREA = EPA *(TEPC - T)/THEPO

C GO TO 40

30 AREA = EPA

40 CD = 0.65

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

C 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      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
C      LOGICAL FIRE, FIREFL
C      REAL MW, MASS, KINVIS
C      DIMENSION Y(30),YP(30)
C
C      COMMON/HEATXG/AROTR,ASIDE,AHOUS,ROTVEL,DCHAR
C      COMMON/BURN/SPBURN,FIRE,FIREFL
C      COMMON/TIMES/ TIPO, TIPC, TEPO, TEPC, THIPO, THEPO, TSPARK
C      COMMON/CREV/DRHODP,CSUBT,MW,ITERAS,DVDT,CSUBP,DRHODT,HIMM,
C      &          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
      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
      UNITS OF HTRCOE ARE ERG/CM**2 SEC K
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
      FIND THE TOTAL HEAT TRANSFER FROM THE CHAMBER

```

```
C      THTRAN = HTXRO + HTXSI + HTXHO
C
C          IF (ABS(THTRAN) .LE. .0002) GO TO 40
C          QFRRO = 100.* HTXRO/THTRAN
C          QFRSI = 100.* HTXSI/THTRAN
C          QFRHO = 100.* HTXHO/THTRAN
C
C      GO TO 40
C
C
C      40 CONTINUE
C
CJ      QTOTAL = THTRAN
C      RETURN
C      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
C      SUBROUTINE MFLRT (CD, AREA, PO, MW, TO, PS, GAMMA, FLRT)
C
C      REAL MW
C
C      FLRT = 0.0
C      IF (PO .EQ. PS) GO TO 20
C      GI   = 1.0/GAMMA
C      SUM  = GAMMA * MW/TO
C      CONST = 111.12272 * CD * AREA * PO * SQRT(SUM)
C
C      RATIO = PS/PO
C      CRIT  = ( 2./ (GAMMA + 1.) )**( GAMMA/(GAMMA - 1.) )
C
C          CHECK IF FLOW IS CHOKED
C
C      IF (RATIO .LT. CRIT) GO TO 10
C
C          SUBSONIC FLOW

```

```
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
C      SUBROUTINE CSAVDV (T, VOLUME, DVDT)
C      COMMON/EPARAM/ ECCEN, ROTRAD, DEPTH, VFLANK
C      COMMON/DTDTH/ ESPDI, RPM
C      COMMON/HEATXG/AROTOR, ASIDE, AHOUS, ROTVEL, DCHAR
C
C      PI=3.1415926
C      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
C      THETA =(T+90.) * PI/180.
C      ALPHA = THETA/3.
C      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
      FUNCTION GINT2 (DT, DY, DYP)
      REAL*8 DT,DY(30),DYP(30),GINT2

```

```

C
      GINT2 = DY(1)

```

```

C
      RETURN
      END

```

```

C
      FUNCTION GCMP (DT, DY, DYP)
      REAL*8 DT,DY(30),DYP(30),GCMP

```

```

C
      GCMP = 10.0

```

```

C
      RETURN
      END

```

```

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 'EXHAUST',
 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

PARAMETER	INPUT	OUTPUT	DESCRIPTION
DT	YES	NO	CURRENT TIME (DEG)
DY	YES	NO	CURRENT SOLUTION VECTOR
IWHERE	YES	NO	1 = INTAKE; 2 = CMPRES;
-----	---	--	3 = CMBSTN; 4 = EXHAUST
XXX	NO	NO	DUMMY VARIABLE

C

C REMARKS

C NONE

C

C SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED

C INTAKE CMPRES CMBSTN EXHAUST

C

C METHOD

C SEE PURPOSE, ABOVE

C

C WRITTEN BY S. G. POULOS

C EDITED BY S. G. POULOS

C

C SUBROUTINE HELPHT (DT, DY, IWHERE)

C REAL*8 DT, DY(30), XXX(30)

C

C IF (IWHERE.EQ.1) CALL INTAKE (DT, DY, XXX)

C IF (IWHERE.EQ.2) CALL CMPRES (DT, DY, XXX)

C IF (IWHERE.EQ.3) CALL CMBSTN (DT, DY, XXX)

C IF (IWHERE.EQ.4) CALL EXHAUST (DT, DY, XXX)

C

C RETURN

C 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
C      SUBROUTINE BTRANS (TEMP, GAMMA, CP, DYNVIS, THRCON)
C
C      COMMON/FUEL/ FUELTP, ENW, CX, HY, OZ, DEL, PSI, PHICON, PHI,
C      &          QLOWER, FASTO, HFORM
C
C      DYNVIS = 3.3E-6 * (TEMP**.7)/(1.0 + .027 * PHI)
C      PRNDTL = 0.05 + 4.2 * (GAMMA - 1.0) - 6.7 * (GAMMA - 1.0) *
C      &          (GAMMA - 1.0)
C      THRCON = DYNVIS * CP*1.E+4/PRNDTL
C      IF ((PHI .LE. 1.0) .OR. (TEMP .LE. 1500.)) RETURN
C      PRNDTL = PRNDTL/(1.0 + 1.5E-8 * PHI * PHI * TEMP * TEMP)
C      THRCON = DYNVIS * CP*1.E+4/PRNDTL
C
C      RETURN
C      END

```

SUBROUTINE THERMO

PURPOSE

'THERMO' IS CALLED BY THE THE 4 PROCESS ROUTINES AND BY 'MAIN' AND RETURNS WITH THE REQUIRED THERMODYNAMIC PROPERTIES IN EACH CASE. IT CALLS 'UPROP' AND OR 'BPROP' AS REQUIRED FOR EACH PROCESS, AND THEN CALCULATES FROM THE RETURNED DATA ANY ADDITIONAL PROPERTIES OR COMBINATIONS OF PROPERTIES OF INTEREST. 'THERMO' ALSO CONVERTS ALL VALUES TO UNITS THAT ARE CONSISTENT WITH THOSE USED IN THE REST OF THE PROGRAM.

USAGE

CALL THERMO (T, TEMP, P, FR, ENTHLP,
 CSUBP, CSUBT, CSUBF,
 RHO, DRHODT, DRHODP, DRHODF,
 GAMMA, MW, EDUMY, FDUMY, GDUMY, HDUMY)

DESCRIPTION OF PARAMETERS

PARAMETER	INPUT	OUTPUT	DESCRIPTION
T	YES	NO	CRANK ANGLE (DEG)
TEMP	YES	NO	TEMPERATURE (K)
P	YES	NO	PRESSURE (ATM)
-----	---	--	(=1. FOR BURNED ZONE)
FR	YES	NO	CHAMBER FUEL FRACTION
ENTHLP	NO	YES	ENTHALPY -----
CSUBP	NO	YES	-----
CSUBT	NO	YES	-----
CSUBF	NO	YES	-----
RHO	NO	YES	DENSITY
DRHODT	NO	YES	-----
DRHODP	NO	YES	-----
DRHODF	NO	YES	-----
MW	NO	YES	MOLECULAR WEIGHT
GAMMA	NO	YES	RATIO OF SPECIFIC HEATS
EDUMY	NO	YES	SEE ASSIGNMENT STATEMENTS BELOW
FDUMY	NO	YES	SEE ASSIGNMENT STATEMENTS BELOW
GDUMY	NO	YES	SEE ASSIGNMENT STATEMENTS BELOW
HDUMY	NO	YES	SEE ASSIGNMENT STATEMENTS BELOW

REMARKS

HDUMY IS NOT USED IN THE WANKEL PROGRAM
 BUT HAS BEEN LEFT INTACT FOR FUTURE USE, IF NECESSARY.

SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED

HPROD CLDPRD

METHOD

SEE PURPOSE, ABOVE

WRITTEN BY S. G. POULOS

EDITED BY S. G. POULOS, AND T. J. NORMAN

