THE EFFECT OF COMBUSTION CHAMBER GEOMETRY ON S.I. ENGINE COMBUSTION RATES - A MODELING STUDY

by

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ABSTRACT

Faster burning in SI engines improves tolerance to very lean operation and to burning of low grade fuels. One way to raise the burning rate is to design the combustion chamber to increase flame front area. In this work, the mechanism by which combustion chamber geometry affects burn duration in SI engines is studied using a quasi-dimensional cycle simulation. Specifically, the importance of chamber geometry, the relative merits of ten different chamber geometries, and the relative merits of chamber design vs. amplified turbulence in reducing burn duration are investigated.

Purely geometric effects are studied using a model for the geometric interaction between a spherical flame and a general combustion chamber geometry. Spark plug location is found to be more important than chamber shape in determining flame front area. Results obtained with the geometric model are then used by the cycle simulation in three studies in which flow, chemical, and geometric effects are allowed to interact in determining burn duration. The model predicts that the effect of chamber geometry on burn duration is large and is roughly independent of engine speed, equivalence ratio, and load. Both retarded spark timing and EGR are found to reduce gains achieved through improvements in chamber design. Differences in burn duration obtained with ten different chambers are presented and discussed.

Relocation of the spark plug from the side to the center of a chamber is found to cause a much larger rise in burn rate during the main stage of combustion (10-90% burn) than in the early stage (0-10% burn). In contrast, amplifying the turbulence level produces a uniform rise in burn rate throughout combustion. A model for the mechanism by which changes in combustion chamber geometry interact with other factors affecting burn duration is presented. This model is contrasted with a similar model for the effect of amplified turbulence. Significant feedback effects are shown to exist in both mechanisms.

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TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

Increasing fuel cost has led to intense efforts by researchers to improve the operating efficiency of spark-ignition (SI) engines. One way of raising efficiency is to increase the rate of combustion. While faster burning has only a small direct effect on engine efficiency, it can extend the range of stable engine operation to allow very dilute fuel/air mixtures to be burned, thus indirectly raising efficiency. Alternatively, rapid burning can permit burning of less expensive, lower grade fuels without excessive knock. A good review of the merits and some of the drawbacks of fast burning in SI engines is given by Mattavi (1).

Two methods are commonly used to increase burning rates in SI engines. The first involves the generation of highly turbulent charge motion via the use of intake flow restrictions or combustion chambers with large "squish" regions. Increased turbulence results in higher energy transport rates and in increased distortion of the flame front. Both of these effects accelerate the rate of engulfment of unburned charge by the propagating flame, and therefore increase the burning rate. However, penalties must be paid for generating turbulence. Not only do intake restrictions reduce air flow through the engine and hence power output, but the vigorous gas motion results in a substantial rise in heat loss through the combustion chamber walls.

The second approach to reducing burn duration is to increase the frontal area of the flame as it propagates into the unburned charge. Simply put, the larger the exposed flame front area, the more mass can be engulfed per unit time. To achieve faster burning by this method requires

a combustion chamber designed to minimize contact between the propagating flame and the chamber walls. Increasing the burn rate can therefore be accomplished by use of a more compact (small surface to volume ratio) combustion chamber, and by moving the spark plug to a more central location in the chamber. The advantages of using chamber design over turbulence generation to achieve faster burning are that no air flow penalties need be incurred, and that heat losses can be minimized. The drawback of this approach is that compact chambers with central spark plug locations are difficult to implement in practical engines, where valve location can place severe constraints on chamber design. However, such design problems are by no means unsurmountable --compact fast burn chambers are already being used in some production engines (2). It is therefore of interest to examine quantitatively the extent to which chamber design can be used to achieve faster burning and to study, in some detail, how burn duration depends on combustion chamber geometry.

Early investigations into the effect of combustion chamber geometry on burn duration consisted mainly of experimental parametric studies (3,4). While these studies supplied quantitative evidence of the importance of engine geometry in determining burn rates, they provided little insight into the detailed mechanism by which chamber shape and spark plug location affect the combustion process. More recently, with the advent of engine cycle simulations and the development of predictive models for the combustion process (5,6), some investigators have tried to model the interaction between the flame and the combustion chamber. Hires et al (7) combined a thermodynamic model of the SI engine cycle with the "quasi-dimensional" combustion model of Tabaczynski et al. (6) to make predictions of burn duration for three engines with differing chamber geometries. Mattavi et

al. (8) and Lienesch (9) applied similar modeling techniques to compare wedge and open chambers and, from their results, suggested changes in chamber geometry leading to improvements in engine performance. Lately, Lucas and Brunt (10) performed an extensive study of the effect of combustion chamber shape on burn rates. Their work, which coupled experimental observations with model predictions, showed that, while flame speed was largely independent of chamber geometry, changes in chamber geometry had a strong effect on burn rate, cylinder pressure, and cycle by cycle variations. Davis and Borgnakke (11) extended the basic combustion model of Tabaczynski et al. by adding a k-ε turbulence model to incorporate effects of in-cylinder flows on combustion. They examined the effects of swirl, squish, and turbulence intensity on burn duration for bowl-in-piston chamber geometries providing varying degrees of squish and for a disk chamber with single and dual spark plugs. Research dealing with geometric effects on burn duration remains active as of this writing.

The goal of this thesis is to provide a better understanding of the mechanism by which combustion chamber geometry affects burn duration in SI engines. Greater emphasis is placed on geometrical effects on burn rate than on engine performance gains resulting from faster burning. The approach taken is to use an engine cycle simulation to perform fundamental illustrative calculations dealing with the effect of combustion chamber geometry on burn duration. These calculations are aimed at addressing three basic issues: (i) the importance of combustion chamber geometry in determining burn duration; (ii) the relative merits of different combustion chamber shapes and spark plug locations in achieving faster burning; and (iii) the relative merits of combustion chamber design vs. increased turbulence generation as means to reducing burn duration.

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The remainder of the thesis is arranged as follows. Chapter 2 is a description of the SI engine cycle simulation developed for the investigation. Chapter 3 describes a model for the geometric interaction between a propagating flame and an arbitrary combustion chamber. Chapter 4 summarizes the calibration of the cycle simulation with experimental data. Chapter 5 explains the procedure taken and presents the predictions of the modeling study. A summary and conclusions of the study are given in Chapter 6.

CHAPTER 2

SI ENGINE CYCLE SIMULATION

2.1 Background

An engine cycle simulation is a mathematical model of the processes occuring in an engine over a complete cycle. Cycle simulations are typically classified as zero-dimensional or multi-dimensional (one-, two-, or three-dimensional). Zero-dimensional models, also known as thermodynamic models, follow changes in only the bulk properties of the cylinder charge. In their basic form, they require the rate of combustion as an input to the calculation. These models are therefore of little value in assessing the effect of changes in engine geometry on burn duration. In contrast, multi-dimensional models generate spatially resolved predictions and can operate without a specified energy release schedule. However, current multi-dimensional calculations are only one- or two-dimensional. In addition, these models require very large computational effort when applied to even the simplest of engine geometries. They are therefore poorly suited to studies in which combustion chamber shape is the main parameter of interest.

The most versatile model for predictive studies involving engine geometry, and that which is used in this study, is a zero-dimensional cycle simulation combined with a phenomenological model for combustion which includes the gross interaction between the propagating flame and the combustion chamber. The combined model, referred to as a quasi-dimensional simulation, allows general changes in combustion chamber geometry to be investigated with only moderate computational requirements.

The SI engine cycle simulation developed in this work is based on an existing simulation for indirect-injection diesel engines (12). The SI

simulation retains many of the basic modeling assumptions as well as the modular structure and efficient computational algorithm of the parent diesel code. The major changes required were the removal of the pre-chamber from all parts of the simulation, the replacement of the diesel combustion model by a phenomenological model for homogeneous combustion, and change from tables of thermodynamic properties to a set of approximate thermodynamic property routines. Also, many minor changes were needed to complete the transformation from a diesel to an SI engine simulation.

The cycle simulation is designed to predict the details of the combustion process over a broad range of operating and design conditions, including detail variations in combustion chamber geometry. In what follows, the basic assumptions and the individual sub-models of the SI engine simulation are presented. In addition, an outline of the computational algorithm and a list of inputs and outputs to the calculation are given.

2.2 Basic Framework and Assumptions of the Model

The SI engine cycle is treated as a sequence of continuous processes, viz., intake, compression, combustion (including expansion), and exhaust. The durations of the individual processes are as follows. The intake process begins when the intake valve opens (IVO) and ends when the intake valve closes (IVC). The compression process begins at IVC and ends at the time of spark ignition. The combustion process begins at spark ignition and ends when the exhaust valve opens (EVO). The exhaust process begins at EVO and ends at IVO (and not when the exhaust valve closes (EVC)).

In this simulation, the system of interest consists of the instantaneous contents of a single engine cylinder. In general, the system is open to the transfer of mass, enthalpy, and energy in the form of work

and heat. Throughout the cycle, the cylinder is treated as a variable volume plenum i.e., spatially uniform in pressure. During intake, compression, and exhaust, the cylinder charge is assumed to be a homogeneous mixture of non-reacting ideal gases. Thus, the composition of the charge is assumed frozen and the charge is characterized by a single mean temperature. During intake and compression, the charge consists of a mixture of air, fuel vapor, and residual burned gas. During exhaust, the products of complete combustion are assumed to be the only component gas. For the combustion process, the cylinder is divided into an unburned zone and a burned zone. Each of these zones is assumed to be uniform in temperature and composition. The unburned zone is treated in the same way as the entire charge is treated during intake and compression. The burned charge is treated as a homogeneous mixture of ideal gases in chemical equilibrium.

For the purpose of modeling NO formation, the burned zone is further divided into an adiabatic core and a thermal boundary layer (see Fig. 1). This more realistic representation of the temperature distribution in the burned zone is aimed at obtaining more accurate predictions of NO formation than would be possible with a single temperature model. However, division of the burned zone into sub-zones is only performed after the overall burned zone state is known. Additional assumptions are presented in the descriptions of the individual sub-models.

2.3 Thermodynamic Analysis of the Cylinder Contents

To follow changes in the thermodynamic state of the cylinder contents, an expression is required for the time rate of change of temperature of a general open system. In this simulation, the general system is a mixture

of at most two component gases (to account for residual gas accompanying the fresh charge), both of which are at the same temperature and pressure. To be useful, such an equation must not explicitly depend on the rate of change of pressure of the system. Once the general solution is obtained, it is applied to each zone in the chamber during each of the four cycle processes. In this section, the basic equations used in the thermodynamic analysis are presented.

The general energy equation for an open system is given by:

$$\dot{E} = \sum \dot{m}_j h_j - \dot{Q}_w - \dot{W} \tag{2.1}$$

with, $\dot{E} = (\dot{m}h) - (\dot{p}V)$: rate of change of energy (2.2)

$\sum \dot{m}_j h_j$: net rate of influx of enthalpy

$\dot{Q}_w$: rate of heat transfer to walls (heat <u>loss</u> is positive)

$\dot{W} = p\dot{V}$: rate of doing work (work <u>by</u> the system is positive) (2.3)

and the dots denote differentiation with respect to time. If the fresh charge and the residual gas are both assumed to be ideal gases, then their properties are related to those of the mixture by,

$$h = x_1 h_1 + x_2 h_2 \tag{2.4}$$

$$R = x_1 R_1 + x_2 R_2 \tag{2.5}$$

where,

x_i : mass fraction of component i

i = 1: fresh change (air + fuel vapor)

i = 2: residual burned gas

h : enthalpy

R : specific gas constant

For ideal gases, the following relations must also apply,

$$\dot{p}/p = \dot{T}/T + \dot{\rho}/\rho + \dot{R}/R \tag{2.6}$$

$$\dot{h}_i = C_{p_i}\dot{T} + C_{T_i}\dot{p} \; ; \; i = 1,2 \tag{2.7}$$

$$C_p \equiv (\partial h/\partial T)_p$$

$$C_T \equiv (\partial h/\partial p)_T$$

$$\dot{\rho} = (\partial\rho/\partial T)_p\dot{T} + (\partial\rho/\partial p)_T\dot{p} \tag{2.8}$$

Combining the previous equations, the rate of change of pressure can be expressed as:

$$\dot{p} = \frac{\rho}{(\partial\rho/\partial p)_T}\left\{ \frac{(R_1-R_2)}{R}\dot{x}_1 - \frac{\dot{V}}{V} - \frac{1}{\rho}\left(\frac{\partial\rho}{\partial T}\right)_p\dot{T} + \frac{\dot{m}}{m} \right\} \tag{2.9}$$

Returning to the basic energy equation, (2.1), and introducing equations (2.2) through (2.9), the general solution for the rate of change of temperature of an open system consisting of two ideal gases at the same temperature and pressure is:

$$\dot{T} = \frac{B}{A}\left\{ \dot{x}_1\left(\frac{R_1-R_2}{R} + \frac{h_2-h_1}{B}\right) + \frac{\dot{m}}{m}\left(1 - \frac{h}{B}\right) - \frac{\dot{V}}{V} + \frac{1}{Bm}\left(\sum \dot{m}_j h_j - \dot{Q}_w\right) \right\} \tag{2.10}$$

where,

$$A = C_p + \frac{(\partial\rho/\partial T)_p}{(\partial\rho/\partial_p)_T}\left(\frac{1}{\rho} - C_T\right) \tag{2.11}$$

$$B = (1 - \rho C_T)/(\partial\rho/\partial p)_T \tag{2.12}$$

Equation (2.10) can now be applied to the individual zones in the chamber for the four processes of the cycle. The resulting expressions are:

Intake:

$$\dot{T} = \frac{B}{A}\{ \dot{x}_1(\frac{R_1-R_2}{R} + \frac{h_2-h_1}{B}) + \frac{\dot{m}}{m}(1 - \frac{h}{B}) - \frac{\dot{V}}{V}$$

$$+ \frac{1}{Bm}(\dot{m}_{in}h_{in} - \dot{m}_{ex}h - \dot{Q}_w) \} \qquad (2.13)$$

Compression:

$$\dot{T} = \frac{B}{A}\{ - \frac{\dot{V}}{V} - \frac{\dot{Q}_w}{Bm} \} \qquad (2.14)$$

Combustion:

i) unburned zone:

$$\dot{T}_u = \frac{B_u}{A_u}\{ \frac{\dot{x}_b}{x_b-1} - \frac{\dot{V}_u}{V_u} - \frac{\dot{Q}_{wu}}{B_u m_u} \} \qquad (2.15)$$

ii) burned zone:

$$\dot{T}_b = \frac{B_b}{A_b}\{ \frac{\dot{x}_b}{x_b}(1 + \frac{h_u-h_b}{B_b}) - \frac{\dot{V}_b}{V_b} - \frac{\dot{Q}_{wb}}{B_b m_b} \} \qquad (2.16)$$

Exhaust:

$$\dot{T} = \frac{B}{A}\{ - \frac{\dot{m}}{m} - \frac{\dot{V}}{V} - \frac{\dot{Q}_w}{Bm} \} \qquad (2.17)$$

The thermodynamic properties needed in the solution of equations (2.13) through (2.17) are calculated from a set of approximate polynomial expressions developed by Martin and Heywood (13) for hydrocarbon-air

mixtures. Separate expressions are used for unburned mixture, low temperature (frozen composition) combustion products, and high temperature (equilibrium) combustion products.

2.4 Modeling of Engine Processes

2.4.1 Gas Exchange

A one-dimensional quasi-steady compressible flow model is used for mass exchange between the engine cylinder and the intake and exhaust manifolds. The manifolds are treated as infinite plenums with specified pressures. The intake charge is a mixture of fresh charge (fuel vapor and air) and recirculated exhaust gas (EGR). The temperature of the fresh charge, as well as the mass fraction and temperature of the recirculated gas are inputs to the calculation. The exhaust charge consists of fully burned combustion products at the instantaneous temperature of the cylinder contents. If a back-flow into the intake manifold occurs during the intake process, the mass which leaves the cylinder is assumed to have the temperature and composition of the cylinder charge. Any mixing between the back-flowing mass and the intake charge is neglected. Therefore, all of the out-flowing mass must return to the cylinder before more fresh charge can be inducted.

At each step of the gas exchange process, values for the valve open areas and discharge coefficients are obtained from tabular data. Given the open area, the discharge coefficient, and the pressure ratio across a particular valve, the mass flow rate across that valve is calculated as,

$$\dot{m} = c_d A \frac{p_o}{RT_o} \sqrt{\gamma R T_o} \left\{ \frac{2}{\gamma-1} \left[\left(\frac{p_s}{p_o}\right)^{2/\gamma} - \left(\frac{p_s}{p_o}\right)^{(\gamma+1)/\gamma} \right] \right\}^{1/2} \qquad (2.18)$$

where, c_d: discharge coefficient

A : valve open area

p_o: stagnation pressure upstream of restriction

p_s: static pressure at restriction

T_o: stagnation temperature upstream of restriction

γ : ratio of specific heats

R : gas constant

When the kinetic energy in the cylinder is negligible, the stagnation pressure and temperature reduce to the static pressure and temperature, respectively. For the case of choked flow, equation (2.18) reduces to,

$$\dot{m} = c_d A \frac{P_o}{RT_o} \sqrt{\gamma R T_o} \left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/2(\gamma-1)} \tag{2.19}$$

The convention for mass flows used in this model is as follows: flow into the cylinder through the intake valve is positive; flow out of the cylinder through the exhaust valve is positive. The mass in the cylinder at any time, t, is found from,

$$m(t) = m_o + \int_{t_o}^{t} \dot{m}_{int}\, dt - \int_{t_o}^{t} \dot{m}_{exh}\, dt \tag{2.20}$$

where, $m(t)$: mass in the cylinder at time t

m_o : mass in the cylinder at start of cycle (t_o)

2.4.2 Turbulent Flow

Both the combustion model and the heat transfer model of the cycle simulation require estimates of characteristic velocity and length scales. To estimate these scales in a way which incorporates the key physical

mechanisms affecting charge motion in the cylinder, a turbulent flow model was used. The present model is a variation of the model used by Mansouri et al. (12) in the diesel engine simulation from which this simulation is derived.

The turbulence model consists of a zero-dimensional energy cascade: mean flow kinetic energy is supplied to the cylinder through the valves; mean kinetic energy is converted to turbulent kinetic energy through a turbulent dissipation process; turbulent kinetic energy is converted to heat through viscous dissipation. When mass flows out of the cylinder, it carries with it both mean and turbulent kinetic energy. Figure 2 illustrates the energy cascade model.

At any time during the cycle, the mean flow velocity, U, and the turbulent intensity, u', are found from knowledge of the mean and turbulent kinetic energies, respectively. Thus, the following expressions apply:

$$K = \frac{1}{2} m U^2 \tag{2.21}$$

$$k = \frac{3}{2} m u'^2 \tag{2.22}$$

where the factor 3 in equation (2.22) comes from assuming that the small scale turbulence is isotropic and accounting for all three orthogonal fluctuating velocity components.

With this model, the time rate of change of mean kinetic energy, K, is given by:

$$\frac{dK}{dt} = \frac{1}{2} \dot{m}_i V_i^2 - P - K \frac{\dot{m}_e}{m} \tag{2.23}$$

Similarly, the rate of change of turbulent kinetic energy, k, is:

$$\frac{dk}{dt} = P - m\varepsilon - k\frac{\dot{m}_e}{m} \tag{2.24}$$

and

$$\varepsilon \simeq u'^3/\ell = (2k/3m)^{3/2}/\ell$$

where,

- m : mass in the cylinder
- $\dot{m}_i$: mass flow rate into the cylinder
- $\dot{m}_e$: mass flow rate out of the cylinder
- V_i: jet velocity into the chamber
- P : rate of turbulent kinetic energy production
- ε : rate of turbulent kinetic energy dissipation per unit mass
- ℓ : characteristic size of the large-scale eddies.

The production term, P, in equations (2.23) and (2.24) is a complicated function of local flow conditions in the cylinder. However, since this model does not predict spatially resolved flow parameters, P must be estimated from mean flow quantities only. The approach taken here is to assume that turbulence production in an engine cylinder is similar to turbulence production in a turbulent boundary layer over a flat plate. P can then be modeled as (14),

$$P = \mu_t \left(\frac{\partial U}{\partial y}\right)^2 \tag{2.26}$$

where,

$\mu_t = c_\mu k^2/(m\varepsilon)$: turbulent viscosity

$c_\mu = 0.09$: a universal constant

Since the velocity gradient in equation (2.26) is not known, it is modeled as

$$\left(\frac{\partial U}{\partial y}\right)^2 = c_\beta \left(\frac{U^2}{L^2}\right) \tag{2.27}$$

where c_β is an adjustable constant and L is a geometric length scale. Combining equations (2.26) and (2.27) results in the following expression for P:

$$P = 2(3/2)^{3/2} c_\mu c_\beta (K\ell/L^2)(k/m)^{1/2} \tag{2.28}$$

To complete the turbulence model, assumptions for the length scales, and L, are required. Throughout this cycle simulation, the macroscale of turbulence and the representative geometric length scale are assumed to be given by:

$$\ell = L = V/(\pi B^2/4) \tag{2.29}$$

where, V = instantaneous volume of the combustion chamber

B = cylinder bore

subject to the restriction that

$$L \leqslant B/2 \tag{2.30}$$

Equation (2.28) can now be simplified to it's final form:

$$P = 0.3307 c_\beta (K/L)(k/m)^{1/2} \tag{2.31}$$

As will be discussed in the description of the combustion model, the evolution of the turbulent intensity and the turbulence macroscale during combustion is governed by conservation of angular momentum for the large

scale eddies. The turbulence model supplies the initial conditions for the start of combustion. Once combustion begins, the production term, P, continues to be calculated for use in equation (2.23). However, P is assumed to be zero in equation (2.24). When the combustion process is over, the macroscale and turbulent intensity calculated from conservation of eddy angular momentum become the initial conditions for the remainder of the cycle, and normal functioning of the turbulence model is resumed.

2.4.3 Heat Transfer

Heat transfer in SI engines is dominantly due to convection from the turbulent flow in the cylinder to the combustion chamber walls. In the model presented here, both radiation heat transfer and heat loss in the exhaust port are neglected. If convection is assumed to be the only mode of heat transfer, then the heat transfer rate can be expressed as

$$\dot{Q}_w = hA(T_g - T_w) \tag{2.32}$$

where,

- h : convective heat transfer coefficient
- A : surface area
- T_g: gas temperature
- T_w: wall temperature

The value of h is calculated using the following expression for steady turbulent flow in a pipe (15):

$$Nu = \alpha Re^d Pr^e \tag{2.33}$$

where, $Nu = hL/\lambda$: Nusselt number

$Re = VL/\nu$: Reynolds number

$Pr = \mu c_p/\lambda$: Prandtl number $\simeq 1.0$

α : constant

d : constant $\simeq 0.8$

e : constant $\simeq 0.33$

L : characteristic length

λ : thermal conductivity

V : characteristic velocity

$\nu = \mu/\rho$: kinematic viscosity

μ : dynamic viscosity

ρ : density

c_p : specific heat at constant pressure

For this model, the characteristic length scale is taken to be the macroscale of turbulence, as calculated in equations (2.29) and (2.30) of section 2.4.2. V is postulated to be an effective velocity due to contributions from the mean kinetic energy, the turbulent kinetic energy, and piston motion:

$$V = \{U^2 + u'^2 + (\frac{1}{2}V_p)^2\}^{1/2} \tag{2.34}$$

where, U : mean flow velocity

u': turbulent intensity

V_p: instantaneous piston speed

This expression for V is speculative. However, increases in any of the three component velocities should lead to increases in the heat transfer rate. Also, the form of equation (2.34) is such as to reduce errors due to overestimating the contributions from any of the individual sources. Clearly, more experimental and modeling work is needed before any formulations for the characteristic velocity can be either justified or disproved. For the present investigation, though, the proposed model is believed to be adequate, providing that the parameter, α, is suitably adjusted.

The gas temperature in equation (2.32) is assumed to be the mean temperature of the gas under consideration. During combustion, equation (2.32) is applied separately to the unburned and burned zones. Calculation of the surface area for the two zones during combustion is explained in Chapter 3.

The viscosity and thermal conductivity needed to solve for h in equation (2.33) are found from experimental correlations. For the unburned gas, μ and c_p are assumed to be the same as for air. Therefore, a correlation for air (16) is used. For the burned gas, a correlation for the viscosity and Prandtl number of hydrocarbon-air combustion products (17) is used.

2.4.4 Combustion

The SI engine combustion process is modeled with a phenomenological model. In contrast to fundamental models (18,19), which are based on a detailed description of the turbulent reacting flow, phenomenological models combine some fundamental knowledge with physical intuition to postulate a simplified mechanism for the combustion process. Typically,

only mean or bulk quantities define the state of the cylinder charge. The combustion model used in this simulation was first postulated by Blizard and Keck (5) and was later extended by Tabaczynski et al. (6,20). The present model retains the extended version of the combustion mechanism but it is coupled with a simple turbulence model in an attempt to more directly link in-cylinder flows with the combustion process.

The model is described in three sections. First, the basic assumptions about the character and behaviour of the flow field are presented. Next, assumptions about the burning mechanism are given. Finally, the equations governing the combustion process are developed. For a detailed derivation of the combustion model, the reader is referred to the original works referenced above.

2.4.4.1 Assumptions About The Flow Field

Real turbulent flows are characterized by a spectrum of eddy sizes and velocities. In this model, the entire turbulence spectrum is represented by three length scales and by one velocity, the turbulent intensity. The flow field is assumed to consist of coherent large eddies, the scale of which is given by the macroscale of turbulence, L. The Kolmogorov scale, η, is the smallest eddy size and also the scale at which most dissipation of turbulent kinetic energy occurs. In this model, the Kolmogorov scale is associated with the size of the vortex tubes. The spacing of the vortex tubes is assumed to be given by the Taylor microscale, λ. The model further assumes that diffusion is laminar on the Taylor microscale. Fig. 3 depicts the three length scales characterising the flow and the way in which they relate to one another.

The turbulent flow field in the chamber is assumed to be isotropic. At the start of combustion, the turbulence is also assumed to be homogeneous. Initial values for the turbulent intensity and the macroscale are supplied by the turbulence model (see section 2.4.2). Once combustion begins, the unburned gas is assumed to be compressed by the flame at a rate sufficiently high that, on the time scale for flame propagation, dissipation of turbulent kinetic energy in the large eddies can be neglected. As a result, the evolution of the macroscale and the turbulent intensity after ignition are calculated by assuming conservation of angular momentum for the large eddies.

2.4.4.2 Assumptions About the Combustion Mechanism

Combustion is modeled as two simultaneous processes. The first process is the entrainment of unburned mixture by the flame. The entrainment velocity is modeled as the sum of a convective component, the turbulent intensity, and a diffusive component, the laminar flame speed. In this model, the entrainment velocity is the speed at which ignition sites (locations with high concentrations of active species) propagate into the unburned mixture along vortex tubes. Fig. 4 depicts an idealization of the entrainment process.

The second process in the combustion mechanism is the burnup of charge within the flame. Burning on the Taylor microscale is at the laminar flame speed, since diffusion is assumed to be laminar on that scale. Burning on the Kolmogorov scale is assumed instantaneous. With the above assumptions, the burnup time for an entrained eddy of scale λ is just the Taylor microscale divided by the laminar flame speed. Fig. 4 illustrates the burnup of entrained eddies inside the flame. Note that, with the proposed

two-process combustion mechanism, the burn rate is limited both by the ability of the flame to entrain unburned gas, and by the time required for subsequent burnup within the flame.

2.4.4.3 Governing Equations

2.4.4.3.1 Entrainment Rate

To obtain the entrainment rate, $\dot{m}_e$, mass conservation is applied at the moving entrainment front:

$$\dot{m}_e = \rho_u A_f (u' + S_L) \tag{2.35}$$

where, $\dot{m}_e$: rate of mass entrainment into the flame

ρ_u : density of the unburned mixture

A_f : gross entrainment area

u' : turbulent intensity

S_L : laminar flame speed

Note that the entrainment area, A_f, is the outer area of the entrainment front and not the total exposed area of the unburned eddies within the flame (see Fig. 4). The laminar flame speed is calculated from an empirical correlation due to Metghalchi and Keck (21), modified by a correction to account for mixture dilution by residual gases. The correction term is a function of burned gas fraction and is based on data by Rhodes (22) from experiments with constant volume combustion of Indolene-air mixtures. The complete form of the laminar flame speed correlation is,

$$\frac{S_L}{S_{L\infty}} = \left(\frac{T_u}{T_\infty}\right)^{\alpha} \left(\frac{p}{p_\infty}\right)^{\beta} (4.706f^2 - 4.062f + 1) \tag{2.36}$$

where, T_u : unburned gas temperature

T_∞ : 298 K

p : cylinder pressure

p_∞ : 1 atm

S_{L_∞} : laminar flame speed at T_∞ and p_∞ with $f = 0$

α : correlation parameter

β : correlation parameter

f : residual gas fraction

2.4.4.3.2 Burning Rate

In section 2.4.4.2, the assumption was made that the time to burn an eddy of size λ could be given by,

$$\tau = \frac{\lambda}{S_L} \tag{2.37}$$

At any time during combustion, the flame contains many such unburned eddies. The mass rate of burning for each eddy is approximately,

$$\dot{m}_\lambda = \frac{m_\lambda}{\tau} \tag{2.38}$$

where, m_λ : mass of a single eddy of scale λ

Since the small eddies are burning simultaneously, the overall mass burn rate is the total mass in the unburned eddies within the flame divided by the characteristic burning time for each (and every) individual eddy:

$$\dot{m}_b = \frac{m_e - m_b}{\tau} \tag{2.39}$$

2.4.4.3.3 Evolution of Turbulence Parameters

Once combustion begins, conservation of angular momentum is applied to the large eddies. The assumption of discrete coherent large eddies implies that, as the flame propagates, the mass of the individual eddies is conserved. However, the number of eddies in the unburned region decreases due to engulfment by the flame. Conservation of mass for a single eddy of volume V_L requires that,

$$\rho_u V_L = \rho_{uo} V_{Lo} \tag{2.40}$$

where

ρ_u : unburned mixture density

and subscript o refers to conditions at the time of spark. Then since,

$$V_L \sim L^3 \tag{2.41}$$

where

L : macroscale of turbulence

one can write for the evolution of the macroscale:

$$\rho_u L^3 = \rho_{uo} L_o^3 \tag{2.42}$$

or, rearranging,

$$\frac{L}{L_o} = \left(\frac{\rho_{uo}}{\rho_u}\right)^{1/3} \tag{2.43}$$

Conservation of eddy angular momentum requires that

$$u_\omega L = u_{\omega o} L_o \tag{2.44}$$

where, u_ω : characteristic velocity due to eddy vorticity

Combining equations (2.43) and (2.44) with the assumption that

$$u_\omega \sim u' \tag{2.45}$$

the following relation is obtained for the evolution of the turbulent intensity during combustion:

$$\frac{u'}{u'_o} = \left(\frac{\rho_u}{\rho_{uo}}\right)^{1/3} \tag{2.46}$$

Throughout the combustion process, the Taylor microscale is related to the macroscale and to the turbulent intensity by the following expression for isotropic turbulence (14):

$$\frac{\lambda}{L} = c\left(\frac{u'L}{\nu}\right)^{-1/2} \tag{2.47}$$

where

c = constant (= $\sqrt{15}/A$ for perfect isotropy; $A \sim 1$)

2.4.5 NO Formation

2.4.5.1 Adiabatic Core / Boundary Layer Model:

The formation rate of nitrous oxide (NO) in SI engines is extremely temperature dependent. As a result, modeling NO formation based on an average temperature for the entire burned zone can lead to inaccurate predictions. In this simulation, the burned zone is divided into a high temperature adiabatic core and a lower temperature (frozen composition) thermal boundary layer (refer to Fig. 1). The temperature of the boundary layer is taken as,

$$T_{bl} = \frac{T_b + T_{wb}}{2} \tag{2.48}$$

where T_{wb} is the area weighted mean of the wall temperatures in the burned zone, and T_b is the burned zone temperature. The temperature of the adiabatic core is found by requiring that

$$x_b h_b = x_{bl} h_{bl} + x_a h_a \tag{2.49}$$

where, x_i: mass fraction in zone i

$i = b$: burned zone

$i = bl$: boundary layer

$i = a$: adiabatic core

and solving for T_a from knowledge of h_a and p. At any instant, the value of x_{bl} is found by integrating the following equation from the start of combustion up to the time of interest:

$$\dot{x}_{bl} = \frac{\left(1 - \frac{x_{bl}}{x_b}\right)\left\{ A_{bl} x_{bl} \left(\dot{T}_{bl} - \frac{B_{bl}}{\rho_{bl} A_{bl}}\left[\left(\frac{\partial \rho}{\partial T}\right)_{bl} \dot{T}_{bl} + \left(\frac{\partial \rho}{\partial p}\right)_{bl} \dot{p}\right] + \frac{\dot{Q}_{wb}}{m}\right\}}{h_b - h_{bl}} \tag{2.50}$$

2.4.5.2 NO Formation Mechanism:

The rate of formation of NO is assumed to be governed by the extended Zeldovich mechanism (23):

$$N_2 + O \overset{k_1}{\leftrightarrow} N + NO \tag{2.51}$$

$$N + O_2 \overset{k_2}{\leftrightarrow} NO + O \tag{2.52}$$

$$N + OH \overset{k_3}{\leftrightarrow} NO + H \tag{2.53}$$

where, $k_1 = 7.6 \times 10^{13} \exp(-38{,}000/T)$ $(cm^3 gmole^{-1} sec^{-1})$ (2.54)

$k_2 = 1.5 \times 10^{9} \exp(-19{,}500/T)$ $(cm^3 gmole^{-1} sec^{-1})$ (2.55)

$k_3 = 4.1 \times 10^{13}$ $(cm^3 gmole^{-1} sec^{-1})$ (2.56)

T : temperature (K)

Once the properties of the adiabatic core and boundary layer are known, the rate of NO formation in the adiabatic core is found from,

$$\frac{d\{NO\}_a}{dt} = \frac{2M_{NO}R_1(1 - \alpha^2)}{\rho_a(1 + K\alpha)} - \frac{\dot{m}_{b1}}{m_a}\{NO\}_a \tag{2.57}$$

where, $\{NO\}$: mass fraction of $\{NO\}$

M_{NO} : molecular weight of NO

α : $\lfloor NO \rfloor / \lfloor NO \rfloor_e$

$\lfloor \quad \rfloor_e$: equilibrium mole fraction

ρ_a : adiabatic core density

$$K = R_1/(R_2 + R_3) \tag{2.58}$$

$$R_1 = k_1 \lfloor N_2 \rfloor_e \lfloor O \rfloor_e \tag{2.59}$$

$$R_2 = k_2 \lfloor N \rfloor_e \lfloor O_2 \rfloor_e \tag{2.60}$$

$$R_3 = k_3 \lfloor N \rfloor_e \lfloor OH \rfloor_e \tag{2.61}$$

The NO formation model assumes that the gas composition in the thermal boundary layer is frozen. The rate of change of $\{NO\}$ in the boundary layer due to mass transfer from the adiabatic core is given by:

$$\frac{d\{NO\}_{b1}}{dt} = \frac{\dot{m}_{b1}}{m_{b1}}\{NO\}_a \tag{2.62}$$

The total mass of NO in the cylinder at the end of one complete cycle is found by integrating equations (2.57) and (2.62) over the duration of the combustion process and appropriately summing their individual contributions.

2.5 Method of Solution

When the individual sub-models of the cycle simulation are brought together to form a complete model, the result is a set of twenty first-order ordinary differential equations. To perform predictive calculations with the cycle simulation, these equations must be simultaneously integrated over the full operating cycle. However, some of the governing equations (e.g. rate of mass flow through the intake valve and rate of mass burning) apply only during parts of the cycle. Lists of the non-zero derivatives which must be integrated in each stage of the cycle are contained in Appendix A.

Integration of the governing equations is performed numerically using a standardized code developed by Shampine and Gordon (24). To maximize efficiency, the integration routine calculates it's own optimal integration time step. The detailed procedure followed in performing the integration is documented within the code (see Appendix A).

A flow chart showing the overall structure of the cycle simulation is shown in Fig. 5. The main program performs initialization of variables prior to integration, determines which sets of equations the integrator will work with, and calculates and prints out results as the cycle proceeds. Four secondary routines are called in turn by the integration routine to supply it with the derivatives of the variables which it must integrate. The four secondary routines correspond to the intake, compression, combustion, and exhaust processes, respectively. A third level of routines is called by the second level routines to help in evaluating the necessary derivatives at each step. Examples of third level subroutines are thermodynamic and transport property routines, tables of

valve flow areas and discharge coefficients, and tables for the geometric interaction between the flame and the combustion chamber.

The cycle simulation requires estimates for the cylinder pressure, temperature, mean kinetic energy, and turbulent kinetic energy at the start of the first calculated cycle. Appropriate estimates to cause the cycle to converge are not a priori known. Therefore, in general, more than one iteration is required to model an engine operating under steady conditions. Once the first cycle has been completed, a check for convergence is performed and, if convergence is not achieved, the final pressure, temperature, and kinetic energies of the cycle are used as estimates for the start of another iteration. If reasonable guesses are made, a second iteration will normally yield final pressures and temperatures within less than 1% of the initial values for that iteration.

2.6 Inputs and Outputs of the Model

2.6.1 Model Inputs

To operate the cycle simulation, a set of input parameters must be specified. These input parameters are grouped into the following categories:

i) Operating Mode

The operating mode can be either motoring (no combustion), firing with a predicted burn rate (using the phenomenological combustion model), or firing with a specified burn rate (using a Wiebe function to control the mass fraction burned vs. crank angle). If the specified burn rate is used, the burn duration and two parameters which adjust the shape of the Wiebe function must be specified.

ii) Operating Conditions

Basic operating parameters other than conditions at the intake and exhaust manifolds are included in this category. The operating parameters are fuel type (isooctane or propane), fuel/air equivalence ratio, ignition timing, and engine speed.

iii) Manifold Conditions

Manifold conditions include intake and exhaust manifold pressures, exhaust gas recirculation (EGR, expressed as a percentage of mass flow through the intake manifold), fresh charge and EGR temperatures, and the ambient pressure and temperature.

iv) Heat Transfer and Turbulence Parameters

This grouping contains the adjustable parameters associated with the turbulence and heat transfer models of the cycle simulation. They are the heat transfer constant, α, and Reynolds number exponent, d, the temperatures of the piston, cylinder head, and cylinder wall, the turbulent dissipation constant, c_β, and a constant which can artificially amplify the calculated turbulence intensity during the combustion process.

v) Basic Engine Design Parameters

Required engine design parameters are the cylinder bore, crankshaft stroke, connecting rod length, displaced volume, clearance volume, and the crank angles at which the intake and exhaust valves open and close.

vi) Computational Parameters

A set of fourteen parameters affecting the performance of calculations and the error tolerances used in the integration algorithm must be specified. These parameters are discussed in more detail in the cycle simulation code (see Appendix A).

In addition to the list of inputs given above, the cycle simulation must have access to tables for the geometric interaction betweeen the propagating flame and the combustion chamber being used. Generation of such detailed geometric data for a particular combustion chamber is discussed in Chapter 3.

2.6.2 Model Outputs

Four types of outputs are generated by the cycle simulation:

i) Input Echo

A listing of all the input parameters except for the detailed geometric data is returned. The list includes some quantities derived directly from the given inputs (e.g. compression ratio).

ii) Main Crank Angle by Crank Angle Results

At specified crank angle intervals, cylinder pressure, temperature of each zone in the chamber, heat transfer rate, work done, and a code which monitors the performance of the integration routine, are returned. Depending on the part of the cycle being calculated, other output parameters are also listed. During intake, the mass flows and velocities at each valve, the mass fraction of fresh charge in the cylinder, and a code indicating whether fresh charge or back-flowing cylinder charge is flowing through the intake valve are returned. During combustion, the mass fractions entrained and burned are listed. During exhaust, the mass flow rate and velocity at the exhaust valve are returned.

iii) Integrated Results - Cycle Performance

Once the cycle is over, a summary of results obtained by integrating some of the governing equations over the cycle is given. Integrated

results include volumetric and thermal efficiencies, gross indicated and pumping mean effective pressures, total heat loss, burn duration (0-10% and 10-90% burn angles), NO emissions, and an estimated mean exhaust temperature. In addition to these performance parameters, a listing of the mass in the cylinder at IVO and at IVC, the mass of air and fuel inducted, and the residual fraction are returned. Finally, heat and work transferred during each process of the cycle and the results of an overall energy balance are shown.

iv) Sub-Model Results

After the overall cycle results are listed, results for the main sub-models of the cycle simulation are given at specified crank angle intervals. Detailed results are given in sections for flame propagation, adiabatic core and boundary layer development, NO formation, turbulent flow, and heat transfer. In each of these sections, the evolution of the main variables of interest is recorded throughout the cycle.