```

C      SUBROUTINE THERMO (T, TEMP, P, FR, ENTHLP,
&          CSUBP, CSUBT, CSUBF,
&          RHO, DRHODT, DRHODP, DRHODF,
&          GAMMA, MW, EDUMY, FDUMY, GDUMY, HDUMY)
C
C      REAL MW
C
C      CALL HPROD (P, TEMP, FR, ENTHLP,
&          CSUBP, CSUBT, CSUBF,
&          RHO, DRHODT, DRHODP, DRHODF)
C
C      CONVERT TO UNITS NEEDED IN MAIN PROGRAM
C
C      ENTHLP = ENTHLP * 4.184E+6
C      CSUBP = CSUBP * 4.184E+3
C      CSUBT = CSUBT/1000.
C      CSUBF = CSUBF * 4.184E+6
C
C      RHO = RHO*1000.
C      DRHODP = DRHODP/101.325
C      DRHODT = DRHODT*1000.
C      DRHODF = DRHODF * 1000.
C
C      CALCULATE GAS CONSTANT, MOLECULAR WEIGHT AND GAMMA
C
C      RGAS = 1.01325E+5*P/(RHO*TEMP)
C      MW = 8.3145E+3/RGAS
C      GAMMA = CSUBP/( CSUBP - RGAS )
C
C      CALCULATE THE DUMMY VARIABLES
C
C      EDUMY = CSUBP + ( DRHODT/DRHODP )*( 1./RHO - CSUBT)
C      FDUMY = ( 1. - RHO*CSUBT)/DRHODP
C      GDUMY = CSUBF + ( DRHODF/DRHODP )*(1./RHO - CSUBT)
C
C      RETURN
C      END

```

SUBROUTINE HPROD

PURPOSE

TO CALCULATE THE PROPERTIES OF THE PRODUCTS OF HYDROCARBON-AIR COMBUSTION AS A FUNCTION OF TEMPERATURE AND PRESSURE, USING AN APPROXIMATE CORRECTION FOR DISSOCIATION.

H AND RHO ARE CALCULATED AS FUNCTIONS OF R, T, AND PHI.

THE PARTIAL DERIVATIVES OF H AND RHO WITH RESPECT TO P, T AND PHI ARE ALSO CALCULATED

USAGE

CALL HPROD (P, T, FR, H, CP, CT, CF
RHO, DRHODT, DRHODP, DRHODF)

DESCRIPTION OF PARAMETERS

GIVEN:

P : ABSOLUTE PRESSURE OF PRODUCTS (ATM)
T : TEMPERATURE OF PRODUCTS (DEG K)
PHI : EQUIVALENCE RATIO
DEL : MOLAR C:H RATIO OF PRODUCTS
PSI : MOLAR N:O RATIO OF PRODUCTS

RETURNS:

H : SPECIFIC ENTHALPY OF PRODUCTS (ATM)
CP : PARTIAL DERIVATIVE OF H WITH RESPECT TO T
(CAL/G-DEG K)
CT : PARTIAL DERIVATIVE OF H WITH RESPECT TO P (CC/G)
CF : PARTIAL DERIVATIVE OF H WITH RESPECT TO PHI (KCAL/G)
RHO : DENSITY OF THE PRODUCTS (G/CC)
DRHODT: PARTIAL DERIVATIVE OF RHO WITH RESPECT TO T
(G/CC-DEG K)
DRHODP: PARTIAL DERIVATIVE OF RHO WITH RESPECT TO P
(G/CC-ATM)
DRHODF: PARTIAL DERIVATIVE OF RHO WITH RESPECT TO PHI
(G/CM**3)

RETURNS IN COMMON AREA /FROZEN/:

CPFROZ: FROZEN SPECIFIC HEAT (CAL/G-DEG K)

RETURNS IN COMMON AREA /MBARB/:

MBARB : AVERAGE MOLECULAR WEIGHT OF BURNED GASES

REMARKS

- 1) ENTHALPY DATUM STATE IS AT T = 0 ABSOLUTE WITH O₂, N₂, H₂ GASEOUS AND C SOLID GRAPHITE
- 2) MULTIPLY ATM-CC BY 0.0242173 TO CONVERT TO CAL
- 3) MODIFIED VERSION OF MIKE MARTIN'S PROGRAM
- 4) COMMON BLOCK MBARB ADDED BY B. BEARD 5/10/79
- 5) EXACTLY THE SAME LOGIC AS VERSION 3.5 (5/10/79), BUT WITH CLEANED UP CODE AND DOCUMENTATION BY S. POULOS. 2/12/82

SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED

CLDPRD

```

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
C      LOGICAL RICH, LEAN, NOTHOT, NOTWRM, NOTCLD
C      REAL MCP, MWT, K1, K2
C      REAL MBARB
C      COMMON/FUEL/ FUELTP, ENW, CX, HY, OZ, DEL, PSI, PHICON, PHI,
&      QLOWER, FASTO, HFORM
C      COMMON/FROZEN/ CPFROZ
C      COMMON/MBARB/ MBARB
C
C      INITIALIZE PARAMETERS USED IN THE CALCULATION
C
C      DATA R, ROVER2 /1.9869, 0.99345/, PSscale /2.42173E-2/
C      DATA TCOLD, THOT /1000., 1100./
C
C      PHI = FR / (FASTO * (1. - FR))
C      RICH = PHI .GE. 1.0
C      LEAN = .NOT. RICH
C      NOTHOT = T .LT. THOT
C      NOTCLD = T .GT. TCOLD
C      NOTWRM = .NOT. (NOTCLD .AND. NOTHOT)
C      EPS = (4.*DEL)/(1. + 4.*DEL)
C
C      USE SIMPLE ROUTINE FOR LOW TEMPERATURE MIXES
C
C      IF (NOTCLD) GO TO 5
C      CALL CLDPRD (P, T, FR, H, CP, CT, CF,
&      RHO, DRHODT, DRHODP, DRHODF, IER)
C      RETURN
C
C      CALCULATE EQUILIBRIUM CONSTANTS FOR DISSOCIATION (EQS. 3.9
C      & 3.10) (NOTE THAT THESE HAVE UNITS ATM**(.5) )
C
C      5 K1 = 5.819E-6 * EXP(0.9674*EPS + 35810./T)
C      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
C      C5 = 2. - EPS + PSI
C      A = (C5/(4.*P*K1*K1*EPS))**(.33333333)
C
C      C6 = EPS + 2.*C5
C      X = A*EPS*(3.*C5 + C6*A)/(3.*(1. + 2.*A)*C5 + 2.*C6*A*A)
C
C      Z = ABS((1.-PHI)/X)
C      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

C

FOLLOWING USES EQS. 5.23, 5.19-5.22, 5.18-5.14, 5.12, & 5.13

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

C

FOLLOWING USES EQS. 5.10, & 5.11

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

C

FOLLOWING USES EQS. 5.46, 5.35-5.37, 5.33, & 5.34

DMCPDF = 8. * EPS + 4.

C

IF(RICH)GO TO 55

C

C

C

LEAN CASE

DYDF = 1./3. * (Y/X)**3 * (1.+2.*X)
DC1DF = (9. - 8 *EPS) + 5.*DYDF
DC2DF = 2. * (5. - 3. *EPS) - 6.*DYDF
DHFD = 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

```

SUBROUTINE CLDPRD

PURPOSE

TO CALCULATE THE SPECIFIC ENTHALPY OF THE PRODUCTS OF HC-AIR COMBUSTION AT TEMPERATURES AND PRESSURES WHERE DISSOCIATION OF THE PRODUCT GASES MAY BE IGNORED. THE DENSITY OF THE PRODUCT GAS IS ALSO CALCULATED, AS ARE THE PARTIAL DERIVATIVES OF BOTH OF THESE QUANTITIES WITH RESPECT TO PRESSURE AND TEMPERATURE.

USAGE

CALL CLDPRD (P, T, FR, ENTHLP, CP, CT, CF,
& RHO, DRHODT, DRHODP, DRHODF, IER)

DESCRIPTION OF PARAMETERS

GIVEN:

P : ABSOLUTE PRESSURE OF PRODUCTS (ATM)
T : TEMPERATURE OF PRODUCTS (DEG K)
PHI : EQUIVALENCE RATIO
DEL : MOLAR C:H RATIO OF PRODUCTS
PSI : MOLAR N:O RATIO OF PRODUCTS

RETURNS:

H : SPECIFIC ENTHALPY OF PRODUCTS (KCAL/G)
CP : PARTIAL DERIVATIVE OF H WITH RESPECT TO T
(CAL/G-DEG K)
CT : PARTIAL DERIVATIVE OF H WITH RESPECT TO P (CC/G)
CF : PARTIAL DERIVATIVE OF H WITH RESPECT TO PHI (KCAL/G)
RHO : DENSITY OF THE PRODUCTS (G/CC)
DRHODT: PARTIAL DERIVATIVE OF RHO WITH RESPECT TO T
(G/CC-DEG K)
DRHODP: PARTIAL DERIVATIVE OF RHO WITH RESPECT TO P
(G/CC-ATM)
DRHODF: PARTIAL DERIVATIVE OF RHO WITH RESPECT TO PHI
(G/CC)
IER : FLAG, SET TO 1 FOR T < 100 DEG K
2 FOR T > 6000 DEG K
0 OTHERWISE

RETURNS IN COMMON AREA /FROZEN/:

CPFROZ: FROZEN SPECIFIC HEAT (CAL/G-DEG K)

RETURNS IN COMMON AREA /MBARB/:

MBARB : AVERAGE MOLECULAR WEIGHT OF BURNED GASES

REMARKS

- 1) ENTHALPY DATUM STATE IS AT T = 0 ABSOLUTE WITH O₂, N₂, H₂ GASEOUS AND C SOLID GRAPHITE
- 2) MULTIPLY ATM-CC BY 0.0242173 TO CONVERT TO CAL
- 3) MODIFIED VERSION OF MIKE MARTIN'S PROGRAM
- 4) COMMON BLOCK MBARB ADDED BY B. BEARD 5/10/79
- 5) EXACTLY THE SAME LOGIC AS VERSION 3.1 (5/10/79), BUT WITH CLEANED UP CODE AND DOCUMENTATION BY S. POULOS. 2/12/82