CHAPTER 3

MODEL OF THE GEOMETRIC INTERACTION BETWEEN A PROPAGATING FLAME AND AN ARBITRARY COMBUSTION CHAMBER

3.1 Background and Basic Assumptions

The combustion model of the cycle simulation requires an estimate of the outer area of the flame front in order to calculate the rate of entrainment of unburned charge by the flame (see section 2.4.4.3.1). Also, to adequately account for the different heat transfer rates in the unburned and burned zones during combustion, an estimate is required for the surface of the combustion chamber wetted by the burned gases as the flame propagates. Hence, to perform an investigation involving changes in combustion chamber design, a model was needed for the geometric interaction between a propagating flame and an arbitrary combustion chamber.

Photographic records (25,26) of combustion in SI engines show the flame starting as a small, roughly spherical kernel centered around the spark plug electrodes. The flame then interacts with the turbulent flow in the chamber and propagates into the unburned gas. As it propagates, the flame's initially spherical shape may be distorted and it's apparent center may be convected away from the spark plug electrodes. Thus, an accurate calculation of flame geometry requires spatially resolved information about in-cylinder flows. Since the turbulent flow model in this cycle simulation is fundamentally zero-dimensional, a detailed description of the flow is not available. However, experimental evidence suggests that, at least for quiescent chambers (i.e., without excessive swirl or squish effects), the flame develops roughly as a sphere with it's center fixed at the spark plug electrodes and truncated by the chamber walls.

Previous studies using quasi-dimensional models have almost invariably assumed the simplified flame geometry described above. The general agreement obtained between predictions using the spherical flame assumption and experimental data suggests that such an assumption is generally valid. The same assumption is therefore used in this study. As will be discussed in Chapters 5, motion of the flame center away from the spark plug electrodes can lead to sizable variations in the flame front area. It is probable, in fact, that differences in the paths taken by the flame centers of consecutive cycles are a major cause of cycle-by-cycle variations in peak cylinder pressure. Nevertheless, since this study is concerned with performing illustrative calculations for which cyclic dispersion is of secondary interest, convection of the flame is neglected.

3.2 Methodology

In the past, two basic approaches have been taken to solve for the interaction between the flame and the combustion chamber walls. Most researchers (5,6,10) have restricted there attention to simple geometries and have solved analytically for the flame area and wetted wall area. These solutions are of course very accurate. However, use of analytical methods with more complex geometries is not practical. The other approach has been to apply computer-aided-design techniques using elementary geometric shapes (spheres, planes, etc.) combined to form the approximate shape of the combustion chamber. Such techniques allow almost any combination of combustion chamber shape and spark plug location to be modeled, but may require special computer software/hardware packages.

For this study, an approximate model for the flame-combustion chamber interaction has been developed which can be applied to any arbitrary

combustion chamber shape with any spark plug location. In view of the uncertainty introduced by assuming a spherical flame with a fixed center, the fact that the results of the calculation are approximate is not considered to be important. All calculations are performed using a simple FORTRAN code with moderate computational requirements. For each piston position corresponding to an increasing crank angle from top center, a series of individual calculations are performed at equal flame radius increments until the flame passes through the chamber. At each individual radius step, the flame area, enflamed volume, and flame wetted wall area are calculated. When the entire calculation has been executed, the end result is a table in which the independent variables are crank angle from top center and flame radius, and the dependent variable is the enflamed volume. Thus,

$$V_e = f_1(\Theta, r_e) \tag{3.1}$$

where, V_e: enflamed volume

Θ : crank angle from top center

r_e: flame radius corresponding to Θ and V_e

f_1: a function

The geometric table is stored by the main cycle simulation. During combustion, the cycle simulation enters the table with known values of crank angle and enflamed volume and iterates to locate the correct flame radius. Once the flame radius is found, the flame area corresponding to the known radius and crank angle can be obtained from the table as follows:

$$A_f = f_2(\Theta, r_e) \tag{3.2}$$

where, f_2: a function different from f_1

The same procedure is used to find the wetted wall areas, except that the burned volume (which is generally less than the enflamed volume) is used as the dependent variable. The wetted wall area is thus calculated as:

$$A_w = f_3(\Theta, r_b) \tag{3.3}$$

where, A_w: chamber wall area wetted by the burned volume

r_b: flame radius corresponding to Θ and V_b

V_b: burned volume

f_3: a function different from f_1 and f_2

Note that, in calculating wetted wall area, the assumption is made that, like the entrained volume, the burned volume is shaped like a sphere centered at the ignition source and truncated by the combustion chamber walls.

In the remainder of this chapter, the method used to model the combustion chamber geometry, the three required calculations, and the model validation are described.

3.3 Modelling the Combustion Chamber Geometry

The surface of the combustion chamber is approximated by flat triangular facets, as shown in Fig. 6. The individual facets are identified by integer indices. The index for a given facet is associated with indices for the three points at the apices of the facet. The index for each of the three points is in turn associated with a set of x, y, and z coordinates which locate the point in space. The coordinate system used has it's origin at the intersection of the axis of symmetry of the engine cylinder with the mating plane between the cylinder and the cylinder head. The z axis is oriented vertically, while the x and y axes can have any azimuthal orientation provided they remain orthogonal to each other and to

the z axis. The location of the ignition source is specified by it's x, y, and z coordinates.

To account for piston motion as crank angle is changed, the facets on the piston must be shifted vertically and those on the cylinder walls must be "stretched". Translation or stretching of a facet is accomplished by translating all or some of the points of the facet. To know which points must be translated when the crank angle is changed, all points are initially labeled as being fixed or movable. The facets are also labeled to identify them as being located on the cylinder head, piston, or cylinder wall. Labeling of facets in this fashion permits the wetted wall areas on each of the three regions of the combustion chamber to be calculated.

3.4 Calculation of Flame Front Area

For a given crank angle and flame radius, the procedure for calculating the flame front area consists of the following basic steps. First, a pseudo-random number generator is used to generate a large number of points on the surface of a sphere centered at the ignition source and having the given flame radius. Next, each point on the sphere is tested for inclusion by the volume of the combustion chamber. The area of the flame is then calculated as:

$$A_f(r_f,\Theta) = A_{sph}(r_f) \times \frac{N_{in}}{N_{total}} \tag{3.4}$$

where, $A_{sph}(r_f)$: surface area of a sphere with the flame radius

N_{in} : number of points on the flame sphere which lie inside the combustion chamber

N_{total} : total number of points on the flame sphere

The accuracy of the calculation depends on the number of points tested on the surface of the sphere. To decide whether a test point on the surface of the sphere lies within the chamber or not, the following geometric principle (27) is applied (see Fig. 7):

> If a point which lies within an arbitrary volume in space is connected by a line segment to a test point anywhere in space, then the number of times, N_x, that the line segment connecting the two points intersects the surface of the volume determines whether the test point lies inside (in which case N_x is even) or outside (in which case N_x is odd) of the volume.

If the interior point is taken as the location of the ignition source, the volume as the volume of the combustion chamber, and the test point is located somewhere on the surface of a sphere with the flame radius, then the principle stated above can be applied to the problem of deciding whether a point on the flame sphere is inside the chamber (see Fig. 7). The problem is now reduced to counting the number of facets on the surface of the chamber which are intersected by a segment connecting the ignition source to a test point on the surface of the flame sphere. Thus, each facet must be tested to see whether the intersection between the line segment and the plane of the facet lies within the facet itself or elsewhere on the plane of the facet. Unless the intersection lies on the facet itself, the facet is not intersected. Once all of the facets have been tested, the number of them intersected is known, and if that number is even, the point lies inside the chamber and the number of interior points, N_{in}, is incremented by one. The procedure is then repeated for another point on the sphere. When all of the points on the sphere have been tested against all of the facets on the chamber, equation (3.4) is applied to

calculate the flame area. To improve the accuracy of the results, the entire flame area calculation is repeated approximately ten times using different sets of random points on the flame sphere. The flame area is taken as the average of the results of the individual calculations. While not discussed here, the actual calculation procedure takes advantage of several features of the problem to reduce computational effort. Additional information about the calculation of flame area is given in the internal documentation of the geometric code (see Appendix D).

3.5 Calculation of Enflamed Volume

Once the flame area corresponding to a given flame radius and crank angle has been calculated, the incremental enflamed volume located between the current flame radius and the previous flame radius is found using the following approximate expression (see Fig. 8):

$$\Delta V_e(r_f,\Theta) = \left\{\frac{A_f(r_f,\Theta) + A_f(r_f - \Delta r_f,\Theta)}{2}\right\}\Delta r_f \tag{3.5}$$

where, $\Delta V_e(r_f,\Theta)$: enflamed volume between r_f and $r_f - \Delta r_f$

(r_f is an integer multiple of Δr_f)

Δr_f : specified flame radius increment

To obtain the total enflamed volume for a given flame radius and crank angle, the incremental contributions calculated with equation (3.5) are summed over all radius increments up to the radius of interest:

$$V_e(r_f,\Theta) = \Delta V_e(r_f,\Theta) + \Delta V_e(r_f - \Delta r_f,\Theta) + \ldots + \Delta V_e(\Delta r_f,\Theta) \tag{3.6}$$

The accuracy of this calculation increases as the radius increment is decreased and as the accuracy of the flame area calculation increases.

3.6 Calculation of Wall Area Wetted by the Flame

The surface area of the combustion chamber which is wetted by the flame at a given crank angle and flame radius is calculated as follows. Considering first a single facet on the surface of the chamber, the distances from each of the three apices of the facet to the ignition source are calculated (see Fig. 9). If all three of these distances are greater than the flame radius, then the facet must lie outside of the flame. If the three distances are all less than the flame radius, then the facet must lie within the flame (i.e., the facet is wetted by the enflamed volume).

Repeating the above procedure for all the facets on the chamber, the wetted area is then the sum of the areas of the facets found within the flame. If a facet is only partially wetted by the flame, then interpolation will yield the fraction of the facet surface area which is wetted by the flame. The wetted portion of this facet is then added to the total wetted area. The total area outside the flame is equal to the total area of the facets on the chamber wall minus the total wetted area.

3.7 Geometric Model Validation

To confirm that the algorithms presented in sections 3.4 through 3.6 were implemented correctly and to find a minimum value for N_{total} which would yield acceptable accuracy in calculating A_f, two test geometries were modelled for which analytical solutions could be found. Both test chambers were right circular cylinders with the piston position fixed at top center and with the ignition source located at the center of the top surface.

However, the heights of the two chambers were different, so that the order in which the flame contacted the surfaces of each chamber differed.

Calculated flame area vs. flame radius for both cases are plotted together with the exact solutions in Fig. 10. The results shown were obtained using a random point density equivalent to 100 points on an area equal to the cross sectional area of the bore and with 5 iterations of the calculation process. Agreement was good between the approximate solutions and the exact solutions.

Calculated wetted wall areas were found to be in close agreement with the analytical solutions. This result was expected since the accuracy of the calculation depends only on the closeness with which the facets on the chamber surface approach an exact right circular cylinder. The results of the enflamed volume calculation were also adequate. Since the enflamed volume is the integral of the flame area over the flame radius, accuracy depended on both the flame area calculation and on the magnitude of the radius increment, Δr_f. Small local errors in calculating A_f tended to be integrated out when V_e was calculated. The two cases shown used 13 radius increments, though points corresponding to additional radii also appear on the graphs.

CHAPTER 4

CALIBRATION OF THE CYCLE SIMULATION

4.1 Background

Before the cycle simulation could be used to perform useful calculations, the unknown parameters of the model had to be adjusted. To set the values of the parameters, model predictions were compared with measurements taken with a firing engine.

Usually, a cycle simulation is calibrated by adjusting model parameters so that quantities of interest in the investigation agree in magnitude with real engine measurements at a specific operating point. The calibration is then checked by repeating the comparison at several different operating conditions and seeing if measured and predicted trends for changes in the important quantities are in agreement. If the calibration is successful, the model will adequately predicts engine behaviour for the test engine geometry over the range of operating conditions for which the model was calibrated. However, if the model is then applied to an engine with a different geometry or operating under conditions differing from those examined in the calibration, agreement between predictions and measurements will often apreciably deteriorate.

Because this study involved only illustrative calculations, and since several different combustion chamber geometries were to be modelled, the procedure adopted was to perform a limited calibration in which rough agreement between predictions and measurements of key cycle parameters was sought. Experimental data came from a separate study in progress at M.I.T. (28) during this investigation. Another reason for the simplified calibration was that the test engine from which measurements were taken had

features which conflicted with some assumptions made in developing the cycle simulation. Thus, the test engine was equipped with a shrouded intake valve, and the resulting in-cylinder swirl is likely to have distorted the flame front from even a roughly spherical geometry. Also, unusually large crevice volumes in the cylinder, for which the model does not account, were noted in other studies with the same engine (29).

While the experimental calibration was performed at a single operating point, the model was also indirectly tested over a range of operating parameters. These further tests are discussed in detail in Chapter 5. Though a complete calibration of the simulation was not feasible, the limited calibration performed is believed to be suitable for the present application. However, if used to make precise predictions or as a guide in a specific engine design, the model should first undergo a more extensive calibration.

4.2 Experimental Facility

The calibration was performed using a single-cylinder Cooperative Fuels Research (CFR) engine with a disc combustion chamber and side ignition. A shrouded valve replaced the standard intake valve, so that combustion was exceptionally rapid for an engine of this type. Fundamental geometric parameters of the test engine are listed in Table 1.

The engine was coupled to a Dynamatic DR (model IU) dynamometer. Cylinder pressure, the fundamental quantity used in the calibration, was measured with an AVL type 8QP500c water-cooled quartz pressure transducer connected to a Kistler Model 504 charge amplifier. Transducer voltage was sampled every crank angle and temporarily stored in Camac Crate memory modules. Data from 44 consecutive cycles was then sent to a PDP 11/60

computer for statistical analysis and cycle heat release calculation.

Fuel-air mixture was fed to the engine through a large heated mixing tank. Air flow rate was measured with an orifice plate and fuel flow with a rotameter. Engine speed was measured with a digital tachometer. A more detailed discussion of the experimental facility is given by Leyes (28).

4.3 Calibration Procedure

Operating conditions for the calibration are listed in Table 2. The operating point was chosen from the available data because it was closest to the base operating point to be used in predictive studies with the cycle simulation.

Engine design data required by the simulation for the comparison were the overall engine geometry (see Table 1) and the detailed combustion chamber geometry, modeled as a right circular cylinder with the approximate spark plug location of the test engine. Approximate valve open area and valve timing data profiles were used. Valve discharge coefficients as a function of valve lift and pressure ratio across the valves were not available. Therefore, constant discharge coefficients were assumed. A discharge coefficient of 1.0 was assumed for the exhaust valve while the value for the intake valve was left as a variable to be calibrated.

The first step in the calibration was to adjust the model so that the inducted mass agreed with engine measurements. Matching was achieved by adjusting the intake valve discharge coefficient to a value of 0.57. Next, the value of the turbulent dissipation constant, c_β, was adjusted to give roughly realistic profiles of u' and U (see Section 2.4.2) during the whole cycle. A value for c_β of 1.5 was found to work best. Exact calibration of c_β was not possible. However, despite a strong dependence of u' on c_β

during the intake process, the dependence on turbulent intensity during combustion was much smaller, so that precise setting of c_β was not essential to the correct prediction of entrainment velocity and other quantities dependent on u' during flame propagation.

With the mass flow and turbulence dissipation rates fixed, the next step was to calibrate the heat transfer rate by adjusting the heat transfer constant, α. The value of α was set to maximize agreement between predicted and measured cylinder pressure vs. crank angle. Using a value for α of 0.07, measured and predicted peak pressures approximately agreed (see Fig. 11) . However, the crank angle at which peak pressure occured was then overpredicted by 5°. Also, the rates of pressure rise differed somewhat during the compression process. Mass loss to crevice volumes or out of the cylinder as well as possible deficiencies in the heat transfer model of the simulation may account for these discrepancies. Table 3 lists measured and predicted values for the main cycle parameters of interest. Good agreement was found between predicted and measured burn duration, the main quantity of interest for the present study. The model was able to adequately predict all major cycle parameters, with the exception of NO emissions. The fact that predictions of NO were only half of the measured amount is believed to be due to overprediction of NO decomposition by the model.

CHAPTER 5

MODEL PREDICTIONS

5.1 Background

As stated in Chapter 1, the purpose of this investigation is to provide a better understanding of the mechanism by which combustion chamber geometry affects burn duration in homogeneous-charge SI engines. To gain access to the underlying mechanism, three basic questions were formulated and illustrative calculations aimed at answering them were performed using an engine cycle simulation. The three basic questions are:

i) How important is combustion chamber geometry in determining burn duration?

ii) How do different combustion chamber geometries affect burn duration?

iii) How does changing combustion chamber geometry compare with increasing turbulence as a means to achieving faster burning?

To answer these questions, four separate studies were performed. The first study consisted of applying the geometric model described in Chapter 3 to ten different combustion chamber geometries and comparing the results. Thus geometrical constraints on flame travel were investigated without the use of the engine cycle simulation. In the second study, operating conditions and model parameters were individually varied from a base operating point and changes in burn duration predicted by the cycle simulation were recorded. Calculations were performed for two different spark plug locations on the same combustion chamber. In the third study, ten different chamber geometries were compared for burn duration. The fourth study was a comparison between reduced burn duration achieved by relocation of

the spark plug and an equal reduction achieved by increased turbulence generation. Two chambers were examined in this study.

This chapter presents and discusses the results of the four studies outlined above. In Chapter 6, results applicable to the three basic questions dealing with geometric effects on burn duration are summarized.

A few definitions and conventions are needed to allow the results which follow to be quantified. In this study, burn duration is used as the primary measure of how fast the mixture burns. The burn duration is the number of crank angle degrees required for the mixture to burn completely. To allow more precise analysis, the burn duration is here divided into an early stage (0-10% of mass burned), denoted by $\Delta\theta_b'$, and a main stage (10-90% of mass burned), denoted by $\Delta\theta_b''$ (see Fig. 12). Difficulties in predicting burning rates in the very late stages of combustion make analysis unreliable after 90% of the mass has burned. In addition, late burning has a much smaller effect on engine performance than do the early and main stages of combustion. Therefore, an effective burn duration, $\Delta\theta_b$, equal to the sum of the durations of the early and main stages of combustion, is used as an indication of the overall burn duration.

To permit quantitativee comparison between burn durations obtained with different chambers, results for a disc chamber with side ignition were taken as a reference. This geometry was chosen because it invariably resulted in the longest burn duration when compared to other geometries tested under the same operating conditions. The ratio of the burn duration exhibited by any chamber to the burn duration exhibited by the reference chamber at the same operating conditions is defined here as the burn angle ratio, R_θ. Corresponding quantities for the early and main stages of combustion are the early angle ratio, R_θ', and the main angle ratio, R_θ'',

respectively.

Throughout this thesis, the term "combustion chamber geometry" is used to refer to the combination of a combustion chamber shape and a specific spark plug location. Thus, two different spark plug locations on the same combustion chamber are considered as two distinct chamber geometries.

5.2 Combustion Chamber Geometries Tested

Ten different combustion chamber geometries were investigated. They consisted of four combustion chamber shapes, each with at least two different spark plug locations. The ten combinations of chamber shapes and spark plug locations are shown in Fig. 13.