```

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,
C      & RHO, DRHODT, DRHODP, DRHODF, IER)
C
C      LOGICAL RICH, LEAN
C      REAL*4 MBAR, K
C      REAL MBARB,MCP
C      DIMENSION A(6,6,2), X(6), DX(6)
C      DIMENSION A1(36), A2(36)
C      DIMENSION TABLE(7)
C      COMMON/FUEL/ FUELTP, ENW, CX, HY, OZ, DEL, PSI, PHICON, PHI,
C      & QLOWER, FASTO, HFORM
C      COMMON/FROZEN/ CPFROZ
C      COMMON/MBARB/ MBARB
C      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
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/
C      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/
C      DATA TABLE /-1.,1.,1.,-1.,0.,0.,0./
C
C      PHI = FR / (FASTO * ( 1. - FR ))
C      RICH = PHI .GT. 1.0
C      LEAN = .NOT. RICH
C      EPS = 4.*DEL/(1. + 4.*DEL)
C      IER = 0
C      IR = 1
C      IF (T .LT. 500.) IR = 2
C
C      GET THE COMPOSITION IN MOLES/MOLE OXYGEN
C
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 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 USAGE

C CALL ITRATE (T, TGUESS, P, RESFRK, ENTHLP, CSUBP, CSUBT,
C & CSUBF, RHO, DRHODT, DRHODP, DRHODF, GAMMA, MW)

C DESCRIPTION OF PARAMETERS

PARAMETER	INPUT	OUTPUT	DESCRIPTION
T	YES	NO	CRANK ANGLE (DEG)
TGUESS	YES	YES	TEMPERATURE GUESS (K)
-----	---	--	(CORRECTED VALUE IS RETURNED)
P	YES	NO	PRESSURE (ATM)
RESFRK	YES	NO	MASS BURNED / TOTAL MASS
-----	---	--	(<1. FOR UNBURNED ZONE ONLY)
ENTHLP	YES	NO	ENTHALPY ON WHICH TO ITERATE (ERG)
HGUESS	NO	NO	ENTHALPY GUESS (ERG)
CSUBP	NO	YES	DH/DT @ CONSTANT P (ERG/K)
CSUBT	NO	YES	DH/DP @ CONSTANT T (ERG/ATM)
CSUBF	NO	YES	DH/DPHI @ CONSTANT P AND T
RHO	NO	YES	DENSITY
DRHODT	NO	YES	PARTIAL OF RHO WITH RESPECT TO T
DRHODP	NO	YES	PARTIAL OF RHO WITH RESPECT TO P
DRHODF	NO	YES	PARTIAL OF RHO WITH RESPECT TO PHI
MW	NO	YES	MOLECULAR WEIGHT
GAMMA	NO	YES	RATIO OF SPECIFIC HEATS

C REMARKS

C NONE

C SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED

C THERMO

C METHOD

C SEE PURPOSE, ABOVE

C WRITTEN BY S. G. POULOS

C EDITED BY S. G. POULOS

C SUBROUTINE ITRATE (T, TGUESS, P, RESFRK, ENTHLP, CSUBP, CSUBT,
C & 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

```

SUBROUTINE FUELDT

PURPOSE

THIS SUBROUTINE IS CALLED TO SET THE VALUES OF THE FUEL RELATED PARAMETERS AT THE START OF PROGRAM EXECUTION. THE ONLY INPUT REQUIRED IS THE FUEL TYPE. THE PARAMETERS WHICH ARE SET ARE: I) THE ATOM RATIOS WHICH SPECIFY THE PROPERTIES OF THE FUEL- AIR MIXTURE, THE SET OF ENTHALPY COEFFICIENTS ASSOCIATED WITH THE FUEL (USED IN THE PROPERTY ROUTINES), AND THE FUEL HEATING VALUE AND STOICHIOMETRIC FUEL/AIR RATIO; II) THE ATOM RATIOS REQUIRED BY SUBROUTINE 'PTCHEM' FOR CALCULATION OF EQUILIBRIUM BURNED GAS COMPOSITION.

USAGE

CALL FUELDT

DESCRIPTION OF PARAMETERS

PARAMETER	INPUT	OUTPUT	DESCRIPTION
FUELTP	YES	NO	FUEL TYPE
PSI	NO	YES	MOLAR N2 TO O2 RATIO FOR AIR
XI	NO	YES	MOLAR N2 TO O2 RATIO FOR AIR
CX	NO	YES	# OF CARBON ATOMS/FUEL MOLECULE
DEL	NO	YES	CARBON/HYDROGEN RATIO OF FUEL
HY	NO	YES	HYDROGEN ATOMS PER FUEL MOLECULE
ENW	NO	YES	NITROGEN ATOMS PER FUEL MOLECULE
OZ	NO	YES	OXYGEN ATOMS PER FUEL MOLECULE
QLOWER	NO	YES	LOWER HEATING VALUE OF THE FUEL
FASTO	NO	YES	STOICHIOMETRIC FUEL/AIR RATIO
AF(I)	NO	YES	FUEL COEFFICIENT ARRAY
HFORM	NO	YES	HEAT OF FORMATION (DATUM IS 0 K)

REMARKS

ONLY ISSOCTANE AND PROPANE ARE AVAILABLE FOR USE AS FUELS.

SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED

METHOD

SEE PURPOSE, ABOVE

WRITTEN BY S. G. POULOS

EDITED BY S. G. POULOS

SUBROUTINE FUELDT

INTEGER FUELTP

REAL AF(6)

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 ISOCTANE (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

```

```

C *****
C
C   SANDIA MATHEMATICAL PROGRAM LIBRARY
C   APPLIED MATHEMATICS DIVISION 2613
C   SANDIA LABORATORIES
C   ALBUQUERQUE, NEW MEXICO 87115
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C
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C * PART IS SAND77-1441.
C
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        $dy(i)/dt = f(t, y(1), \dots, y(neqn))$ 
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        $G(t, y(1), \dots, y(neqn), yp(1), \dots, yp(neqn)) = 0$ .
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

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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    $ABS(LOCAL\ ERROR) \leq ABS(Y)*RELERR + ABSERR$ 
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    $0.5*ABS(LENGTH\ OF\ INTERVAL) \leq REROOT*ABS(ROOT)+AEROOT$ 

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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
C          SUBROUTINE ODERT(F,NEQN,Y,T,TOUT,RELERR,ABSERR,IFLAG,WORK,IWORK,
1      G,REROOT,AEROOT)
C          IMPLICIT REAL*8 (A-H,O-Z)
D          IMPLICIT INTEGER*2 (I-N)
C
C
C      CCCCC GENERIC
C          LOGICAL START,PHASE1,NORND
C          DIMENSION Y(30),WORK(730),IWORK(5)
C          EXTERNAL F,G
C          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/
C          IYY = 100
C          IWT = IYY + NEQN
C          IP = IWT + NEQN
C          IYP = IP + NEQN
C          IYPOUT = IYP + NEQN
C          IPHI = IYPOUT + NEQN
C          IF(IABS(IFLAG) .EQ. 1) GO TO 1
C          START = WORK(ISTART) .GT. 0.0
C          PHASE1 = WORK(IPHASE) .GT. 0.0
C          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,

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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)

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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.
      REI, EPS = 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(1.0DO, 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)

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      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.ODO,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

```

```

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C WRITTEN BY L. F. SHAMPINE AND M. K. GORDON

C ABSTRACT

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 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 ROUND OFF ERROR AND TO DETECT WHEN THE USER IS REQUESTING
 C TOO MUCH ACCURACY.

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
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,

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```

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      SUBSEQUENT CALLS --

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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.

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C      OUTPUT FROM STEP1

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```

C      SUCCESSFUL STEP --

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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      UNSUCCESSFUL STEP --

```

```

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,
C      1 HOLD,K,KOLD,CRASH,PHI,P,YP,PSI,
C      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
          PHI(L,I) = TEMP1*PHI(L,I)
205      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)

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```

      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
      ***      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      ***
C      400  KOLD = K
C           HOLD = H
C
C      CORRECT AND EVALUATE
C
C           TEMP1 = H*G(KP1)
C           IF(NORND) GO TO 410
C           DO 405 L = 1,NEQN
C               RHO = TEMP1*(YP(L) - PHI(L,1)) - PHI(L,16)
C               Y(L) = P(L) + RHO
C      405  PHI(L,15) = (Y(L) - P(L)) - RHO
C           GO TO 420
C      410  DO 415 L = 1,NEQN
C      415  Y(L) = P(L) + TEMP1*(YP(L) - PHI(L,1))
C      420  CALL F(X,Y,YP)
C
C      UPDATE DIFFERENCES FOR NEXT STEP
C
C           DO 425 L = 1,NEQN
C               PHI(L,KP1) = YP(L) - PHI(L,1)
C      425  PHI(L,KP2) = PHI(L,KP1) - PHI(L,KP2)
C           DO 435 I = 1,K
C               DO 430 L = 1,NEQN
C      430  PHI(L,I) = PHI(L,I) + PHI(L,KP1)
C      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
C           ERKP1 = 0.0
C           IF(KNEW .EQ. KM1 .OR. K .EQ. 12) PHASE1 = .FALSE.
C           IF(PHASE1) GO TO 450
C           IF(KNEW .EQ. KM1) GO TO 455
C           IF(KP1 .GT. NS) GO TO 460
C           DO 440 L = 1,NEQN
C      440  ERKP1 = ERKP1 + (PHI(L,KP2)/WT(L))**2
C           ERKP1 = ABSH*GSTR(KP1)*SQRT(ERKP1)
C
C      USING ESTIMATED ERROR AT ORDER K+1, DETERMINE APPROPRIATE ORDER
C      FOR NEXT STEP
C
C           IF(K .GT. 1) GO TO 445
C           IF(ERKP1 .GE. 0.5*ERK) GO TO 460
C           GO TO 450
C      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
C      SUBROUTINE ROOT(T,FT,B,C,RELERR,ABSERR,IFLAG)
C
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
C      IF(IFLAG.LT.0.0) GO TO 100
C      RE=MAX(RELERR,U)
C      AE=MAX(ABSERR,0.0D0)
C      IC=0
C      ACBS=ABS(B-C)
C      A=C
C      T=A
C      IFLAG=-1
C      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
C  SANDIA MATHEMATICAL PROGRAM LIBRARY
C  APPLIED MATHEMATICS DIVISION 2613
C  SANDIA LABORATORIES
C  ALBUQUERQUE, NEW MEXICO 87115
C  CONTROL DATA 6600/7600 VERSION 7.2  SEPTEMBER 1977
C

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C  * * * * *
C  *
C  * THE PRIMARY DOCUMENT FOR THE LIBRARY OF WHICH THIS ROUTINE IS
C  * A PART IS SAND75-0545.
C  *
C  * * * * *
C
C  WRITTEN BY L. F. SHAMPINE AND M. K. GORDON
C
C  ABSTRACT
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)
      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      ALBUQUERQUE, NEW MEXICO 87115
C      CONTROL DATA 6600/7600 VERSION 7.2  SEPTEMBER 1977
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C * * * * *
C *
C * THE PRIMARY DOCUMENT FOR THE LIBRARY OF WHICH THIS ROUTINE IS
C * A PART IS SAND75-0545.
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 DMAX = 0.000

>>>> OPERATING CONDITIONS

FUEL USED IS ISOCTANE
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 CLOSURES = -180.0 DEG CA
 EXHAUST PORT OPENS = 199.0 DEG CA
 EXHAUST PORT CLOSURES = 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 # = 2
 TPRINT 10.00
 TPRINX 1.00
 XBZERO 0.00030
 XESTOP 0.00000
 XBSTOP 0.99500
 CTINTG 0.000100
 CBINTG 0.000100
 CEINTG 0.00010
 AREROT 0.000100
 REL 0.000100
 ERMAX 0.000000
 MAXERR 0.000000
 MAXTRY 10

>>>> START OF INTAKE PROCESS

CA (DEG)	P (ATM)	TEMP (K)	MIN (G)	MAX (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	-4333.0	0.00000	0.000000	0.000000	0	2
-520.0	1.0080	643.74	-0.00143	-0.00416	-7521.3	-7513.4	0.00383	0.000022	0.000595	0	0
-510.0	0.9841	633.31	-0.00409	-0.01107	-5821.2	-7880.5	0.00770	0.000021	0.001557	0	0
-508.3	0.9805	631.83	-0.00431	-0.01219	-1042.3	-19717.2	0.00835	0.000021	0.001753	0	0
-503.8	0.7369	428.21	-0.00001	-0.01631	21134.3	-13503.6	0.01002	0.000005	0.002285	0	0
-500.0	0.8677	431.35	0.00918	-0.02022	3888.6	0.0	0.14161	0.000006	0.002722	1	1
-490.0	0.9382	423.62	0.02602	-0.02281	6293.1	0.0	0.30641	0.000005	0.004295	1	1
-480.0	0.9328	394.69	0.04795	-0.02281	6664.5	0.0	0.44312	0.000003	0.006175	1	1
-470.0	0.9387	375.46	0.07404	-0.02281	5259.2	0.0	0.54828	0.000001	0.008343	1	1
-460.0	0.9440	361.95	0.10288	-0.02281	5856.1	0.0	0.62595	-0.000001	0.010777	1	1
-450.0	0.9483	352.20	0.13497	-0.02281	5511.9	0.0	0.68440	-0.000002	0.013445	1	1
-440.0	0.9521	344.97	0.16730	-0.02281	5184.7	0.0	0.72934	-0.000003	0.016312	1	1
-430.0	0.9555	339.50	0.20218	-0.02281	4869.7	0.0	0.76446	-0.000004	0.019336	1	1
-420.0	0.9583	335.28	0.23810	-0.02281	4586.6	0.0	0.79215	-0.000005	0.022482	1	1
-410.0	0.9621	332.00	0.27467	-0.02281	4179.0	0.0	0.81437	-0.000006	0.025702	1	1

100.0	0.865	539.59	0.51080	-0.02281	4133.2	0.00000	0.83182	-0.00007	0.028951
100.0	0.8652	539.56	0.51651	-0.02281	3946.7	0.00000	0.84498	-0.00007	0.032189
100.0	0.8654	539.53	0.51102	-0.02281	3800.3	0.00008	0.85778	-0.00008	0.035347
100.0	0.8656	539.50	0.43776	-0.02281	3589.9	0.00068	0.86745	-0.00068	0.038410
100.0	0.8658	539.47	0.43342	-0.02281	3279.0	0.00009	0.87356	-0.00009	0.041331
100.0	0.8660	539.44	0.40918	-0.02281	2910.3	0.00010	0.87455	-0.00010	0.044968
100.0	0.8662	539.41	0.41332	-0.02281	2720.1	0.00010	0.87444	-0.00010	0.046589
100.0	0.8664	539.38	0.51067	-0.02281	2607.6	0.00010	0.86557	-0.00010	0.048353
100.0	0.8666	539.35	0.51755	-0.02281	2478.8	0.00010	0.86884	-0.00010	0.050785
100.0	0.8668	539.32	0.5181	-0.02281	2319.9	0.00010	0.86982	-0.00010	0.052438
100.0	0.8670	539.29	0.5324	-0.02281	2019.7	0.00010	0.86993	-0.00010	0.053742
100.0	0.8672	539.26	0.51147	-0.02281	1529.7	0.00010	0.86335	-0.00010	0.055587
100.0	0.8674	539.23	0.5604	-0.02281	772.2	0.00010	0.85559	-0.00010	0.055361
100.0	0.8676	539.20	0.5654	-0.02281	-293.9	0.00010	0.85395	-0.00010	0.055442
100.0	0.8678	539.17	0.56358	-0.02281	-677.2	0.00010	0.85472	-0.00010	0.055453
100.0	0.8680	539.14	0.5355	-0.02281	-1796.2	0.00010	0.85553	-0.00010	0.055269
100.0	0.8682	539.11	0.5903	-0.02281	-3240.9	0.00010	0.85392	-0.00010	0.054582
100.0	0.8684	539.08	0.54400	-0.02281	-4973.3	0.00069	0.85449	-0.00069	0.053718
100.0	0.8686	539.05	0.5106	-0.02281	-7173.8	0.00009	0.85333	-0.00009	0.052359
100.0	0.8688	539.02	0.5016	-0.02281	-8262.8	0.00008	0.85334	-0.00008	0.050582
100.0	0.8690	538.99	0.5012	-0.02281	-11122.0	0.00007	0.84946	-0.00007	0.048365