To provide a relatively slow burning reference against which more practical chambers could be compared, a disc chamber was used. A hemispherical (hemi) chamber was selected as representative of common practice in combustion chamber design. Two other chambers were chosen as representative of modern fast burn chamber design. These were, an "open" chamber, shaped as the intersection between two spherical sectors, and a more compact chamber, shaped as a cylindrical bowl in the piston. To investigate effects due to changes in spark plug location, each of the four chamber shapes had at least two allowed spark plug locations.

All of the chamber geometries used in this investigation were applied to the same basic engine design. That is, displaced volume, compression ratio, bore, stroke, and connecting rod length were fixed. The values used for these quantities are given in Table 4. The dimensions were selected as being typical of current automotive engine design practice. Valve timing, lift profiles, and discharge coefficients for a 1979 General Motors 5.7 liter diesel engine were used.

5.3 Modeling Studies

5.3.1 Geometric Model Results -- Spherical Flame Maps

As a first step in understanding the interactions between chamber geometry and other factors affecting combustion, a study of the purely geometric constraints on flame travel was performed. The model for the geometric interaction between a spherical propagating flame and a combustion chamber of arbitrary geometry was applied to the ten test geometries. Results from this study did not depend on any modeling assumptions of the cycle simulation. However, the results did depend on the assumptions for flame geometry given in Section 3.1. Note that the calculation results obtained in this first study were required as inputs for all subsequent studies in which the cycle simulation was used.

Results obtained by applying the geometric model to the disc chamber with side ignition are plotted in Fig. 14. The plot of flame front area vs. flame radius shows the flame area corresponding to a given flame radius for several values of crank angle from top center. Since all allowed combinations of crank angle, flame area, and flame radius are shown, the plot of flame area vs. flame radius and crank angle is called the "spherical flame map" of the given geometry. During combustion, the flame must travel on the flame map along a curve of increasing radius. However, because spark timing normally occurs before top center, the flame will first travel on a path of decreasing crank angle from top center (end of compression stroke), will reach top center, and will then travel along a path of increasing crank angle (start of expansion stroke). Also shown in Fig. 14 are the enflamed volume and the wetted wall areas for the three zones on the chamber as functions of flame radius and crank angle. The three graphs of Fig. 14 constitute the complete set of detailed geometric

data required in order to apply the cycle simulation to a specific chamber geometry.

The spherical flame maps of the ten chambers considered in this study are shown in Figs. 15-18. Several features common to all of the flame maps can be observed. First, flame area is only weakly dependent on crank angle for small displacements of the piston from top center. However, if the piston is more than about 20° from top center, the flame area becomes a strong function of crank angle. Secondly, the flame front area is independent of crank angle for small flame radii. The radius at which the flame area is first affected by crank angle (i.e., the radius at which the flame contacts the piston) equals the distance from the spark plug electrodes to the nearest piston surface. In general, this distance is shortest for chambers with side ignition and longest for chambers with more central ignition.

In the practical region between top center and about 25° from top center, flame area vs. flame radius varies significantly from one chamber shape to another. Thus, for example, the bowl-in-piston chamber with side ignition results in flame areas (evaluated at their peak values and near top center) as much as 30% larger than those obtained with the disc chamber with side ignition (see Fig. 19). A slightly smaller gain (25-30%) is found when the same chamber shapes with central ignition are compared (see Fig. 19). The gain for the hemi chamber with side ignition over the disc chamber with side ignition is about 26%.

For a given chamber shape, flame area has a very strong dependence on spark location. The hemi chamber with central ignition results in flame areas roughly 70% larger than those obtained with the same chamber but using side ignition (see Figs. 16). For the open chamber, a gain in

flame area of about 90% is found when center ignition is compared with side ignition. The largest gain is for the bowl-in-piston chamber; an increase in peak flame area near top center of about 150% is achieved simply by moving the spark plug from the side to the center of the chamber.

When comparing the flame maps for the ten different geometries, one clear pattern can be seen. Regardless of the chamber shape, geometries with side ignition have generally similar flame maps, i.e., flame area rises slowly as radius increases, remains approximately constant for a large radius span, and then decreases slowly to zero. Chambers with central ignition, in contrast, result in an early steep rise in flame area up to a peak, followed by a sharp decrease as the flame suddenly encounters the chamber walls. Fig. 19 illustrates this point for the disc and bowl-in-piston chambers with central and side ignition. The flame map for the hemi chamber with intermediate (1/3) ignition shows, predictably, a compromise between the extremes of side and central ignition (see Fig. 16).

Another consistent feature of the flame maps is that, as the spark plug location approaches the center of the chamber, the flame radius required for the flame to propagate through the entire chamber decreases. This result is expected because, for a fixed crank angle, the volume of all the test chambers is the same. Since the chamber volume is the integral of the flame area over the flame radius, the area under the flame map must be the same for all chambers at the same crank angle. Therefore, a chamber with central ignition, which results in a large initial flame area, will normally also have a short maximum flame radius.

While flame radius has been used as the primary independent variable in the flame maps, enflamed volume can be used instead. A plot of flame

area vs. enflamed volume at top center for the disc and open chambers with side and center ignition is shown in Fig. 20. An important geometric effect apparent from Fig. 20 is that the ratio of flame area for center ignition chambers to that for side ignition chambers increases as more volume is enflamed. This feature suggests that changes in combustion chamber geometry should have a stronger effect on flame area during the main stage of combustion than during the early stage.

Heat loss during combustion reduces the burning rate in SI engines. Therefore, the surface area of the chamber wetted by the flame as it propagates is of considerable interest. The plots of wetted wall area vs. flame radius for the disc chamber with side ignition (Fig. 14) and for the open chamber with center ignition (Fig. 21) provide some useful information about heat loss during combustion. A feature common to both geometries is that the largest surface in contact with the flame is found on the cylinder head. Not until the piston has moved at least 40° from top center does the cylinder wall provide a heat transfer area comparable to that of the cylinder head. The piston area wetted by the flame is normally less than that for the cylinder head, but it is still significant. Note that, for a given flame radius, the wetted cylinder head area is independent of crank angle from top center, the wetted piston area decreases with crank angle, and the wetted cylinder wall area increases with crank angle.

Results from the purely geometric analysis suggest the following four possible conclusions. The first is that chamber geometry has the potential for having a major effect on flame front area during combustion. The second is that relocation of the spark plug from the side to the center of the chamber results in a greater increase (2-5 times) in flame area than do changes in combustion chamber shape alone. The third conclusion is that

the fractional increase in flame area due to changing combustion chamber geometry is greater in the main stage of combustion than in the early stage. However, calculations must be performed in which all of the variables affecting combustion are allowed to interact before the actual effect of chamber geometry on burn duration can be assessed. Such studies are carried out in the following sections.

5.3.2 Model Performance and Sensitivity Study

In the procedure described in Chapter 4, the adjustable constants of the cycle simulation were set to give rough agreement between predicted and measured data at a single operating point. However, for reasons already explained (see Section 4.1), a more extensive parametric study was not undertaken. Therefore, to insure that model predictions were reasonable, both trendwise and in magnitude, a study was performed in which five engine operating parameters were individually varied from a base operating point and the effect on burn duration was recorded.

For each operating parameter varied, model predictions of burn duration were compared with representative data obtained in parametric studies by Mayo (4) and Hires et al. (7). While the results of the cycle simulation do not correspond exactly to the experimental data chosen, the measurements provide at least some guide in evaluiating the success of the model in predicting real engine behaviour. This study was also aimed at learning the extent to which the geometric effect on burn duration depends on operating conditions.

To investigate the sensitivity of model predictions to the calibration procedure, a second study similar to the model performance study was performed. This time the three main adjustable parameters of the model

were varied from their calibrated values and changes in burn duration were observed.

All parts of these two studies were performed using the same two chambers: (i) disc with side ignition (reference chamber, slow burning), and (ii) disc with center ignition (faster burning). The base set of operating conditions is given in Table 5. The load, engine speed, and fuel/air equivalence ratio of the base case were chosen as typical of cruise engine operating conditions. For each of the operating conditions tested, spark timing was adjusted to give maximum brake torque (MBT timing).

5.3.2.1 Effect of Operating Conditions on Burn Duration

Results of the model performance study are plotted in Figs. 22 - 23. These plots show the durations of the early and main stages of combustion for changes in engine speed, fuel/air equivalence ratio, intake manifold pressure (load), EGR, and spark timing.

5.3.2.1.1 Effect of Engine Speed on Burn Duration

As seen in Fig. 22, both early and main stage durations for both chambers increase very slightly with engine speed. Comparing the model predictions with experimental data by Hires et al. for a CFR engine at similar operating conditions (ϕ = 1.0; manifold pressure = 8 psia; EGR = 0%; spark timing @ 30° BTC) suggests that the model slightly underpredicts the effect of speed on burn duration. Trendwise behaviour agrees well with measured trends.

Table 6 shows the ratios of early stage duration. main stage duration, and overall burn duration for the disc chamber with central

ignition to the corresponding values for the same chamber with side ignition. As seen in the first three columns of the table, the model predicts that the geometric effect on the two stages of combustion is independent of engine speed.. However, the effect of relocating the spark plug is felt much more strongly during the main stage of combustion than during the early stage.

5.3.2.1.2 Effect of Fuel/Air Equivalence Ratio on Burn Duration

The model predicts a significant dependence of burn duration on equivalence ratio, ϕ (see Fig. 22). As ϕ is reduced below about 0.8, burn duration begins to increase sharply. Both the early and main stages of combustion reach minimum duration at $\phi \cong 1.1$, as expected.

Comparison of model predictions with measurements by Hires et al. and Mayo suggests that the model slightly underpredicts the effect of equivalence ratio on burn duration, though trendwise behaviour is correct. The longer measured burn durations are partially due to combustion instability during lean operation, for which the model cannot account.

The first, fourth, and fifth columns of table 6 show that the geometric effect on burn duration is independent of ϕ in the early stage of combustion while it decreases by 15% in the main stage when ϕ is varied from 1.0 to 0.8. The overall result is that a change in ϕ from 1.0 to 0.8 results in a 14% reduction in the geometric effect on total burn duration. Once again, the effect of changing chamber design is found to be more pronounced in the main stage of combustion than in the early stage.

5.3.2.1.3 Effect of Intake Manifold Pressure on Burn Duration

The effect of intake manifold pressure (load) on burn duration is shown in Fig. 22. A large effect is observed, particularly as manifold pressure drops below 0.5 atm. The sharp increase in burn duration at low loads is mainly due to increased mixture dilution by residual exhaust gas and reduced unburned gas density. Model predictions agree well both trendwise and in magnitude with data measured in the parametric studies sited above. However, measurements by Hires et al. show a rise in main stage duration as intake pressure is increased above 0.6 atm. Unstable engine operation due to excessive knock is believed to be the cause of the unexpected trend. Neither results from the present study nor the experimental evidence by Mayo show a rise in burn duration with load.

As seen in the first, sixth, and seventh columns of Table 6, the geometric effect on early stage duration is unaffected by load. The effect on main stage duration is somewhat eroded at lower loads. On the whole, the effect of geometry on total burn duration decreases by 20% for a change in manifold pressure from 0.7 atm to 0.3 atm. Here too, early stage duration is less affected by changes in geometry than main stage duration.

5.3.2.1.4 Effect of Exhaust Gas Recirculation (EGR) on Burn Duration

The cycle simulation predicts a large increase in burn duration with addition of EGR (see Fig. 23). The predicted increase is directly dependent on the correlation between exhaust gas fraction and laminar flame speed used in the simulation (see equation 2.36). Model predictions for the early stage of combustion agree in trend with the measurements of Hires et al. and Mayo. The model overpredicts (by a factor of 2) the effect of of EGR on main stage duration when compared to measurements by Mayo.

However, it underpredicts (by a factor of 2) the effect of EGR when compared with measurements by Hires et al. Taking into account differences in the fuels used in the experiments and noting the correct trendwise behaviour of the predictions, the model appears to give, on average, a roughly correct prediction of the effect of EGR on burn duration.

Refering to the first and eighth columns of Table 6, the geometric effect on early stage duration is found to be weakly affected by EGR. On the other hand, the effect on main stage duration is decreased by 38% with 20% added EGR. The effect of geometry on total burn duration decreases by 27% with high EGR. As in the engine speed, load, and equivalence ratio studies, the geometric effect on burn duration is stronger in the main stage of combustion than in the early stage.

5.3.2.1.5 Effect of Spark Timing on Burn Duration

Fig. 23 shows the effect of spark timing on the durations of the two stages of combustion. The model predicts that early stage duration is almost independent of spark timing, while main stage duration depnds heavily on timing.

Model predictions compare favorably in trend and magnitude with measurements by Mayo. Measurements by Hires et al. show a larger effect of spark timing on early stage duration than that predicted by the model. Despite the large changes in spark timing, the effect of varying chamber geometry is always felt more strongly during the main stage of combustion than during the early stage.

The first, ninth, and tenth columns of Table 6 show that, even though spark timing has a large effect on burn duration, the geometric effect on overall burn duration stays approximately constant, i.e., R_θ is only weakly

dependent on spark timing. Note, however, that the geometric effect on early stage duration is reduced by 39% when spark timing is retarded by 10° from MBT timing.

5.3.2.2 Effect of Adjustable Model Parameters on Burn Duration

The effect of variations in model parameters on predicted burn durations is summarized in Table 7. The three parameters studied were the heat transfer constant, α, the turbulent dissipation constant, c_{β}, and a parameter used to artificially scale the turbulence intensity during combustion by a constant factor.

5.3.2.2.1 Effect of Heat Transfer Constant on Burn Duration

The heat transfer constant was adjusted to 50% and 150% of it's calibrated value and the effect on burn duration was recorded (see Fig. 24). As expected, the early and main stage durations increase with rising rate of heat loss. However, the ratios of the early and main stage durations for the center ignition chamber to the corresponding values for the side ignition chamber depend only weakly on heat transfer (see Table 7). The effect of changing chamber geometry remains strongest during the main stage of combustion.

5.3.2.2.2 Effect of Turbulent Dissipation Constant on Burn Duration

The turbulent dissipation constant was adjusted to 50% and 200% of it's calibrated value. Results are plotted in Fig. 24. The durations of the two stages of combustion show some dependence on c_{β}, with the effect increasing as c_{β} approaches zero. The effect of changes in chamber geometry on burn duration, though, is found to be weakly dependent on the

rate of turbulent dissipation (see Table 7). The geometric effect on burn duration is again most pronounced during the main stage of combustion.

5.3.2.2.3 Effect of Turbulent Intensity Multiplier on Burn Duration

The effect of scaling the turbulence level during combustion (only) was studied by raising the turbulence intensity to twice it's calibrated value. Fig. 24 shows a plot of the resulting effect on burn duration. The turbulence level is found to have a strong effect on both early and main stage durations but to have only a very weak influence on the geometric effect on total burn duration (see Table 7). The effect of geometry is consistently stronger in the main stage of combustion than in the early stage.

5.3.2.3 Discussion

Generally, model predictions of the effect of operating conditions on burn duration agreed in trend and roughly in magnitude with typical experimental data. Also, conclusions about geometric effects were found to be insensitive to calibration parameters. Therefore, further elaboration on the predictions of the model is appropriate.

The results of the model performance and sensitivity study reveal some important features of the geometric effect on burn duration. A basic finding is that most operating conditions have only a small effect on the fractional decrease in burn duration achieved by relocation of the spark plug. The major exception to this pattern is addition of EGR, which significantly reduces the effect of geometry on main stage duration. The overall effect of adding 20% EGR is a drop of 27% in the geometric effect on $\Delta\theta_b$. Two other operating conditions which erode the effect of geometry

on main stage duration, though to a lesser extent than EGR addition, are reduced load and a leaner mixture.

Retarded timing results in the largest decrease in the geometric effect on early stage duration. Both advanced timing and EGR increase the geometric effect on early stage duration. Note that EGR and spark timing are the operating conditions with the largest adjustments in spark timing from the base case. Large timing adjustments have the effect of changing flame area as a function of mass fraction burned. It is the increase in flame area achieved through earlier spark timing that allows EGR and 10° spark advance to amplify geometric gains during the early stage of combustion.

The reason why main stage duration is less affected by geometry when 20% EGR is added can be explained by the following analysis of model predictions. During most of the combustion process, increases in the entrainment rate result in increases in the burning rate (see equation 2.39). Once the flame traverces the chamber, though, entrainment stops and burning continues at a slower rate. The drop in burn rate occurs because no further fresh charge is being made available to burn. During this final burn-up period, flame area plays no role in determining the burn rate.

For most operating conditions, only 10-20% of the mass in the chamber remains unburned at the point where entrainment ceases. Thus, most of the mixture burns while entrainment is in progress. However, with heavy EGR, up to 50% of the charge must burn after the end of flame propagation. This portion of the mixture burns without any benefit from a larger flame front area. As a result, the effect of improved combustion chamber design on main stage duration is substantially diminished. In contrast, since entrainment does not end during the early stage of combustion, the

advantage of a larger flame front is fully available and no reduction in the geometric effect on $\Delta\theta_b'$ takes place.

From the above analysis, one expects that any operating condition which leads to a larger delay between the burning and entrainment processes will erode the effect of chamber geometry on main stage duration, and consequently, on total burn duration. Factors which affect the fraction of the mixture which is entrained but not yet burned are the turbulence length scales and, more importantly, the laminar flame speed. Accordingly, results from Table 6 show that light load and a leaner mixture, both of which reduce laminar flame speed, produce the largest reductions in the geometric effect on main stage duration after EGR.

Another result of the study is that the effect of relocating the spark plug to increase flame area is felt only about half as strongly in the early stage of combustion as in the main stage. The different behaviour in the two stages of combustion occurs because, as discussed in section 5.3.1, the ratio of flame area for center ignition chambers to flame area for side ignition chambers increases with enflamed volume (recall Fig. 20). This effect is purely geometric and is therefore not directly affected by operating conditions. Operating conditions can have only an indirect effect by requiring a large adjustment in spark timing which effectively modifies the shape of the chamber as seen by the propagating flame.

Model predictions of the effect of spark timing on burn duration illustrate the fundamental interdependence between thermodynamic, flow, and geometric factors. As discussed in section 5.3.2.1.5, early stage duration is only weakly affected by spark timing, while main stage duration depends heavily on timing. Concidering, for example, the disc chamber with center ignition, one notes that the main stage in the MBT case lasts from 2° ATC

to 19° ATC, while that of the 10° retarded case lasts from 14° ATC to 35° ATC. One expects, therefore, that the flame area of the retarded case will be larger than that of the MBT case (by about 20-30%, judging from Fig. 15).

If the only effect of retarded spark timing was to increase flame area, then burn duration should decrease with spark retardation. However, the model predicts just the opposite behaviour. Close analysis of the model predictions confirms the gain in flame area due to later spark timing: an advantage of about 35% is observed. Compensating for the increase in flame area, however, is a substantial decrease in the entrainment velocity. Later spark timing allows the turbulent intensity in the chamber to undergo added decay before amplification by flame compression can begin. Of greater importance, though, is that cylinder pressure during the main stage of combustion is much higher in the MBT case than in the retarded case. Unburned gas temperature, on the other hand, is only slightly higher for the MBT case. The resulting higher mixture density for the MBT case has two effects which make up for the smaller flame area. The first is greater amplification of turbulent intensity (see equation 2.46) and hence a gain in entrainment velocity. The second is a direct advantage in the rate of entrainment (see equation 2.35). At the point where half the mixture has burned ($x_b = 0.5$), for example, the retarded timing case has a density 23% lower (thermodynamic effect) and an entrainment speed 20% lower (flow effect) than the MBT case, although flame area is 38% larger. The combined effect of the three factors is a net advantage in entrainment rate of 16% for the MBT case, despite it's smaller flame area. When the faster entrainment rate of the MBT case is coupled with it's smaller turbulence length scales, burn rate at the point where x_b

= 0.5 is found to be 22% greater than for the retarded case.

If an identical analysis is performed at the crank angles corresponding to x_b = 0.06, approximately in the middle of the early stage of combustion, the relative thermodynamic, flow, and geometric differences between the MBT and the retarded timing case are very much reduced. At that point, the net difference in burn rate is only 4%. That is why early stage duration is only slightly sensitive to spark timing.

To summarize, the model predicts that chamber modifications leading to a larger flame area should result in at least some reduction in burn duration for any fixed engine operating condition. However, as illustrated above, factors other than flame front area also play important roles in determining burn duration. These factors must be accounted for if optimal fast burning chamber design is to be achieved.