100.0	0.8692	538.96	0.55011	-0.02281	-12737.8	0.00006	0.84567	-0.00006	0.045577
100.0	0.8694	538.93	0.55011	-0.02281	-14112.0	0.00004	0.84394	-0.00004	0.042462
100.0	0.8696	538.90	0.55011	-0.02281	-17000.0	0.00003	0.84729	-0.00003	0.038738
100.0	0.8698	538.87	0.55011	-0.02281	-20000.0	0.00003	0.84729	-0.00003	0.038738

CA (DEG)	P (ATM)	TEMP (K)	Q DOT (KJ/DEG)	WORK (KJ)	IFG
-100.0	3.385	359.007	-0.000003	0.03738	N
-100.0	1.750	357.87	-0.000001	0.034394	N
-100.0	1.505	357.35	0.000002	0.023390	N
-100.0	1.8052	368.32	0.000005	0.023653	N
-100.0	2.0741	402.28	0.000009	0.017100	N
-100.0	2.3005	416.85	0.000013	0.006635	N
-100.0	2.7153	433.16	0.000018	0.001750	N
-100.0	3.1091	451.45	0.000025	-0.004866	N
-100.0	3.7229	471.94	0.000034	-0.019339	N
-100.0	4.4037	494.88	0.000044	-0.031592	N
-100.0	5.2556	520.55	0.000057	-0.045335	N
-100.0	6.2673	548.50	0.000075	-0.060611	N
-100.0	7.4873	578.37	0.000096	-0.077329	N
-100.0	8.8128	609.42	0.000123	-0.095165	N
-100.0	11.9365	640.01	0.000153	-0.113412	N
-100.0	14.2288	667.80	0.000186	-0.130828	N

>>>> START OF COMBUSTION AND EXPANSION PROCESSES

CA (DEG)	P (ATM)	TEMP (K)	XEUPND (-)	Q DOT (KJ/DEG)	WORK (KJ)	IFG
-25.0	15.3403	679.80	0.00030	0.000202	-0.136675	0.000000
-24.0	15.5948	683.80	0.00106	0.000206	-0.140143	0.000000
-23.0	15.8272	691.37	0.00335	0.000214	-0.141586	0.000000
-22.0	16.0392	702.47	0.00716	0.000224	-0.142989	0.000000
-21.0	16.2315	717.08	0.01249	0.000237	-0.144375	0.000000
-20.0	16.4039	735.14	0.01935	0.000254	-0.145740	0.000000
-19.0	16.6550	756.57	0.02773	0.000274	-0.147088	0.000000
-18.0	16.7840	781.30	0.03764	0.000297	-0.148414	0.000000
-17.0	16.5895	809.26	0.04907	0.000324	-0.149723	0.000000
-16.0	20.4693	840.34	0.06202	0.000355	-0.151013	0.000000
-15.0	21.4205	874.47	0.07650	0.000389	-0.152281	0.000000
-14.0	22.4397	911.52	0.09250	0.000428	-0.153524	0.000000
-13.0	23.5241	951.41	0.11003	0.000472	-0.154738	0.000000
-12.0	24.6705	994.06	0.12968	0.000520	-0.155916	0.000000
-11.0	25.8788	1039.55	0.14965	0.000575	-0.157054	0.000000
-10.0	27.1347	1087.25	0.17175	0.000637	-0.158145	0.000000
-9.0	28.4335	1137.07	0.19537	0.000702	-0.159179	0.000000
-8.0	29.7753	1189.14	0.22052	0.000772	-0.160149	0.000000
-7.0	31.1574	1243.40	0.24710	0.000846	-0.161045	0.000000
-6.0	32.5725	1299.75	0.27538	0.000926	-0.161858	0.000000
-5.0	34.0171	1358.08	0.30510	0.001012	-0.162576	0.000000
-4.0	35.4859	1418.32	0.33634	0.001104	-0.163190	0.000000
-3.0	36.9744	1480.38	0.36911	0.001201	-0.163688	0.000000
-2.0	38.4775	1544.16	0.40340	0.001304	-0.164058	0.000000
-1.0	39.9906	1609.57	0.43921	0.001413	-0.164288	0.000000
0.0	41.5099	1676.55	0.47655	0.001528	-0.164368	0.000000
1.0	42.9377	1741.07	0.51332	0.001643	-0.164227	0.000000
2.0	44.1800	1799.54	0.54745	0.001749	-0.163587	0.000000
3.0	45.2851	1852.52	0.57918	0.001849	-0.162958	0.000000
4.0	46.2314	1900.46	0.60863	0.001941	-0.162133	0.000000
5.0	47.0391	1943.76	0.63602	0.002026	-0.161109	0.000000
6.0	47.7191	1982.61	0.66146	0.002106	-0.159884	0.000000
7.0	48.2790	2017.32	0.68510	0.002179	-0.158456	0.000000
8.0	48.7281	2049.39	0.70707	0.002247	-0.156825	0.000000
9.0	49.0739	2077.53	0.72749	0.002300	-0.155032	0.000000
10.0	49.3241	2102.58	0.74645	0.002356	-0.153082	0.000000
11.0	49.4861	2124.00	0.76408	0.002416	-0.150958	0.000000
12.0	49.5643	2144.40	0.78045	0.002462	-0.148300	0.000000
13.0	49.5686	2161.00	0.79567	0.002503	-0.145163	0.000000
14.0	49.5003	2176.57	0.80981	0.002538	-0.141563	0.000000
15.0	49.3667	2189.51	0.82254	0.002568	-0.137493	0.000000
16.0	49.1739	2200.57	0.83515	0.002593	-0.132958	0.000000
17.0	48.9268	2209.81	0.84649	0.002613	-0.127934	0.000000
18.0	48.6280	2217.06	0.85693	0.002627	-0.122449	0.000000
19.0	48.2825	2223.85	0.86683	0.002637	-0.116500	0.000000
20.0	47.8957	2228.80	0.87593	0.002642	-0.110192	0.000000
21.0	47.4716	2232.63	0.88438	0.002643	-0.103449	0.000000
22.0	47.0132	2235.22	0.89224	0.002640	-0.096254	0.000000
23.0	46.5240	2236.78	0.89954	0.002633	-0.088500	0.000000
24.0	46.0084	2237.39	0.90632	0.002622	-0.080192	0.000000
25.0	45.4651	2237.09	0.91263	0.002608	-0.071349	0.000000

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26.0	0.002590	0.101388
27.0	0.002570	-0.096816
28.0	0.002547	-0.002140
29.0	0.002521	-0.002167
30.0	0.002494	-0.002503
31.0	0.002464	-0.077555
32.0	0.002432	-0.072531
33.0	0.002398	-0.067436
34.0	0.002364	-0.062277
35.0	0.002328	-0.057059
36.0	0.002291	-0.051789
37.0	0.002253	-0.046474
38.0	0.002215	-0.041117
39.0	0.002176	-0.035725
40.0	0.002137	-0.030392
41.0	0.002099	-0.024855
42.0	0.002060	-0.019387
43.0	0.002022	-0.013903
44.0	0.001983	-0.008407
45.0	0.001945	-0.002904
46.0	0.001908	-0.002603
47.0	0.001871	0.005109
48.0	0.001835	0.013612
49.0	0.001799	0.019108
50.0	0.001764	0.024593
51.0	0.001730	0.030065
52.0	0.001696	0.035522
53.0	0.001663	0.040959
54.0	0.001630	0.046376
55.0	0.001599	0.051769
56.0	0.001568	0.057137
57.0	0.001538	0.062477
58.0	0.001508	0.067788
59.0	0.001479	0.073068
60.0	0.001451	0.078315
61.0	0.001424	0.083528
62.0	0.001397	0.088705
63.0	0.001371	0.093845
64.0	0.001345	0.098948
65.0	0.001321	0.104012
66.0	0.001296	0.109035
67.0	0.001273	0.114019
68.0	0.001250	0.118960
69.0	0.001228	0.123859
70.0	0.001206	0.128716
71.0	0.001184	0.133529
72.0	0.001164	0.138299
73.0	0.001144	0.143024
74.0	0.001124	0.147705
75.0	0.001105	0.152341
76.0	0.001086	0.156932
77.0	0.001068	0.161477
78.0	0.001050	0.165978
79.0	0.001033	0.170432
80.0	0.001016	0.174842
81.0	0.000999	0.179206
82.0	0.000983	0.183524
83.0	0.000967	0.187797
84.0	0.000952	0.192025

>>>> START OF EXHAUST PROCESS

CA (DEG)	P (ATM)	TEMP (K)	MEX (G)	VEY (M/SEC)	Q DOT (KJ/DEG)	WORK (KJ)	IFG
199.0	3.7583	1237.28	-0.02281	0.3	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	251.0	0.000214	0.468635	2
230.0	2.5580	1127.66	0.07508	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	980.89	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	0.000068	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	875.78	0.33873	62.8	0.000061	0.470101	2
350.0	1.0453	869.59	0.34876	70.8	0.000059	0.467407	2
360.0	1.0531	860.84	0.36033	80.0	0.000058	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	0.000051	0.457872	2
390.0	1.0762	821.68	0.40442	99.5	0.000048	0.454346	2
400.0	1.0787	809.00	0.42109	100.0	0.000046	0.450734	2
410.0	1.0788	797.20	0.43809	98.1	0.000043	0.447093	2
420.0	1.0772	786.20	0.45507	94.7	0.000040	0.443479	2
430.0	1.0738	775.88	0.47181	80.1	0.000038	0.439947	2
440.0	1.0687	765.88	0.48803	64.8	0.000036	0.436549	2
450.0	1.0632	756.54	0.50343	79.2	0.000034	0.433335	2
460.0	1.0578	746.96	0.51782	70.8	0.000032	0.430347	2
470.0	1.0501	737.31	0.53114	61.8	0.000030	0.427623	2
480.0	1.0429	727.62	0.54306	52.7	0.000028	0.425200	2
490.0	1.0368	717.80	0.55344	41.3	0.000027	0.423104	2
500.0	1.0303	707.43	0.56223	36.7	0.000026	0.421359	2
510.0	1.0282	697.14	0.56914	21.6	0.000024	0.419984	2
520.0	1.0229	685.82	0.57433	15.8	0.000023	0.418992	2
530.0	1.0215	674.78	0.57747	14.0	0.000023	0.418393	2
540.0	1.0205	663.59	0.57858		0.000022	0.418193	2
550.0	1.0188	651.41	0.57755			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/KN-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 (θ - 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	

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

HEAT1 = -0.000767 KJ (TIPO - -270)
 WORK1 = 0.055453 KJ
 HEATC = 0.007708 KJ (-270 - TSPARK)
 WORKC = -0.194128 KJ

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	=	0.03098 KJ
(ENERGY GAIN)/(ENTHALPY IN)	=	18.61953 %
(ENERGY GAIN)/(MFUEL*LHV)	=	2.39426 %

HEAT TRANSFER DATA

CA (DEG)	VELHTX (CM/SEC)	HTPAHO (KW/M**2)	HTPAHI (KW/M**2)	HTPAHO (KW/M**2)	CR ROTOR (%)	CR SIDE (%)	CR 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	3.7	3.7	3.7	41.191	6.564	52.215
-480.0	824.7	3.3	3.3	3.3	39.076	7.949	52.075
-470.0	824.7	3.5	3.5	3.5	38.665	9.443	51.852
-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	35.816	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	51.111
-420.0	824.7	-2.1	-2.1	-2.1	31.037	17.110	50.955
-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	50.213
-360.0	824.7	-2.8	-2.8	-2.8	25.993	23.883	50.075
-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	22.899	27.307	49.704
-280.0	824.7	-2.9	-2.9	-2.9	22.606	27.436	49.688
-272.4	824.7	-2.9	-2.9	-2.9	22.341	27.476	49.683
-270.0	824.7	-2.9	-2.9	-2.9	22.089	27.478	49.683
-260.0	824.7	-2.9	-2.9	-2.9	21.839	27.436	49.688
-250.0	824.7	-2.9	-2.9	-2.9	21.589	27.307	49.704
-240.0	824.7	-2.9	-2.9	-2.9	21.344	27.092	49.768
-230.0	824.7	-2.9	-2.9	-2.9	21.104	26.789	49.816
-220.0	824.7	-2.9	-2.9	-2.9	20.871	26.396	49.875
-210.0	824.7	-2.9	-2.9	-2.9	20.644	25.911	49.946
-200.0	824.7	-2.9	-2.9	-2.9	20.421	25.333	50.029
-190.0	824.7	-2.9	-2.9	-2.9	20.204	24.658	50.123
-180.0	824.7	-2.9	-2.9	-2.9	20.000	23.883	50.231
-170.0	824.7	-2.9	-2.9	-2.9	19.806	23.008	50.350
-160.0	824.7	-2.9	-2.9	-2.9	19.620	22.029	50.483
-150.0	824.7	-2.9	-2.9	-2.9	19.448	20.948	50.628
-140.0	824.7	-2.9	-2.9	-2.9	19.284	19.764	50.785
-130.0	824.7	-2.9	-2.9	-2.9	19.127	18.483	50.953
-120.0	824.7	-2.9	-2.9	-2.9	18.976	17.110	51.131
-110.0	824.7	-2.9	-2.9	-2.9	18.831	15.656	51.317
-100.0	824.7	-2.9	-2.9	-2.9	18.692	14.137	51.508
-90.0	824.7	-2.9	-2.9	-2.9	18.559	12.576	51.702
-80.0	824.7	-2.9	-2.9	-2.9	18.432	10.999	51.902
-70.0	824.7	-2.9	-2.9	-2.9	18.311	9.443	52.102

[illegible]

9464	9356	9320	9304	9288	9272	9256	9240	9224	9208	9192	9176	9160	9144	9128	9112	9096	9080	9064	9048	9032	9016	9000	8984	8968	8952	8936	8920	8904	8888	8872	8856	8840	8824	8808	8792	8776	8760	8744	8728	8712	8696	8680	8664	8648	8632	8616	8600	8584	8568	8552	8536	8520	8504	8488	8472	8456	8440	8424	8408	8392	8376	8360	8344	8328	8312	8296	8280	8264	8248	8232	8216	8200	8184	8168	8152	8136	8120	8104	8088	8072	8056	8040	8024	8008	7992	7976	7960	7944	7928	7912	7896	7880	7864	7848	7832	7816	7800	7784	7768	7752	7736	7720	7704	7688	7672	7656	7640	7624	7608	7592	7576	7560	7544	7528	7512	7496	7480	7464	7448	7432	7416	7400	7384	7368	7352	7336	7320	7304	7288	7272	7256	7240	7224	7208	7192	7176	7160	7144	7128	7112	7096	7080	7064	7048	7032	7016	7000	6984	6968	6952	6936	6920	6904	6888	6872	6856	6840	6824	6808	6792	6776	6760	6744	6728	6712	6696	6680	6664	6648	6632	6616	6600	6584	6568	6552	6536	6520	6504	6488	6472	6456	6440	6424	6408	6392	6376	6360	6344	6328	6312	6296	6280	6264	6248	6232	6216	6200	6184	6168	6152	6136	6120	6104	6088	6072	6056	6040	6024	6008	5992	5976	5960	5944	5928	5912	5896	5880	5864	5848	5832	5816	5800	5784	5768	5752	5736	5720	5704	5688	5672	5656	5640	5624	5608	5592	5576	5560	5544	5528	5512	5496	5480	5464	5448	5432	5416	5400	5384	5368	5352	5336	5320	5304	5288	5272	5256	5240	5224	5208	5192	5176	5160	5144	5128	5112	5096	5080	5064	5048	5032	5016	5000	4984	4968	4952	4936	4920	4904	4888	4872	4856	4840	4824	4808	4792	4776	4760	4744	4728	4712	4696	4680	4664	4648	4632	4616	4600	4584	4568	4552	4536	4520	4504	4488	4472	4456	4440	4424	4408	4392	4376	4360	4344	4328	4312	4296	4280	4264	4248	4232	4216	4200	4184	4168	4152	4136	4120	4104	4088	4072	4056	4040	4024	4008	3992	3976	3960	3944	3928	3912	3896	3880	3864	3848	3832	3816	3800	3784	3768	3752	3736	3720	3704	3688	3672	3656	3640	3624	3608	3592	3576	3560	3544	3528	3512	3496	3480	3464	3448	3432	3416	3400	3384	3368	3352	3336	3320	3304	3288	3272	3256	3240	3224	3208	3192	3176	3160	3144	3128	3112	3096	3080	3064	3048	3032	3016	3000	2984	2968	2952	2936	2920	2904	2888	2872	2856	2840	2824	2808	2792	2776	2760	2744	2728	2712	2696	2680	2664	2648	2632	2616	2600	2584	2568	2552	2536	2520	2504	2488	2472	2456	2440	2424	2408	2392	2376	2360	2344	2328	2312	2296	2280	2264	2248	2232	2216	2200	2184	2168	2152	2136	2120	2104
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824	824	824	824	826	832	836	842	849	856	865	875	887	899	909	921	935	949	964	979	1011	1028	1062	1089	1099	1116	1132	1146	1159	1171	1181	1191	1199	1207	1213	1219	1230	1234	1238	1241	1244	1247	1251	1252	1254	1255	1257	1258	1258	

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230.0	824.7	53.0	19.0	0.0	0.0	49.768
240.0	824.7	53.4	19.5	0.7	26.789	49.770
250.0	824.7	55.7	20.7	1.3	27.592	49.770
260.0	824.7	58.7	21.4	2.0	27.436	49.688
280.0	824.7	60.4	21.0	2.4	27.436	49.688
290.0	824.7	60.0	20.0	2.0	27.307	49.704
300.0	824.7	59.0	19.0	1.0	27.092	49.730
310.0	824.7	58.0	18.5	0.4	26.789	49.768
320.0	824.7	57.4	18.4	0.3	26.396	49.816
330.0	824.7	56.0	18.4	0.3	25.911	49.875
340.0	824.7	55.0	18.2	0.1	25.333	49.946
350.0	824.7	54.0	18.0	0.0	24.658	50.029
360.0	824.7	53.0	18.0	0.0	23.883	50.123
370.0	824.7	52.0	18.0	0.0	23.008	50.231
380.0	824.7	51.0	18.2	0.0	22.029	50.350
390.0	824.7	50.0	18.0	0.0	19.764	50.483
400.0	824.7	49.0	17.5	0.0	18.483	50.628
410.0	824.7	48.0	17.0	0.0	17.110	50.785
420.0	824.7	47.0	16.5	0.0	15.656	50.953
430.0	824.7	46.0	16.0	0.0	14.137	51.131
440.0	824.7	45.0	16.0	0.1	12.576	51.317
450.0	824.7	44.0	15.7	0.0	10.993	51.508
460.0	824.7	43.0	15.0	0.0	9.443	51.702
470.0	824.7	42.0	14.7	0.0	7.949	51.892