5.3.3 Comparison Between 10 Combustion Chamber Designs

In this study, 10 different combustion chambers were analyzed using the cycle simulation. Each geometry was tested at base operating conditions (see Table 5) and also, because of the large effect of EGR on gains achieved through chamber redesign, with 20% EGR added. The aims of the study were to test the generality of the results obtained with the disc chamber and to provide some general guidance for design of optimal fast burning combustion chambers.

The results of the study are given in Tables 8-10. Table 8 lists the early stage, main stage, and overall burn durations for the chambers, all normalized by corresponding quantities for the disc chamber with side ignition. Also listed are the gross indicated thermal efficiency and the cycle heat loss, expressed as a percentage of fuel

energy input. Corresponding quantities when 20% EGR is used are shown in Table 9. Finally, Table 10 gives a ranking by burn duration of the 10 chambers at both operating conditions. In what follows, results obtained with the different chambers are presented in four sections corresponding to the four basic combustion chamber shapes. Unless otherwise noted, comments apply to both 0% and 20% EGR cases.

5.3.3.1 Disc Chambers

The disc chambers with side and center ignition were discussed extensively in the previous study. However, comparison with the other geometries helps bring out some further features of the disc design.

As seen in Table 10, the disc chamber with side ignition has the longest early and main stage durations of the chambers tested. It also results in one of the lowest thermal efficiencies of the group. The fact that this chamber burns slowest is in agreement with the purely geometric analysis performed in Section 5.3.1, which showed that it has the smallest average flame area of the 10 chambers studied. It is not surprising that modern SI engines are rarely designed with simple disc chambers.

The model predicts that the disc chamber with center ignition results in faster burning than any of the side ignition chambers. Burn duration results also show that this configuration is approximately comparable to the hemi chamber with center ignition. Both of these results emphasize the importance of spark plug location over chamber shape in determining burn duration. The hemi chamber produces a slightly shorter early stage duration than the disc chamber, but a slightly longer main stage duration. Such behaviour is consistent with the fact that the hemi chamber has a larger flame area than the disc chamber in the early stage and a smaller flame

area in the main stage of combustion.

Despite roughly equal burn durations, the center ignition hemi chamber benefits from reduced heat loss to produce slightly under 1% higher efficiency than the disc chamber with center ignition. The efficiency gain occours because, although burned gas temperatures are slightly higher for the hemi chamber, it's greater distance from the spark plug to the piston translates into about a 40% smaller piston area wetted by the flame.

5.3.3.2 Hemi Chambers

The three hemi chambers examined help to illustrate the effect of spark plug relocation along the surface of a chamber. As shown in Table 10, the relative ranking between these three chambers is the same for both stages of combustion and for both 0% and 20% EGR cases, again confirming the critical importance of spark plug location in determining burn duration.

Relocation of the spark plug from the side to the 1/3 position results in approximately the same reduction in R_θ' as in R_θ'' (see Tables 8-9). When the spark plug is then moved to the center of the chamber, only a minor additional reduction in early stage duration is achieved, while main stage duration is drastically reduced. The net effect is that R_θ is reduced roughly the same amount by the two stages of spark plug relocation. The important result, however, is that, if shorter early stage duration is sought, then most of the gains achievable by spark relocation along the surface of the chamber can be obtained without the need for perfectly central spark location. In contrast, if shorter main stage duration is the goal, the largest gain will come as the spark plug approaches the central position in the chamber. Note also that thermal efficiency increases

steadily as the spark plug nears the center of the chamber.

5.3.3.3 Bowl-in-Piston Chambers

The bowl-in-piston design showed the greatest contrast between side and center ignition of all the chamber shapes tested (see Tables 8-9). Relocation of the spark plug from side to center had an effect three to five times greater on main stage duration than early stage duration, with the smaller effect corresponding to the 20% EGR case.

A change in chamber shape from disc with side ignition to bowl-in-piston with side ignition reduced R_θ only one third as much as converting to bowl-in-piston with center ignition. This result underlines the result found so far, that spark plug relocation is much more effective than changing chamber shape in reducing burn duration.

5.3.3.4 Open Chambers

Just as the hemi chambers illustrate the effect of spark plug relocation from side to center along the chamber wall, the three open chambers illustrate the effect of moving the spark plug first along the wall and then away from the wall toward the true center of the chamber.

The open chamber with top/center ignition, like the hemi and disc chambers with center ignition, shows a large decrease in main stage duration and a smaller decrease in early stage duration when compared with it's side ignition counterpart. If the spark plug is relocated from the top/center position to the center position, a large additional reduction in R_θ' is observed. However, moving the spark plug away from the wall very slightly increases R_θ''. Nevertheless, the major reduction in early stage duration is sufficient to result in a net decrease in R_θ. The reason for

the large reduction in early stage duration is that moving the flame away from the wall greatly reduces wall impingement while the flame is still small compared with the chamber. The small increase in main stage duration when the spark plug is moved away from the wall is due to earlier contact between the flame and the piston, which results in smaller flame areas in the main stage of combustion.

5.3.3.5 Discussion

A few further comments on the findings of the 10 chamber comparison are in order. An important point is that, while some variations in thermal efficiency between the different geometries are evident, the differences are only moderate. This suggests that changes in chamber geometry alone have a limited potential for directly improving engine efficiency. Of course benefits from faster burning, such as increased tolerance to lean operation, can be used to indirectly produce higher efficiencies.

Faster burning generally, though not always, also results in reduced heat loss. While net heat loss was always lower whith 20% EGR, the fraction of the fuel energy lost as heat was usualy slightly lower with no EGR. That the results show no strict correlation between heat loss and burn duration implies that factors other than geometry can act to cancel heat loss reductions due to geometric effects.

Confirming results obtained earlier with the disc chamber, all the chambers showed that EGR slightly decreased R_θ' and significantly increased R_θ''. Operation with 20% EGR required between 9° and 16° more spark advance than when no EGR was used.

The ranking of combustion chambers by burn duration shown in Table 10 underlines some key features about the geometric effect on burn duration.

The first one is that all of the side ignition chambers result in longer burn durations than even the slowest burning center ignition chamber. This result is true for both early and main stages of combustion and for 0% and 20% EGR. Adding to this result is that the hemi chamber with 1/3 ignition, which is a compromise between extreme side and center ignition, falls directly between the two other categories in the burn duration ranking. The conclusion which these results point to is that spark plug location is a very dominant factor in determining burn duration.

Table 10 shows that the same chambers always occupy the bottom four positions in the ranking. On the other hand, no single chamber geometry holds any of the other positions for both stages of combustion and for 0% and 20% EGR. This suggests that, as the maximum potential for reduction in burn duration is approached, i.e., as chamber geometries approach the optimal design for given operating conditions, small differences in geometry are sufficient to make one chamber marginally faster burning than another.

5.3.4 Spark Plug Relocation vs. Increased Turbulence for Faster Burning

5.3.4.1 Model Predictions for Hemi and Bowl-in-Piston Chambers

The last study performed using the cycle simulation was a comparison between spark plug relocation and turbulence amplification as ways of reducing burn duration. This study was aimed at understanding the different ways in which these two approaches affect burn duration.

To compare the effects of changes in geometry and turbulence, two chamber shapes, hemi and bowl-in-piston, were examined. For each chamber shape, base cases for side and center ignition locations were available from the previous study. Next, the side ignition chambers were retested

with c_{mult} adjusted to artificially scale the value of u' as needed so that the side ignition chamber with high turbulence resulted in the same total burn duration as the center ignition chamber. The use of a simple scaling factor to adjust u' is admitedly not representaive of practical methods of increasing in-cylinder velocities. However, given the inability of the present combustion model to account for large mean flows, this approach alows at least some insight into the effect of changing flow parameters on combustion. Spark timing for all cases tested was set for MBT.

The results of this study are given in Table 11 (hemi chamber) and Table 12 (bowl-in-piston chamber). Several features of the results are worth noting. The first is that a significant increase in turbulent intensity is required to match the lower burn duration achieved through spark plug relocation. A value for c_{mult} of 1.55 is needed by the hemi chamber and of 1.70 by the bowl-in-piston chamber. The larger u' scaling factor needed with the bowl-in-piston chamber is because of the greater advantage of center ignition with that chamber shape.

Raising the turbulent intensity to achieve faster burning also has the effect of greatly increasing heat loss and, at least for the cases tested here, also reducing thermal efficiency. Although the magnitudes of the changes in thermal efficiency and heat loss depend on the assumptions of the heat transfer model of the simulation, the trends in these quantities are clear. In contrast, spark plug relocation has the effect of reducing heat loss and of increasing thermal efficiency.

Another difference between the two methods of reducing burn duration is that, while turbulence amplification results in roughly equal fractional reductions in the two stages of combustion, spark plug relocation has a much larger effect on the main stage than on the early stage. This result

underlines the fact that geometric effects are not sensitive to c_{mult}, as discussed in Section 5.3.2.2.3. Thus, while faster burning, the high turbulence chamber still exhibits the uniform reduction in burn duration typical of side ignition chambers. Because spark plug relocation has a smaller effect on early stage duration than turbulence increases, the high turbulence chamber requires less spark advance for MBT.

Figure 25 shows the flame area and mass fraction entrained for the three test conditions using the hemi chamber. The large advantage in flame area for the center ignition chamber is obvious. The crank angle where the center ignition chamber begins to show a gain in flame area is also the point at which it's entrainment rate becomes higher than for the other chambers. The different effect on the two stages of combustion for the center ignition chamber is visible in the plot of entrainment vs. crank angle.

Plots of wall area wetted by the burned gas and turbulent intensity vs. crank angle for the three cases tested are shown in Figure 26. The reduced wall contact of the center ignition chamber is visible in the top plot. The smaller heat loss surface is largely responsible for the reduction in heat loss obtained when the spark plug is moved from side to center.

The plot of turbulence intensity vs. crank angle shows the higher intensity of the amplified turbulence case. Of greater interest, though, is the fact that the center ignition chamber results in about 0.5 to 1.0 m/sec lower turbulent intensity than that of the base side ignition chamber. The reason for the lower intensity with the center ignition chamber is that, because it requires later timing, dissipation of turbulent kinetic energy has more time to occur. Whether this model prediction is

realistic can only be confirmed experimentally. However, such a result is at least intuitively plausible.

5.3.4.2 Causal Models for Geometric and Amplified Turbulence Effects

The fact that turbulence amplification and spark plug relocation affect burn duration in different ways suggests that different mechanisms are at work with these two approaches to faster burning. In this section, findings from the previous studies are brought together and models are proposed for the chain of dominant effects which follow a change in turbulence level or in chamber geometry. In each case, it is assumed that spark timing is corrected for MBT and that no other changes in operating conditions are made.

A model for the interaction between dominat effects which follow a change in combustion chamber geometry is shown in Figure 27. The first step in developing the model was to combine the governing equations for entrainment, burning, and heat transfer with empirical scaling laws for viscosity and laminar flame speed to identify the fundamental variables upon which the three processes depend. Next, those variables with very weak scaling were neglected. A comparison was then performed between values of the remaining parameters at the point where $x_b = 0.5$ for disc chambers with side and center ignition. Those variables found not to vary significantly for the two cases were then also neglected. When only the dominant terms remained, the diagram of Figure 27 was constructed.

While Figure 27 is largely self explanatory, three features of the diagram should be mentioned. First, several positive and negative feedback effects are present, though none of these is large enough to cancel the original gain in burn rate achieved by a larger flame area. Secondly, the

diagram emphasizes the separate nature of entrainment and combustion. Lastly, the model shows possible ways by which a faster burning chamber geometry could lead to a net reduction in thermal efficiency and an increase in heat loss, though the opposite behaviour is more likely.

Figure 28 shows a comparable model for the sequence of events following amplification of turbulent intensity. Note that the model does not necessarily apply to cases where burn rate is increased by inducing large mean flows in the cylinder.

While many parallels exist between the two predicted mechanisms, large differences are apparent as well. The principal difference is that, with spark plug relocation, faster burning is achieved indirectly through an increase in the entrainment rate, while turbulence amplification acts directly on the burn rate. As a result, the effect of higher turbulence on burn duration can be expected to be only weakly affected by heavy EGR, whereas EGR was previously shown to significantly erode gains achieved through spark plug relocation.

CHAPTER 6

SUMMARY AND CONCLUSIONS

6.1 Summary

The purpose of this work was to study the mechanism by which combustion chamber geometry affects burn duration in homogeneous charge SI engines. To that end, a quasi-dimensional SI engine cycle simulation was developed which predicts details of the combustion process for a wide range of operating conditions. Also, a model was developed for the geometric interaction between a spherical propagating flame and a general combustion chamber geometry. Using the results obtained with the geometric model, the cycle simulation was first calibrated against experimental data and then used to study the effect of combustion chamber geometry on burn duration.

To gain insight into the mechanisms at work when changes in combustion chamber geometry are made, four studies were performed: (i) a review of purely geometric constraints on flame propagation calculated with the geometric model for 10 different chamber geometries; (ii) a study on the effect of engine operating conditions and model adjustable parameters on the fractional change in burn duration achievable by spark plug relocation; (iii) a comparison between 10 different combustion chambers for burn duration, thermal efficiency, and heat loss at 0% and 20% EGR; and (iv) a comparison between spark plug relocation and turbulence amplification as means to achieving faster burning.

Model predictions underscored the importance of combustion chamber geometry in determining burn duration. The results showed clear differences between combustion chambers with side ignition and those with center ignition. Spark plug location was found to be more important than chamber shape in governing burn duration.

Addition of exhaust gas recirculation was found to erode reductions in burn duration achieved through relocation of the spark plug. The basic differences between using changes in combustion chamber geometry and using turbulence amplification to reduce burn duration were investigated. Models of the dominant effects involved in these two approaches to faster burning were presented.

6.2 Conclusions

Major conclusions based on the results of the investigation are as follows:

Combustion chamber geometry has a very strong effect on burn duration.

Relocation of the spark plug to a more central location on the chamber is far more effective in reducing burn duration than modifications to the chamber shape alone.

Relocation of the spark plug to a more central location on the chamber causes a much larger rise in burn rate during the main stage of combustion (10-90% burn) than during the early stage of combustion (0-10% burn).

The effect on burn duration of relocating the spark plug to a more central location on the chamber is largely insensitive to changes in engine speed, fuel/air equivalence ratio, intake manifold pressure, and adjustable model parameters.

The effect of chamber geometry on early stage duration is unaffected by addition of EGR.

The effect of geometry on main stage duration is drastically decreased by addition of 20% EGR.

The effect of geometry on main stage duration is reduced by any factor which increases the difference between the entrained mass and the burned mass, i.e., which results in a thicker flame.

The effect of a more central spark plug location on early stage duration decreases with spark retardation and increases with spark advance. Main stage duration is generally insensitive to spark timing.

Changes in chamber geometry to increase the burn rate tend to increase thermal efficiency and reduce heat loss slightly. On the other hand, added turbulence to achieve a comparable reduction in burn duration results in a rise in heat loss and a consequent drop in thermal efficiency.

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TABLE 1

CFR ENGINE GEOMETRY

Bore (mm)	82.55
Stroke (mm)	114.30
Connecting rod length (mm)	254.00
Displaced volume (cm^3)	611.74
Clearance volume (cm^3)	101.77
Compression ratio	7.01:1

Valve timing†:

Intake valve opens (IVO)	10° ATC
Intake valve closes (IVC)	34° ABC
Exhaust valve opens (EVO)	40° BBC
Exhaust valve closes (EVC)	15° ATC

Valve diameters:

Intake valve†† (mm)	34.9
Exhaust valve (mm)	34.7

† nominal values based on full closure
††shrouded intake valve

TABLE 2

MODEL CALIBRATION -- CFR ENGINE OPERATING CONDITIONS

Engine speed (rev/min)	1477
Fuel/Air equivalence ratio:	
based on fuel/air flow rates	0.986
based on exhaust analysis	0.965
MBT spark timing	21° BTC
Intake manifold pressure (atm)	0.94
Mixture temperature (K)	341
EGR (%)	0.0
Coolant temperature (K)	349
Oil temperature (K)	346
Ambient pressure (atm)	1.018
Ambient temperature (K)	298
Fuel:	
molecular structure	C_8H_{18}
stoichiometric fuel/air ratio	0.06618
lower heating value (MJ/kg)	44.4

TABLE 3

MODEL CALIBRATION -- MODEL PREDICTIONS VS. EXPERIMENTAL MEASUREMENTS

Parameter	measured	predicted
air mass / cycle (g)	0.412	0.412
fuel mass / cycle (g)	0.0269	0.0266
residual gas fraction	0.05-0.10 (est.)	0.084
P @ IVC (atm)	1.119	0.789
ΔP IVC $\rightarrow$ spark (atm)	6.525	5.718
ΔP IVC $\rightarrow$ TC (atm)	13.78	13.84
ΔP IVC $\rightarrow P_{max}$ (atm)	26.76	27.36
P_{max} (atm)	27.88	28.15
θ @ P_{max}	13° ATC	18° ATC
$\Delta\theta_b'$ [0-10% burn] (deg)	16-21	18.84
$\Delta\theta_b''$ [10-90% burn] (deg)	18-23	21.49
$\Delta\theta_b$ [0-90% burn] (deg)	38-40	40.33
$\eta_{th_{net\ indicated}}$ (%)	28.8 (est.)	30.0
$\eta_{th_{gross\ indicated}}$ (%)	30.0 (est.)	32.9
$\eta_{th_{brake}}$ (%)	24.5	25.5 (est.)
$ISFC_{gross}$ (g/iKW-hr)	260 (est.)	246.6
$\dot{Q}_{loss}/(\dot{m}_{fuel} \cdot LHV)$ (%)	30-35 (est.)	36.3
NO emissions (ppm)	4000	2057

TABLE 4

ENGINE GEOMETRY FOR ILLUSTRATIVE CALCULATIONS

Bore (mm)	80.00
Stroke (mm)	79.58
Connecting rod length (mm)	140.00
Displaced volume (cm^3)	400.00
Clearance volume (cm^3)	53.33
Compression ratio	8.5:1

Valve timing:

Intake valve opens (IVO)	16° BTC
Intake valve closes (IVC)	38° ABC
Exhaust valve opens (EVO)	64° BBC
Exhaust valve closes (EVC)	17° ATC

Valve diameters:

Intake valve (mm)	47.6
Exhaust valve (mm)	41.3

TABLE 5

BASE OPERATING POINT FOR ILLUSTRATIVE CALCULATIONS

(Disc chamber with side ignition)

Engine speed (rev/min)	1500
Fuel/Air equivalence ratio	1.0
MBT spark timing	21° BTC
Intake manifold pressure (atm)	0.50
Exhaust manifold pressure (atm)	1.00
Mixture temperature (K)	350
EGR (%)	0.0
Chamber wall temperature (K)	400
Ambient pressure (atm)	1.000
Ambient temperature (K)	298
Fuel:	
molecular structure	C_8H_{18}
stoichiometric fuel/air ratio	0.06618
lower heating value (MJ/kg)	44.4
Model parameters:	
heat transfer, α	0.070
turbulent dissipation, c_β	1.50
u' multiplier, c_{mult}	1.00

TABLE 6

EFFECT OF GEOMETRY ON BURN DURATION -- SENSITIVITY TO OPERATING CONDITIONS

(Disc chamber with side and center ignition)

	engine speed			ϕ	
	base	1000 rpm	2000 rpm	0.8	1.2
R_θ' †	0.873	0.875	0.868	0.872	0.874
R_θ''	0.568	0.558	0.549	0.631	0.574
R_θ	0.708	0.701	0.696	0.744	0.715
MBT timing (deg):					
side ignition	-31	-29	-31	-36	-31
center ignition	-20	-18	-23	-24	-20

	P_{im}		EGR	spark timing	
	0.3 atm	0.7 atm	20%	10° adv.	10° ret.
R_θ'	0.874	0.874	0.847	0.841	0.923
R_θ''	0.649	0.546	0.730	0.575	0.566
R_θ	0.755	0.693	0.787	0.711	0.711
MBT timing (deg):					
side ignition	-36	-29	-47	-41	-21
center ignition	-27	-18	-36	-30	-10

† $R_\theta' \equiv \dfrac{\Delta\theta_b'(\text{disc-c})}{\Delta\theta_b'(\text{disc-s})}$, and similarly for R_θ'' and R_θ

TABLE 7

EFFECT OF GEOMETRY ON BURN DURATION -- SENSITIVITY TO MODEL PARAMETERS

(Disc chamber with side and center ignition)

	heat transfer		turb. diss.		u' mult.
	$\alpha = 0.035$	$\alpha = 0.105$	$c_\beta = 0.75$	$c_\beta = 3.0$	$c_{mult} = 2.0$
R_θ'†	0.859	0.881	0.877	0.864	0.907
R_θ''	0.542	0.555	0.546	0.568	0.568
R_θ	0.690	0.701	0.694	0.706	0.717
MBT timing (deg):					
side ignition	-32	-29	-23	-36	-14
center ignition	-23	-20	-15	-24	-6

† $R_\theta' \equiv \dfrac{\Delta\theta_b'(\text{disc-c})}{\Delta\theta_b'(\text{disc-s})}$, and similarly for R_θ'' and R_θ

TABLE 8

BURN DURATIONS AND PERFORMANCE FOR 10 COMBUSTION CHAMBERS

0% EGR

chamber geometry	MBT timing (°)	R_θ' †	R_θ''	R_θ	η_{th} (%) gr. ind.	$\frac{\dot{Q}_{loss}}{\dot{m}_{fuel} \cdot LHV}$ (%)
disc-s	-31	1.000	1.000	1.000	33.3	36.0
disc-c	-20	0.873	0.568	0.708	34.5	33.7
hemi-s	-29	0.943	0.905	0.922	34.2	34.1
hemi-1/3	-25	0.856	0.809	0.830	34.5	33.5
hemi-c	-22	0.848	0.602	0.715	35.3	32.8
bowl-s	-27	0.912	0.872	0.890	32.4	35.8
bowl-c	-22	0.824	0.490	0.644	34.4*	36.3*
open-s	-27	0.902	0.869	0.884	34.6	32.9
open-tc	-22	0.821	0.535	0.666	35.5	32.5
open-c	-22	0.756	0.540	0.639	35.4	33.0

Spark plug locations:

c : center
tc : top center
1/3: approximately halfway between side and center
s : side

† $R_\theta' \equiv \frac{\Delta\theta_b'(\text{any geometry})}{\Delta\theta_b'(\text{disc-s})}$, and similarly for R_θ'' and R_θ

* unreliable data

TABLE 9

BURN DURATIONS AND PERFORMANCE FOR 10 COMBUSTION CHAMBERS

20% EGR

chamber geometry	MBT timing (°)	R_θ' †	R_θ''	R_θ	η_{th} (%) gr. ind.	$\frac{\dot{Q}_{loss}}{\dot{m}_{fuel} \cdot LHV}$ (%)
disc-s	-47	1.000	1.000	1.000	33.0	37.3
disc-c	-36	0.847	0.730	0.787	34.4	35.8
hemi-s	-41	0.933	0.972	0.953	34.2	33.5
hemi-1/3	-39	0.853	0.844	0.848	34.8	34.0
hemi-c	-35	0.831	0.730	0.780	35.3	33.1
bowl-s	-41	0.899	0.969	0.935	33.2	37.0
bowl-c	-33	0.803	0.680	0.740	34.8	35.9
open-s	-41	0.887	0.894	0.890	34.8	33.6
open-tc	-35	0.804	0.672	0.737	35.7	33.1
open-c	-31	0.744	0.727	0.735	35.9	31.6

Spark plug locations:

c : center
tc : top center
1/3: approximately halfway between side and center
s : side

† $R_\theta' \equiv \frac{\Delta\theta_b'(\text{any geometry})}{\Delta\theta_b'(\text{disc-s})}$, and similarly for R_θ'' and R_θ

TABLE 10

RANKING OF COMBUSTION CHAMBER GEOMETRIES BY BURN DURATION

(1: shortest duration ; 10: longest duration)

	0% EGR			20% EGR		
	0-10%*	10-90%	0-90%	0-10%	10-90%	0-90%
1	open-c	bowl-c	open-c	open-c	open-tc	open-c
2	open-tc	open-tc	bowl-c	bowl-c	bowl-c	open-tc
3	bowl-c	open-c	open-tc	open-tc	open-c	bowl-c
4	hemi-c	disc-c	disc-c	hemi-c	hemi-c	hemi-c
5	hemi-1/3	hemi-c	hemi-c	disc-c	disc-c	disc-c
6	disc-c	hemi-1/3	hemi-1/3	hemi-1/3	hemi-1/3	hemi-1/3
7	open-s	open-s	open-s	open-s	open-s	open-s
8	bowl-s	bowl-s	bowl-s	bowl-s	bowl-s	bowl-s
9	hemi-s	hemi-s	hemi-s	hemi-s	hemi-s	hemi-s
10	disc-s	disc-s	disc-s	disc-s	disc-s	disc-s

Spark plug locations:

c : center
tc : top center
1/3: approximately halfway between side and center
s : side

* % of charge burned

TABLE 11

SPARK PLUG RELOCATION VS. TURBULENCE AMPLIFICATION

HEMI COMBUSTION CHAMBER

spark plug location	c_{mult} u'×	$\frac{\Delta\theta_b'}{\Delta\theta_b'(slow)^{\dagger}}$	$\frac{\Delta\theta_b''}{\Delta\theta_b''(slow)}$	$\frac{\Delta\theta_b}{\Delta\theta_b(slow)}$	MBT timing (°)
side	1.0	1.000	1.000	1.000	-29
side	1.55	0.747	0.807	0.779	-18
center	1.0	0.899	0.666	0.775	-22

spark plug location	c_{mult} u'×	η_{th} (%) gr. ind.	$\frac{\dot{Q}_{loss}}{\dot{m}_{fuel} \cdot LHV}$ (%)	u'max', combustion* (m/sec)	NO emissions (ppm)
side	1.0	34.2	34.1	7.38	1459
side	1.55	33.3	37.1	9.60	1442
center	1.0	35.3	32.8	6.83	1482

† "slow" refers to hemi chamber with side ignition and c_{mult} = 1.0

* maximum turbulent intensity during combustion process

TABLE 12

SPARK PLUG RELOCATION VS. TURBULENCE AMPLIFICATION

BOWL-IN-PISTON COMBUSTION CHAMBER

spark plug location	c_{mult} u'×	$\frac{\Delta\theta_b'}{\Delta\theta_b'(slow)^{\dagger}}$	$\frac{\Delta\theta_b''}{\Delta\theta_b''(slow)}$	$\frac{\Delta\theta_b}{\Delta\theta_b(slow)}$	MBT timing (°)
side	1.0	1.000	1.000	1.000	-29
side	1.70	0.715	0.748	0.732	-16
center	1.0	0.904	0.562	0.723	-22

spark plug location	c_{mult} u'×	η_{th} (%) gr. ind.	$\frac{\dot{Q}_{loss}}{\dot{m}_{fuel} \cdot LHV}$ (%)	u'max', combustion* (m/sec)	NO emissions (ppm)
side	1.0	32.4	35.8	7.19	1426
side	1.70	31.8	41.2	10.35	1428
center	1.0	34.4**	36.3**	7.00	1502

† "slow" refers to bowl-in-piston chamber with side ignition and c_{mult} = 1.0

* maximum turbulent intensity during combustion process

** unreliable data

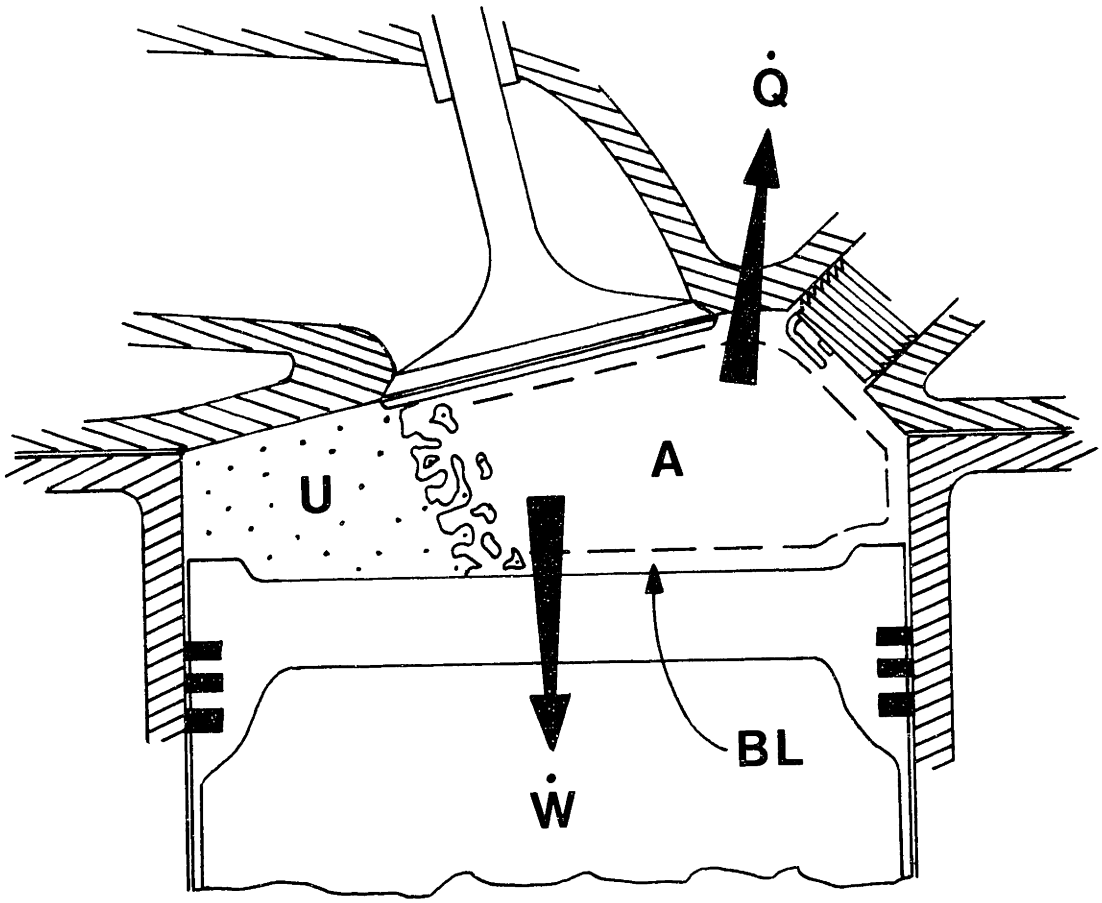


Figure 1. Two-zone thermodynamic model of combustion showing subdivision of burned zone into adiabatic core (A) and thermal boundary layer (BL).

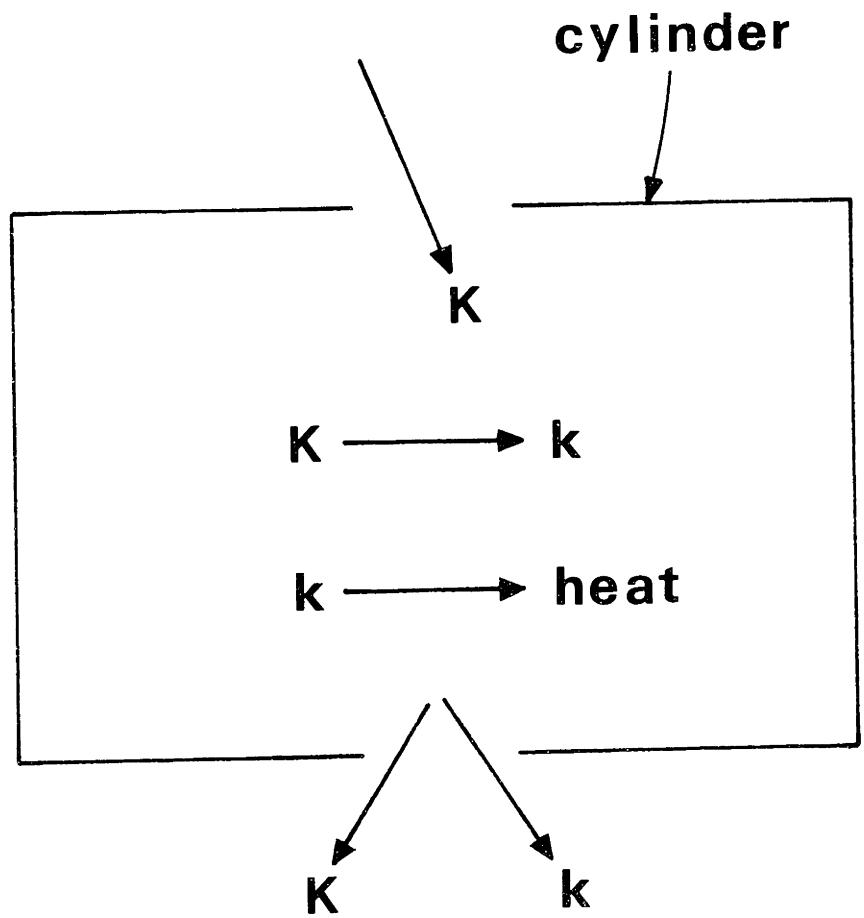


Figure 2. Turbulent energy cascade model. K: mean kinetic energy; k: turbulent kinetic energy

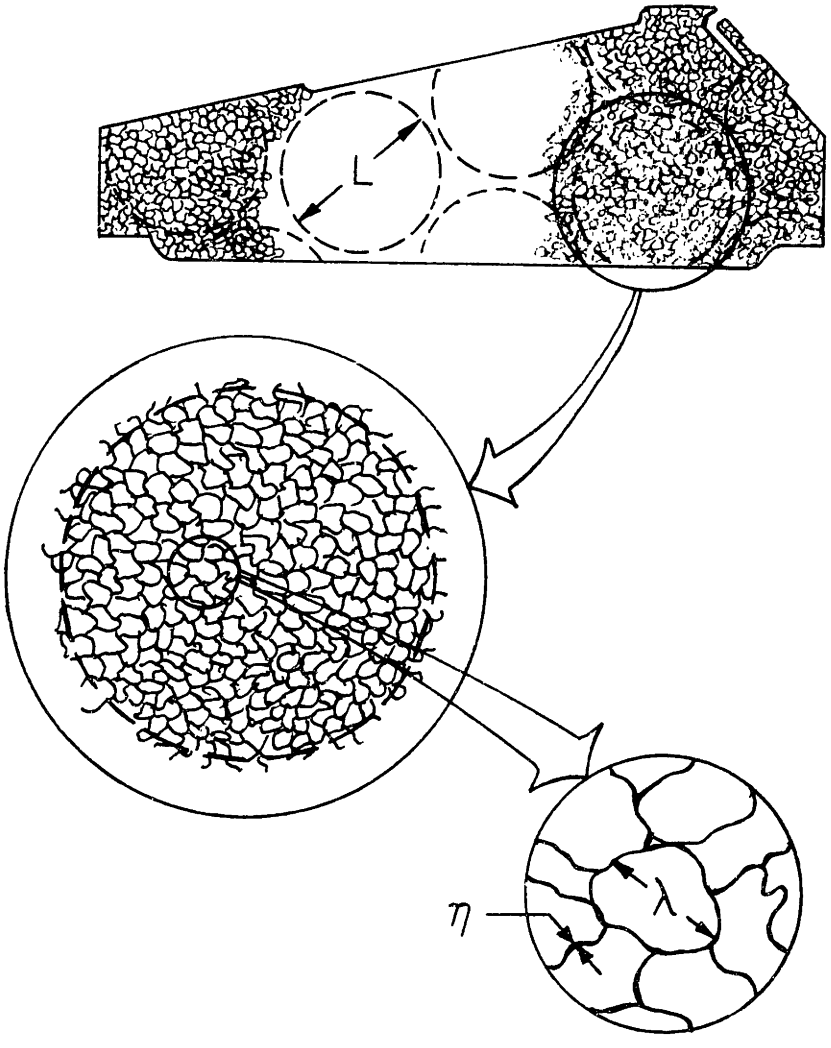


Figure 3. Model of turbulence length scales during combustion. L: macroscale; λ: Taylor microscale; η: Kolmogorov scale

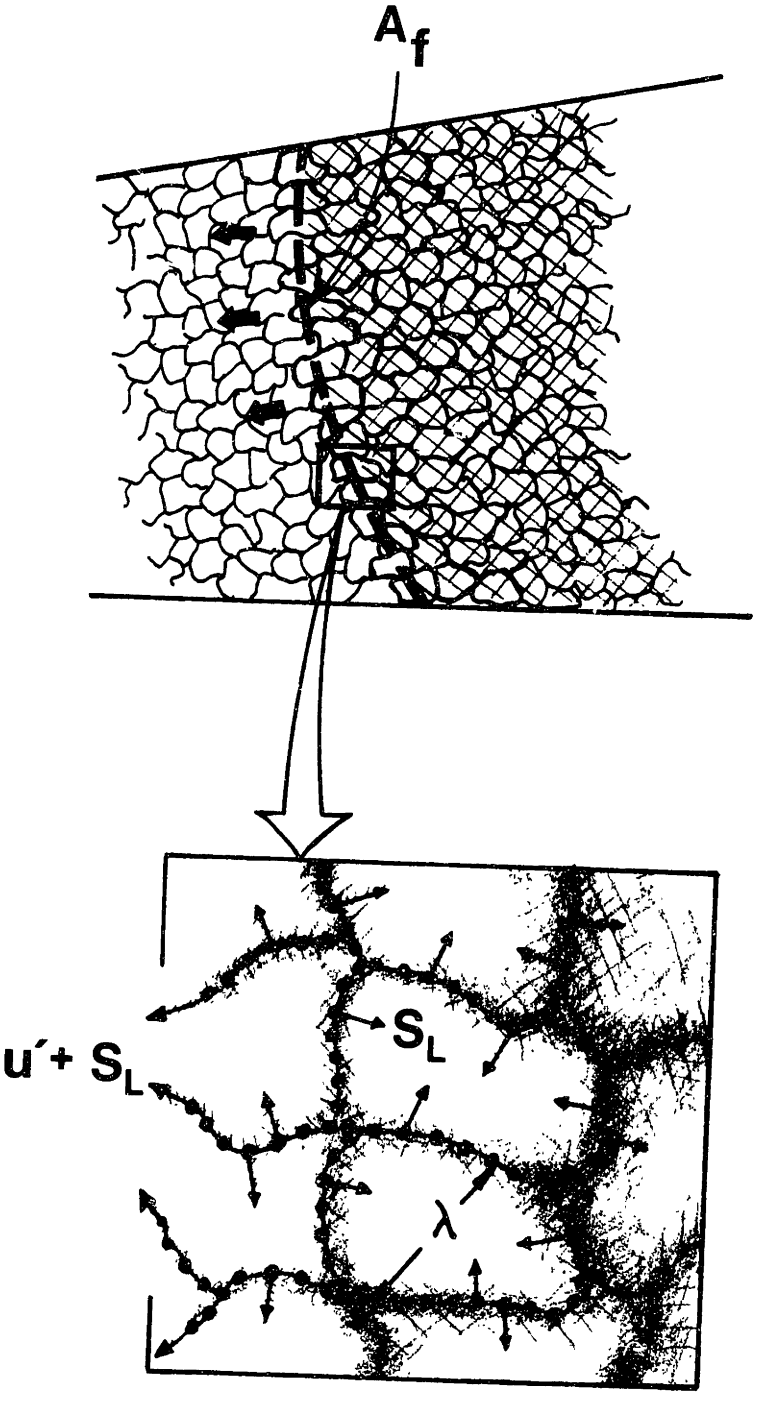


Figure 4. Model of turbulent flame propagation showing entrainment and burnup processes. A_f: flame front area; u': turbulent intensity; S_l: laminar flame speed; λ: Taylor microscale