480.0	824.7	41.0	14.0	0.0	6.564	52.075
490.0	824.7	40.0	14.0	0.0	5.338	52.245
500.0	824.7	39.0	13.8	0.0	4.320	52.395
510.0	824.7	38.0	13.5	0.0	3.556	52.520
520.0	824.7	37.0	13.2	0.0	3.082	52.613
530.0	824.7	36.0	12.9	0.0	2.821	52.691
540.0	824.7	35.0	12.6	0.0	2.682	52.755
550.0	824.7	34.0	12.2	0.0	2.653	52.801

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	-0.000423	-0.000853	0.007675	0.054094
-500.0	0.0560	0.000000	0.000000	-0.000527	-0.000918	0.007680	0.054094
-500.0	0.0694	0.000000	0.000000	-0.000617	-0.001089	0.007694	0.054094
-490.0	0.0894	0.000000	0.000000	-0.000878	-0.001222	0.007705	0.054094
-480.0	0.1119	0.000000	0.000000	-0.001177	-0.001542	0.007730	0.054087
-470.0	0.1385	0.000000	0.000000	-0.001524	-0.001809	0.007744	0.054067
-460.0	0.1679	0.000000	0.000000	-0.001929	-0.002027	0.007744	0.054023
-450.0	0.1997	0.000000	0.000000	-0.002410	-0.002205	0.007744	0.053969
-440.0	0.2336	0.000000	0.000000	-0.002988	-0.002344	0.007744	0.053896
-430.0	0.2693	0.000000	0.000000	-0.003685	-0.002449	0.007744	0.053789
-420.0	0.3061	0.000000	0.000000	-0.004539	-0.002525	0.007744	0.053668
-410.0	0.3440	0.000000	0.000000	-0.005583	-0.002588	0.007744	0.053517
-400.0	0.3813	0.000000	0.000000	-0.006864	-0.002648	0.007744	0.053330
-390.0	0.4186	0.000000	0.000000	-0.008405	-0.002709	0.007744	0.053100
-380.0	0.4550	0.000000	0.000000	-0.010239	-0.002771	0.007744	0.052816
-370.0	0.4903	0.000000	0.000000	-0.012768	-0.002835	0.008608	0.052482
-360.0	0.5240	0.000000	0.000000	-0.016723	-0.002900	0.015610	0.052053
-350.0	0.5552	0.000000	0.000000	-0.022080	-0.002968	0.029920	0.051550
-340.0	0.5831	0.000000	0.000000	-0.027723	-0.003038	0.042820	0.051199
-330.0	0.6077	0.000000	0.000000	-0.032932	-0.003112	0.049063	0.051064
-320.0	0.6292	0.000000	0.000000	-0.037429	-0.003188	0.052055	0.051055
-310.0	0.6472	0.000000	0.000000	-0.041172	-0.003264	0.053399	0.051100
-300.0	0.6618	0.000000	0.000000	-0.044337	-0.003342	0.053935	0.051100
-290.0	0.6720	0.000000	0.000000	-0.046738	-0.003418	0.054117	0.051219
-280.0	0.6793	0.000000	0.000000	-0.048786	-0.003493	0.054156	0.051273
-272.4	0.6812	0.000000	0.000000	-0.050095	-0.003566	0.054146	0.051321
-270.0	0.6814	0.000000	0.000000	-0.050480	-0.003619	0.054130	0.051355
-260.0	0.6801	0.000000	0.000000	-0.051895	-0.003636	0.054125	0.051365
-250.0	0.6768	0.000000	0.000000	-0.053092	-0.003703	0.054107	0.051405
-240.0	0.6729	0.000000	0.000000	-0.054118	-0.003765	0.054095	0.051444
-230.0	0.6708	0.000000	0.000000	-0.055007	-0.003819	0.054091	0.051481
-220.0	0.6712	0.000000	0.000886	-0.055786	-0.003855	0.054092	0.051520
-210.0	0.6717	0.000332	0.000332	-0.056478	-0.003872	0.054093	0.048573
-200.0	0.6720	0.000988	0.000988	-0.057098	-0.003762	0.054093	0.043933
-190.0	0.6720	0.000000	0.001057	-0.057659	-0.003672	0.054094	0.038837
-180.0	0.6723	0.000000	0.001142	-0.058173	-0.003560	0.054094	0.033793
-170.0	0.6726	0.000000	0.001246	-0.058647	-0.003426	0.054094	0.029102
-160.0	0.6727	0.000000	0.001372	-0.059089	-0.003270	0.054094	0.024939
-150.0	0.6727	0.000000	0.001528	-0.059500	-0.003090	0.054094	0.021366
-140.0	0.6727	0.000000	0.001720	-0.059862	-0.002885	0.054094	0.018400
-130.0	0.6724	0.000000	0.001958	-0.060112	-0.002656	0.054094	0.015996
-120.0	0.6725	0.002242	0.002253	-0.060978	-0.002399	0.054087	0.014077
-110.0	0.6701	0.002613	0.002622	-0.059648	-0.002154	0.046302	0.012565
						0.036703	0.011384

100.000000	0.6633	0.003082	0.003090	-0.05236	-0.00131	0.029139	0.010472
-90.000000	0.6625	0.003578	0.003685	-0.05870	-0.00087	0.023359	0.009778
-70.000000	0.6622	0.00442	0.00447	-0.05897	0.000299	0.019024	0.009256
-50.000000	0.6600	0.005412	0.006635	-0.05702	0.000397	0.015833	0.008872
-30.000000	0.6500	0.008143	0.008147	-0.05509	0.001248	0.013524	0.008594
-10.000000	0.6449	0.009907	0.00910	-0.05434	0.002232	0.011885	0.008397
0.000000	0.6395	0.011811	0.011814	-0.05296	0.003568	0.010749	0.008261
20.000000	0.6355	0.012945	0.012945	-0.05174	0.005197	0.009980	0.008168
40.000000	0.6324	0.013221	0.013224	-0.05159	0.006619	0.009647	0.008128
60.000000	0.6318	0.013563	0.013566	-0.051369	0.008344	0.009590	0.008124
80.000000	0.6308	0.013974	0.013974	-0.051174	0.009533	0.009533	0.008125
100.000000	0.6296	0.014447	0.014450	-0.05073	0.009679	0.009483	0.008134
120.000000	0.6284	0.014988	0.014990	-0.05065	0.009695	0.009443	0.008158
140.000000	0.6270	0.015593	0.015595	-0.05048	0.007139	0.009420	0.008199
160.000000	0.6255	0.016261	0.016264	-0.05023	0.007353	0.009419	0.008262
180.000000	0.6240	0.016992	0.016994	-0.05007	0.007581	0.009445	0.008351
200.000000	0.6223	0.017781	0.017783	-0.04984	0.007816	0.009502	0.008469
220.000000	0.6206	0.018627	0.018629	-0.04963	0.008063	0.009594	0.008621
240.000000	0.6188	0.019526	0.019529	-0.04941	0.008311	0.009724	0.008808
260.000000	0.6169	0.020477	0.020480	-0.04913	0.008581	0.009893	0.009032
280.000000	0.6149	0.021479	0.021482	-0.04882	0.008874	0.010104	0.009295
300.000000	0.6128	0.022521	0.022523	-0.04842	0.009171	0.010359	0.009598
320.000000	0.6107	0.023598	0.023598	-0.04804	0.009483	0.010658	0.009941
340.000000	0.6085	0.024710	0.024710	-0.04752	0.009810	0.010996	0.010323
360.000000	0.6063	0.025855	0.025855	-0.04704	0.010145	0.011380	0.010746
380.000000	0.6041	0.026928	0.026928	-0.04662	0.010500	0.011807	0.011210
400.000000	0.6017	0.028225	0.028227	-0.04628	0.010865	0.012277	0.011713
420.000000	0.5993	0.029441	0.029443	-0.04594	0.011278	0.012789	0.012257
440.000000	0.5969	0.030674	0.030676	-0.04550	0.011685	0.013342	0.012839
460.000000	0.5946	0.031918	0.031920	-0.04500	0.012110	0.013936	0.013460
480.000000	0.5923	0.033170	0.033172	-0.04449	0.012544	0.014570	0.014119
500.000000	0.5899	0.034427	0.034428	-0.04411	0.013055	0.015242	0.014814
520.000000	0.5875	0.035687	0.035689	-0.043915	0.013583	0.015952	0.015546
540.000000	0.5851	0.036943	0.036945	-0.043403	0.013989	0.016665	0.016279
560.000000	0.5827	0.038200	0.038202	-0.042878	0.014501	0.017347	0.016976
580.000000	0.5803	0.039457	0.039459	-0.042340	0.015027	0.017995	0.017639
600.000000	0.5779	0.040715	0.040717	-0.04193	0.015564	0.018610	0.018265
620.000000	0.5755	0.041972	0.041974	-0.041538	0.016112	0.019189	0.018855
640.000000	0.5731	0.043230	0.043232	-0.041125	0.016688	0.019734	0.019410
660.000000	0.5707	0.044487	0.044489	-0.040673	0.017232	0.020245	0.019929
680.000000	0.5683	0.045745	0.045747	-0.040104	0.017801	0.020723	0.020414
700.000000	0.5659	0.046999	0.046999	-0.039530	0.018355	0.021167	0.020865