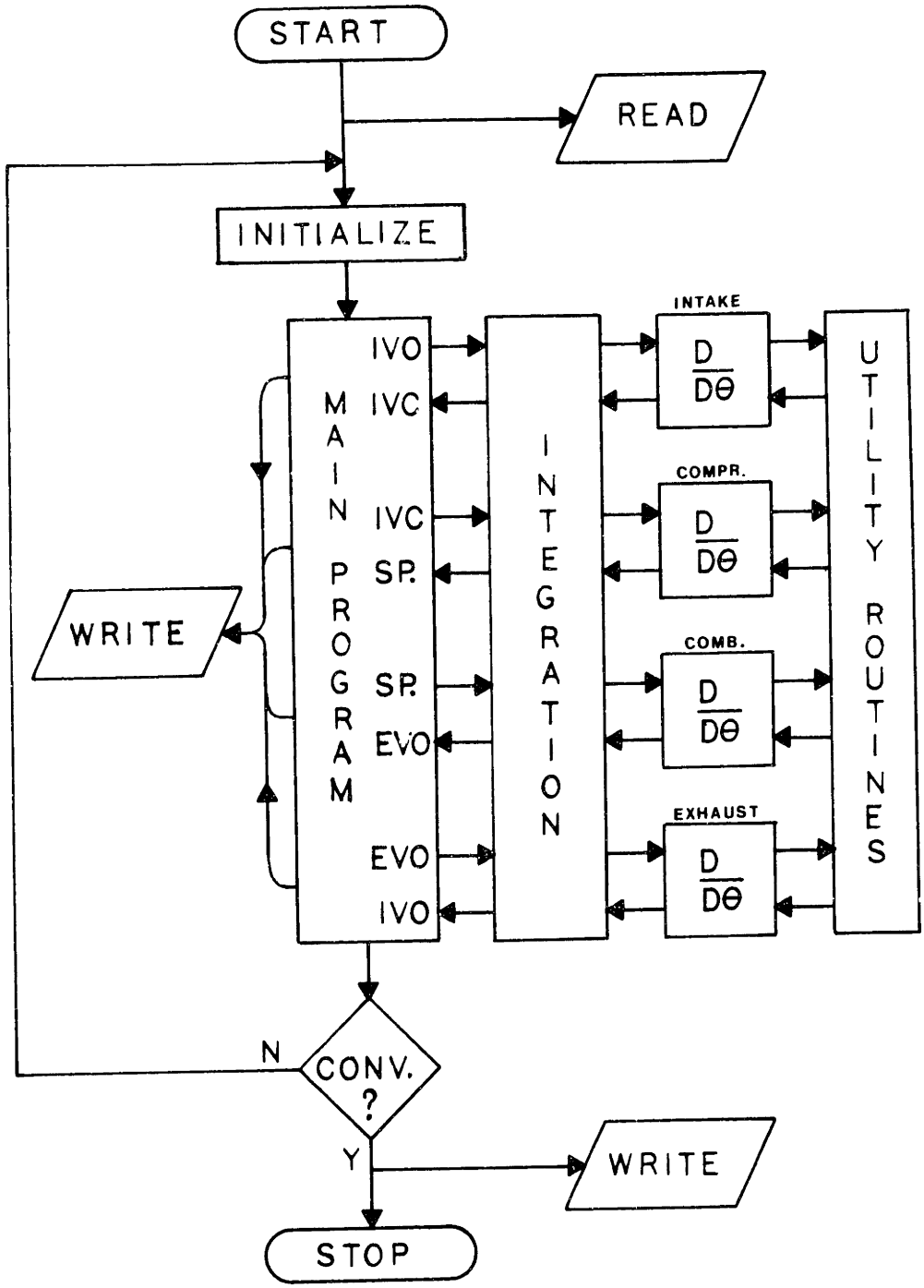


Figure 5. Overall flow chart of cycle simulation showing basic subdivision of computational tasks.

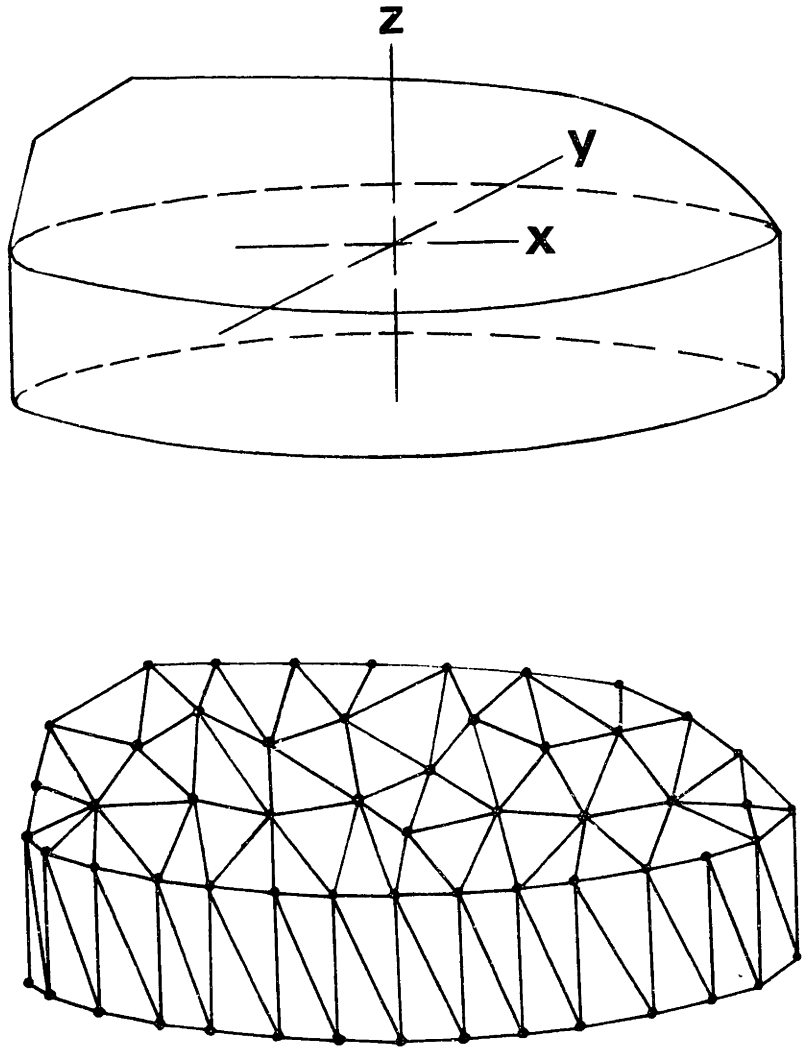


Figure 6. Approximate representation of combustion chamber geometry using flat triangular facets.

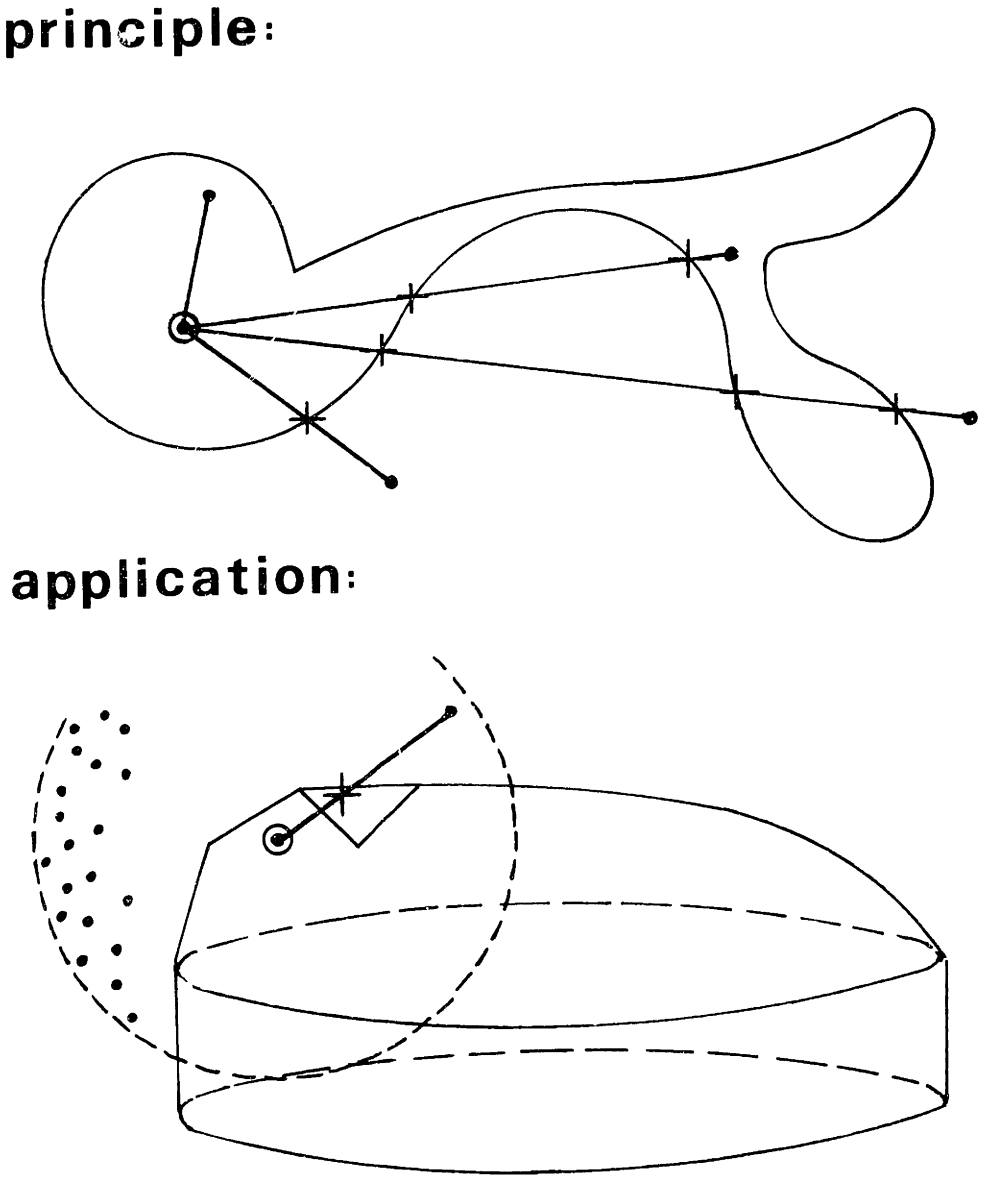


Figure 7. Calculation of flame front area.

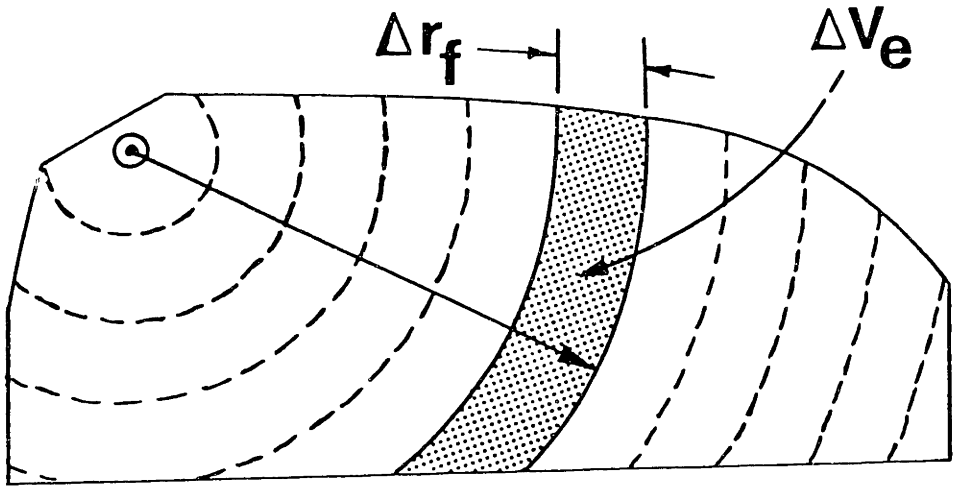


Figure 8. Calculation of enflamed volume.

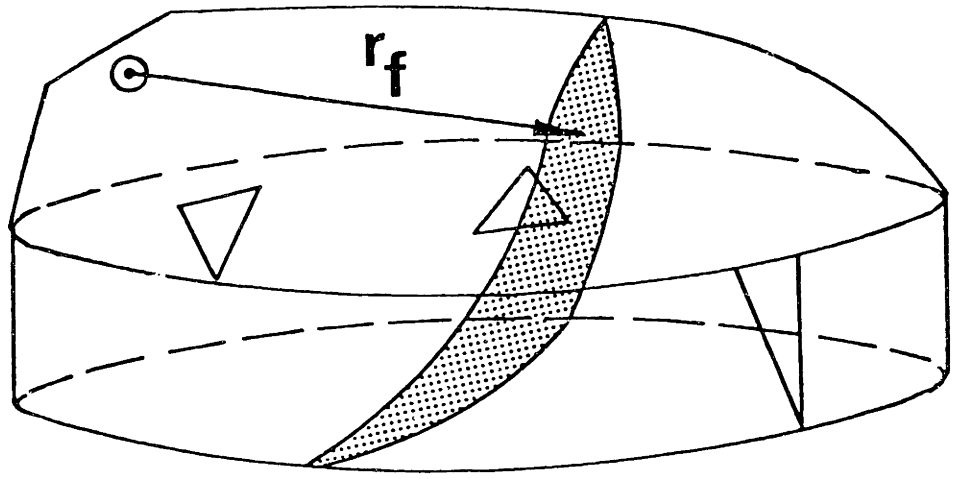
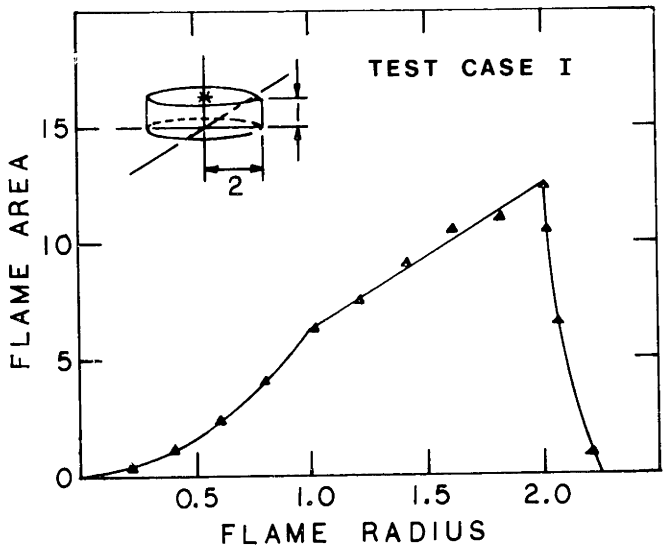


Figure 9. Calculation of chamber wall area wetted by the flame.



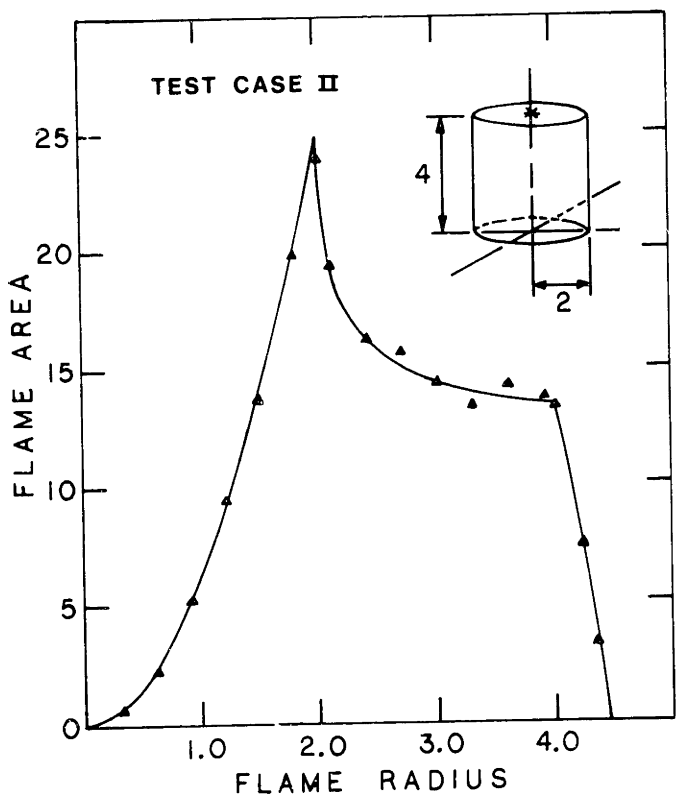


Figure 10. Geometric model validation: comparison between approximate and exact profiles of flame area vs. flame radius for two test cases.

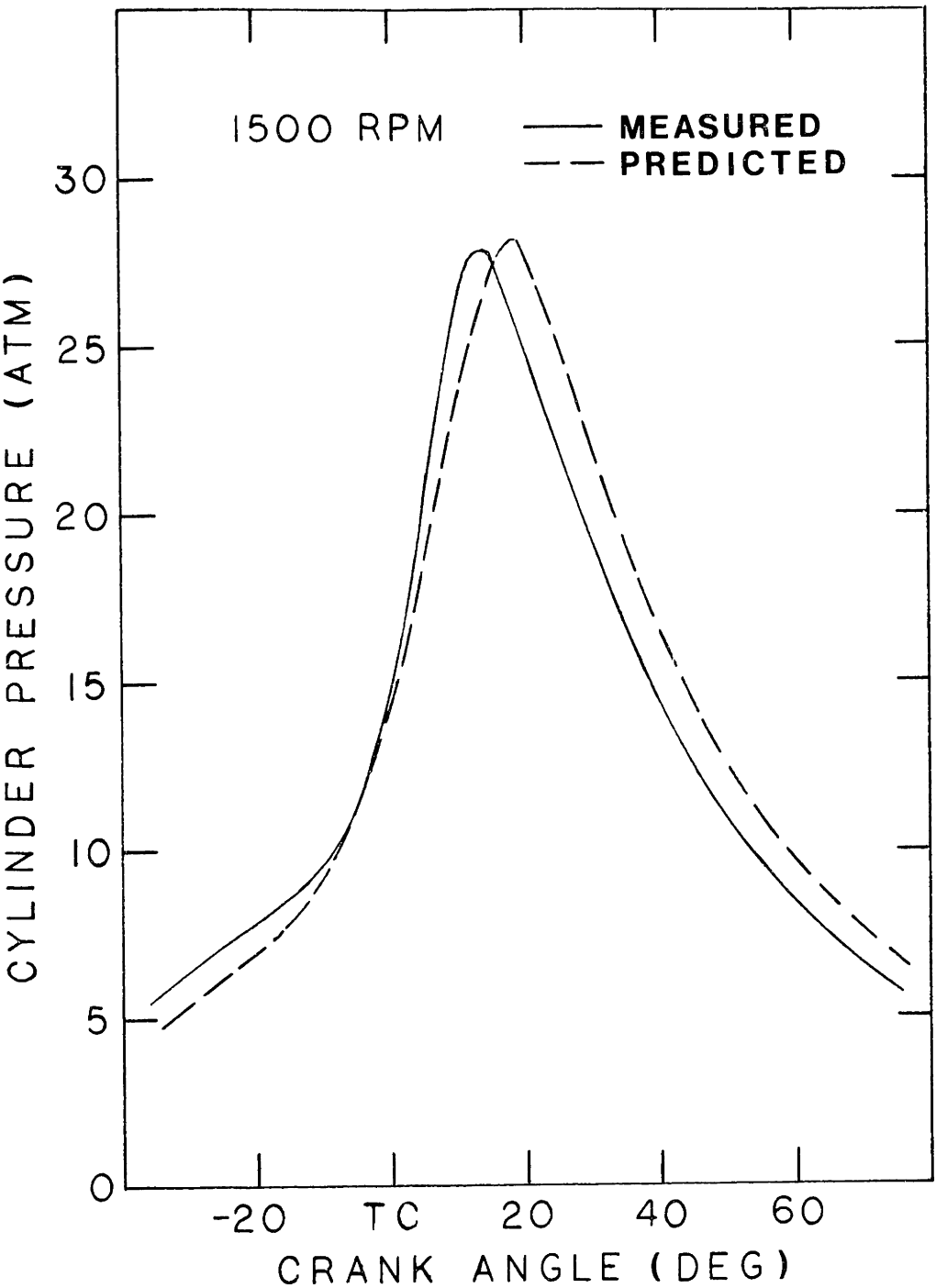


Figure 11. Cycle simulation calibration: comparison between predicted and measured cylinder pressure vs. crank angle.