720.000000	0.5635	0.048257	0.048257	-0.038952	0.018932	0.021581	0.021284
740.000000	0.5611	0.049515	0.049515	-0.038373	0.019522	0.021964	0.021672
760.000000	0.5587	0.050772	0.050772	-0.037791	0.020113	0.022317	0.022030
780.000000	0.5563	0.052030	0.052030	-0.037210	0.020695	0.022642	0.022360
800.000000	0.5539	0.053287	0.053287	-0.036629	0.021278	0.022940	0.022660
820.000000	0.5515	0.054545	0.054545	-0.035971	0.021856	0.023210	0.022934
840.000000	0.5491	0.055803	0.055803	-0.035341	0.022434	0.023456	0.023183
860.000000	0.5467	0.057060	0.057060	-0.034696	0.023009	0.023678	0.023408
880.000000	0.5443	0.058318	0.058318	-0.034024	0.023581	0.023876	0.023608
900.000000	0.5419	0.059575	0.059575	-0.033355	0.024149	0.024052	0.023785
920.000000	0.5395	0.060833	0.060833	-0.032682	0.024713	0.024206	0.023941
940.000000	0.5371	0.062090	0.062090	-0.032018	0.025273	0.024340	0.024077
960.000000	0.5347	0.063348	0.063348	-0.031350	0.025837	0.024455	0.024193
980.000000	0.5323	0.064605	0.064605	-0.030687	0.026395	0.024561	0.024290
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89.0	0.011352	0.011352	-0.010090	0.047816	0.024784	0.024525
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91.0	0.010952	0.010953	-0.009775	0.048131	0.024784	0.024525
92.0	0.010760	0.010760	-0.009621	0.048285	0.024784	0.024525
93.0	0.010572	0.010572	-0.009470	0.048436	0.024784	0.024525
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95.0	0.010209	0.010210	-0.009176	0.048730	0.024784	0.024525
96.0	0.010035	0.010035	-0.009031	0.048873	0.024784	0.024525
97.0	0.009864	0.009864	-0.008892	0.049014	0.024784	0.024525
98.0	0.009698	0.009698	-0.008735	0.049153	0.024784	0.024525
99.0	0.009535	0.009536	-0.008617	0.049289	0.024784	0.024525
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101.0	0.009222	0.009222	-0.008352	0.049554	0.024784	0.024525
102.0	0.009071	0.009071	-0.008222	0.049684	0.024784	0.024525
103.0	0.008923	0.008923	-0.008095	0.049811	0.024784	0.024525
104.0	0.008779	0.008779	-0.007970	0.049936	0.024784	0.024525
105.0	0.008638	0.008639	-0.007846	0.050060	0.024784	0.024525
106.0	0.008501	0.008501	-0.007725	0.050181	0.024784	0.024525
107.0	0.008367	0.008367	-0.007606	0.050300	0.024784	0.024525
108.0	0.008236	0.008236	-0.007488	0.050418	0.024784	0.024525
109.0	0.008108	0.008108	-0.007373	0.050534	0.024784	0.024525
110.0	0.007983	0.007983	-0.007259	0.050647	0.024784	0.024525
111.0	0.007861	0.007861	-0.007147	0.050760	0.024784	0.024525
112.0	0.007741	0.007742	-0.007036	0.050870	0.024784	0.024525
113.0	0.007625	0.007625	-0.006927	0.050979	0.024784	0.024525
114.0	0.007511	0.007511	-0.006820	0.051088	0.024784	0.024525
115.0	0.007400	0.007400	-0.006715	0.051191	0.024784	0.024525
116.0	0.007291	0.007291	-0.006611	0.051295	0.024784	0.024525
117.0	0.007185	0.007185	-0.006508	0.051398	0.024784	0.024525
118.0	0.007081	0.007081	-0.006407	0.051499	0.024784	0.024525
119.0	0.006979	0.006979	-0.006308	0.051598	0.024784	0.024525
120.0	0.006880	0.006880	-0.006210	0.051698	0.024784	0.024525
121.0	0.006783	0.006783	-0.006115	0.051793	0.024785	0.024526
122.0	0.006688	0.006688	-0.006018	0.051888	0.024787	0.024528
123.0	0.006595	0.006596	-0.005924	0.051982	0.024792	0.024533
124.0	0.006505	0.006505	-0.005831	0.052075	0.024801	0.024542
125.0	0.006416	0.006416	-0.005740	0.052167	0.024814	0.024556
126.0	0.006329	0.006329	-0.005649	0.052257	0.024832	0.024573
127.0	0.006245	0.006245	-0.005560	0.052346	0.024851	0.024592
128.0	0.006161	0.006162	-0.005473	0.052434	0.024872	0.024614
129.0	0.006080	0.006080	-0.005386	0.052520	0.024898	0.024640
130.0	0.006001	0.006001	-0.005301	0.052606	0.024928	0.024670
131.0	0.005923	0.005923	-0.005216	0.052690	0.024962	0.024704
132.0	0.005847	0.005847	-0.005135	0.052773	0.024998	0.024741
133.0	0.005773	0.005773	-0.005051	0.052856	0.025038	0.024781
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135.0	0.005628	0.005628	-0.004889	0.053017	0.025128	0.024872
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137.0	0.005490	0.005490	-0.004732	0.053174	0.025230	0.024975
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139.0	0.005358	0.005358	-0.004578	0.053328	0.025345	0.025091
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141.0	0.005231	0.005231	-0.004429	0.053478	0.025473	0.025220

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 144 0 0.005050 0.005050 -0.004210 -0.053696 0.025686 0.025435
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 198 0 0.003110 0.003110 -0.001170 0.056693 0.032915 0.032745
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200.0	0.003090	0.001126	0.056781	0.033253	0.033067
210.0	0.002830	-0.000706	0.057201	0.034377	0.034201
220.0	0.002491	-0.000329	0.057571	0.034671	0.034478
230.0	0.002116	-0.000003	0.057836	0.034666	0.007919
240.0	0.001740	0.000270	0.057713	0.034666	0.007920
250.0	0.001425	0.000493	0.057384	0.034666	0.007920
260.0	0.001188	0.000674	0.056880	0.034666	0.007920
270.0	0.001020	0.000818	0.056502	0.034666	0.007920
280.0	0.000913	0.000925	0.055928	0.034728	0.007920
290.0	0.000860	0.001005	0.055331	0.035302	0.007920
300.0	0.000800	0.001068	0.054580	0.036414	0.007920
310.0	0.000740	0.001129	0.053336	0.037648	0.007920
320.0	0.000681	0.001190	0.052059	0.038818	0.007920
330.0	0.000655	0.001252	0.050521	0.039913	0.007920
340.0	0.000600	0.001316	0.048966	0.040033	0.008922
350.0	0.000564	0.001382	0.046143	0.041674	0.018637
360.0	0.000570	0.001450	0.042141	0.042738	0.030299
370.0	0.000578	0.001520	0.036707	0.043528	0.043318
380.0	0.000585	0.001594	0.030970	0.044236	0.049618
390.0	0.000589	0.001670	0.025678	0.044874	0.052639
400.0	0.000591	0.001747	0.021108	0.045449	0.053997
410.0	0.000590	0.001824	0.017303	0.045869	0.054536
420.0	0.000587	0.001900	0.014188	0.046438	0.054721
430.0	0.000582	0.001975	0.011646	0.046857	0.054761
440.0	0.000578	0.002048	0.009563	0.047232	0.054750
450.0	0.000573	0.002118	0.007841	0.047569	0.054729
460.0	0.000567	0.002185	0.006401	0.047671	0.054711
470.0	0.000561	0.002248	0.005184	0.048129	0.054699
480.0	0.000561	0.002302	0.004141	0.048340	0.054695
490.0	0.000560	0.002338	0.003237	0.007559	0.054696
500.0	0.000560	0.002309	0.002614	0.007614	0.054697
510.0	0.000560	0.002244	0.001741	0.007662	0.054697
520.0	0.000560	0.002154	0.001110	0.007705	0.054697
530.0	0.000560	0.002041	0.000539	0.007745	0.054697
540.0	0.000560	0.001907	0.000016	0.007781	0.054697
550.0	0.000560	0.001750	-0.000466	0.007814	0.054697

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