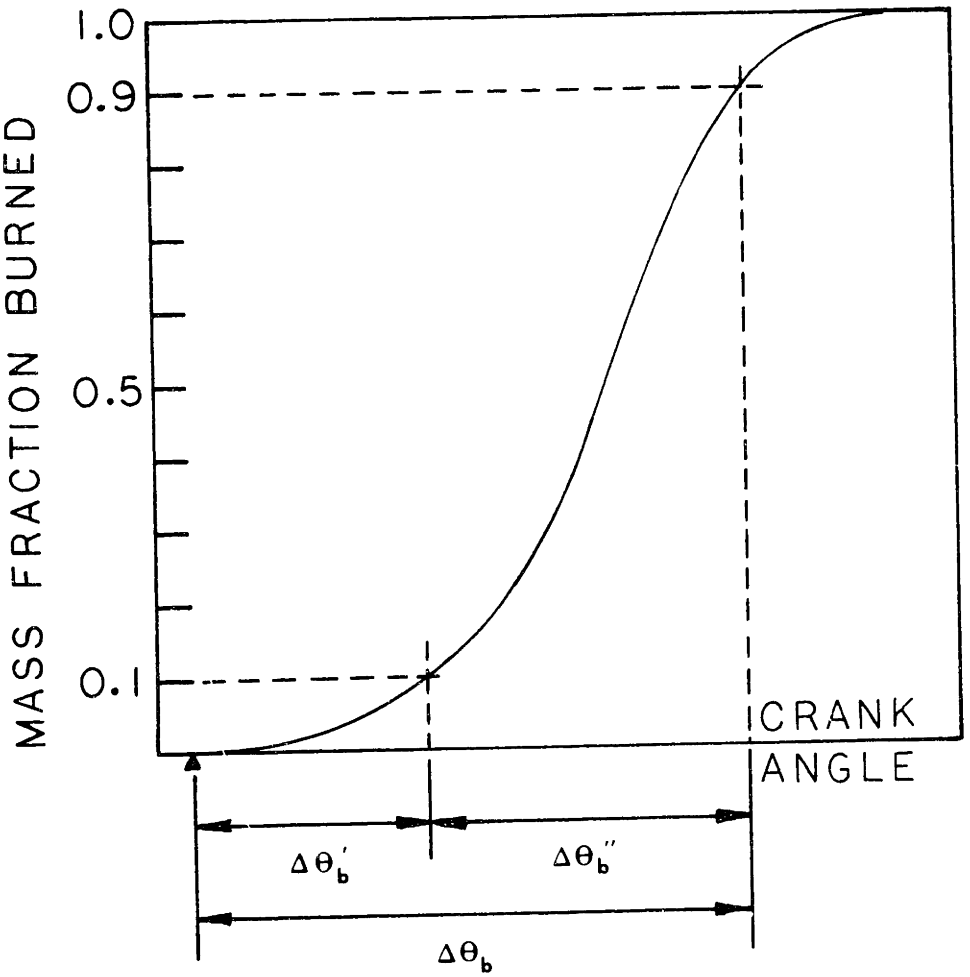


Figure 12. Definitions of early stage (0-10% burn), main stage (10-90% burn), and total (0-90% burn) burn durations.

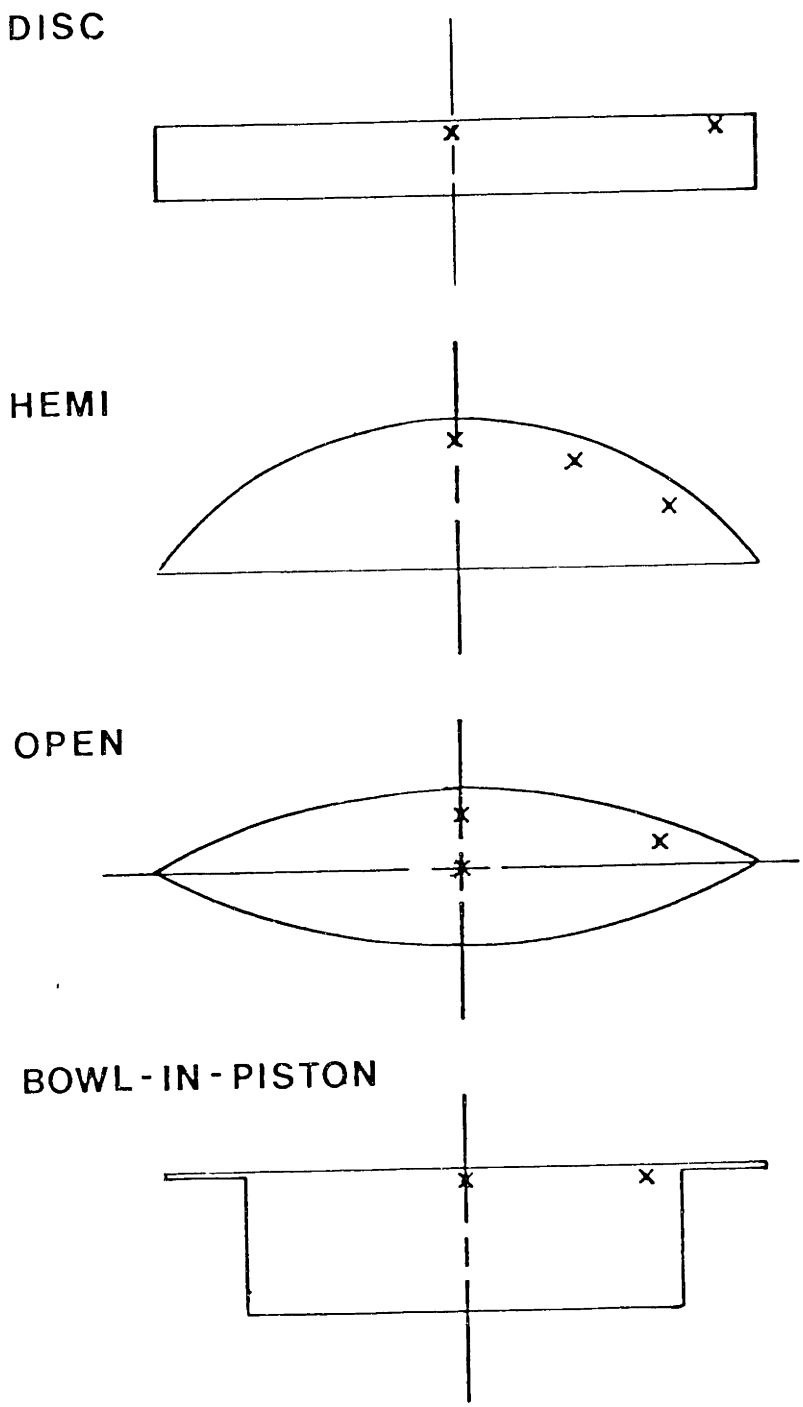


Figure 13. Combustion chamber geometries tested. Chamber shapes shown are all axisymmetric.

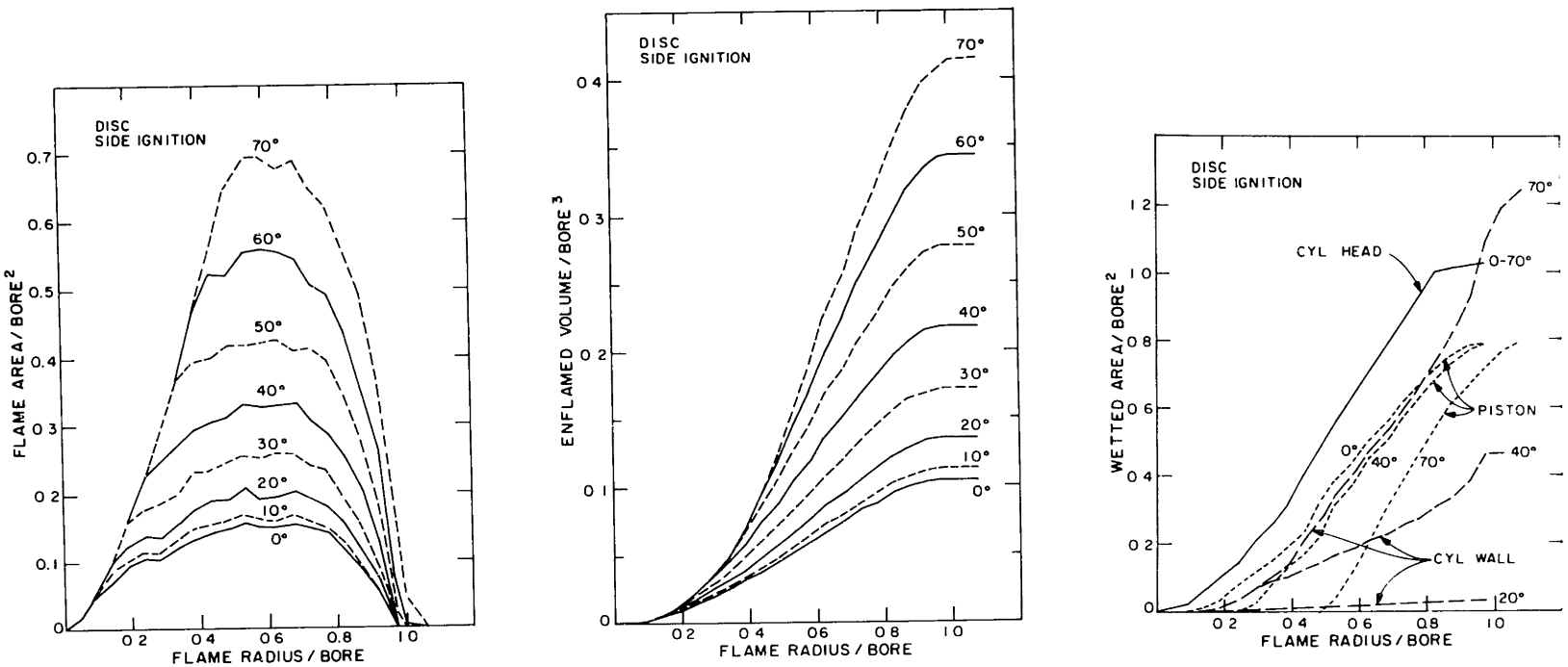


Figure 14: Flame area, enflamed volume, and wetted wall area vs. flame radius and crank angle from top center for disc chamber with side ignition.

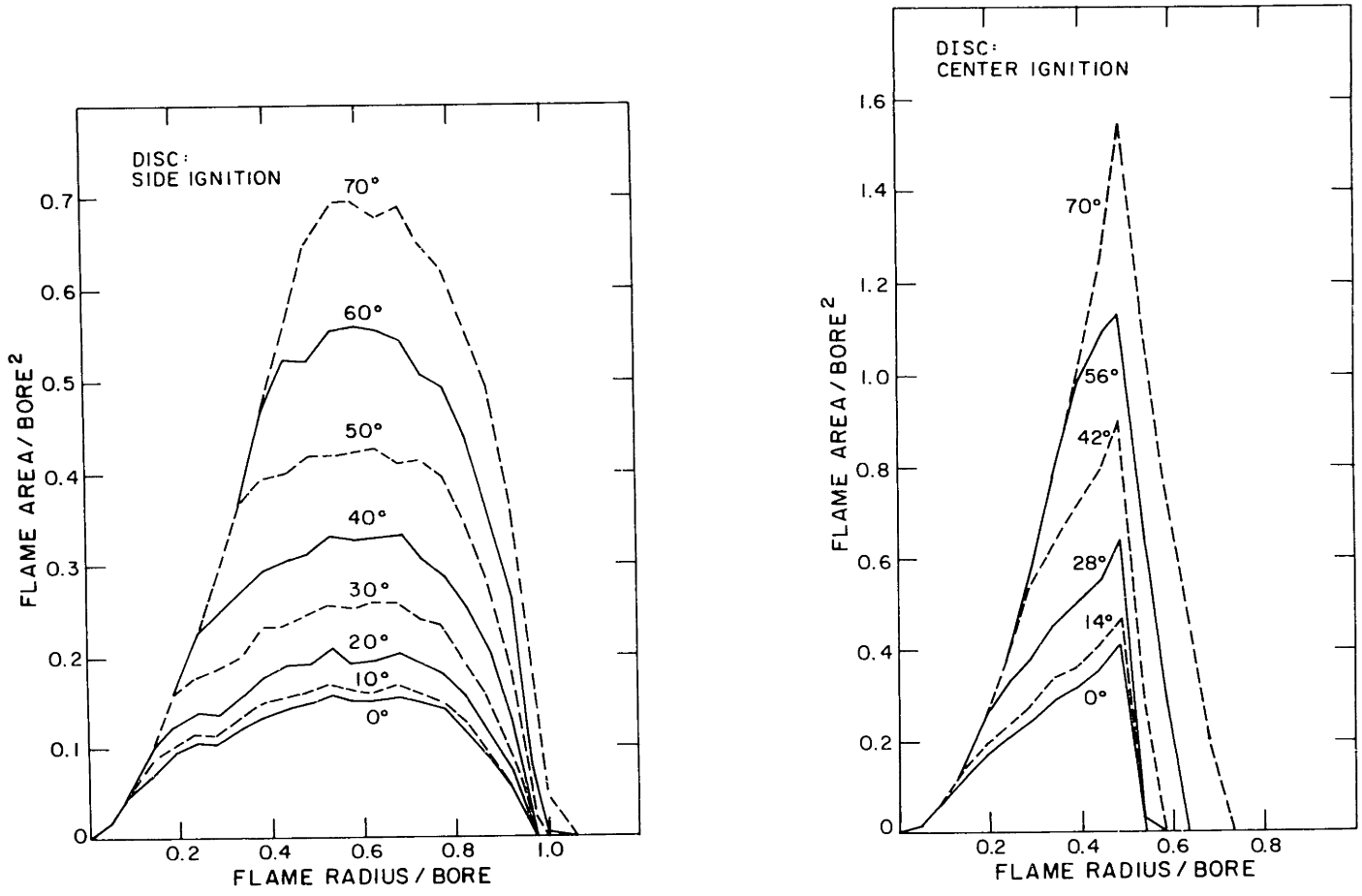


Figure 15: Flame area vs. flame radius and crank angle from top center for disc chamber with side and center ignition.

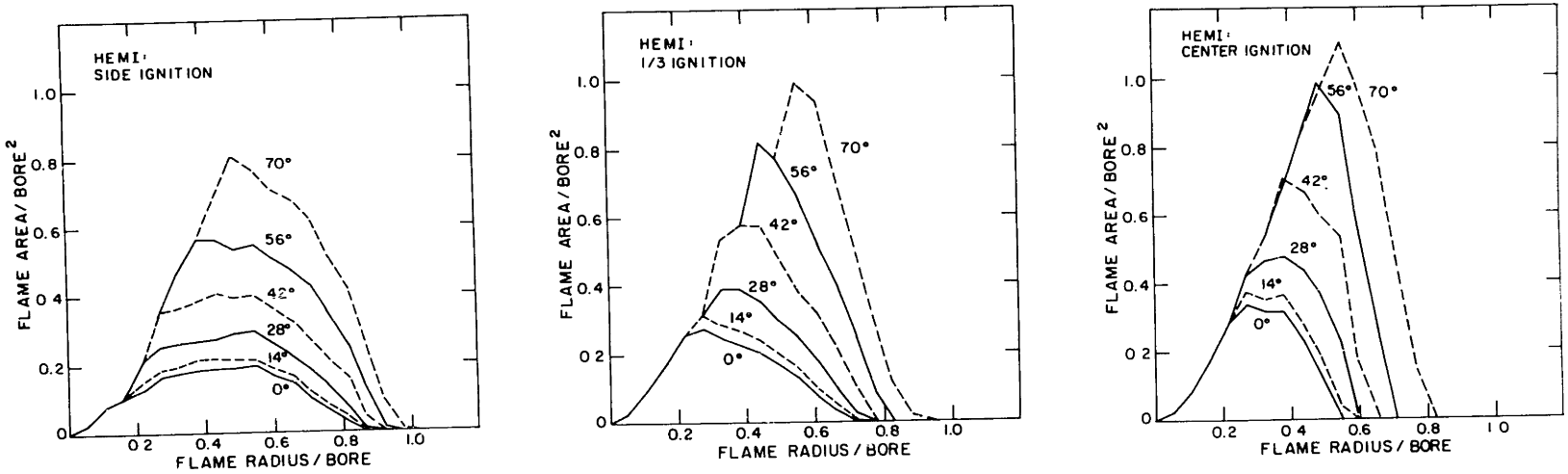


Figure 16: Flame area vs. flame radius and crank angle from top center for hemi chamber with side, 1/3, and center ignition.

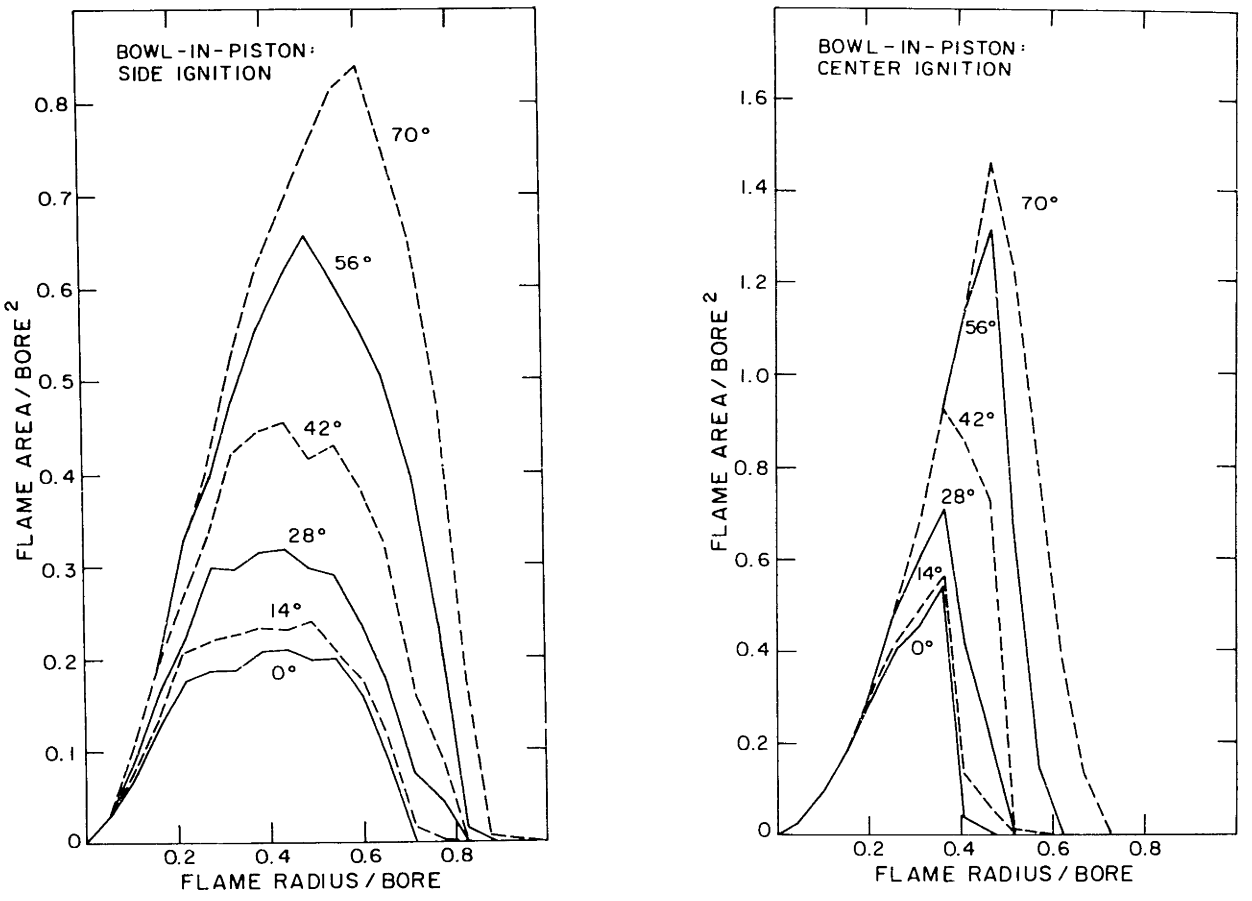


Figure 17: Flame area vs. flame radius and crank angle from top center for bowl-in-piston chamber with side and center ignition.

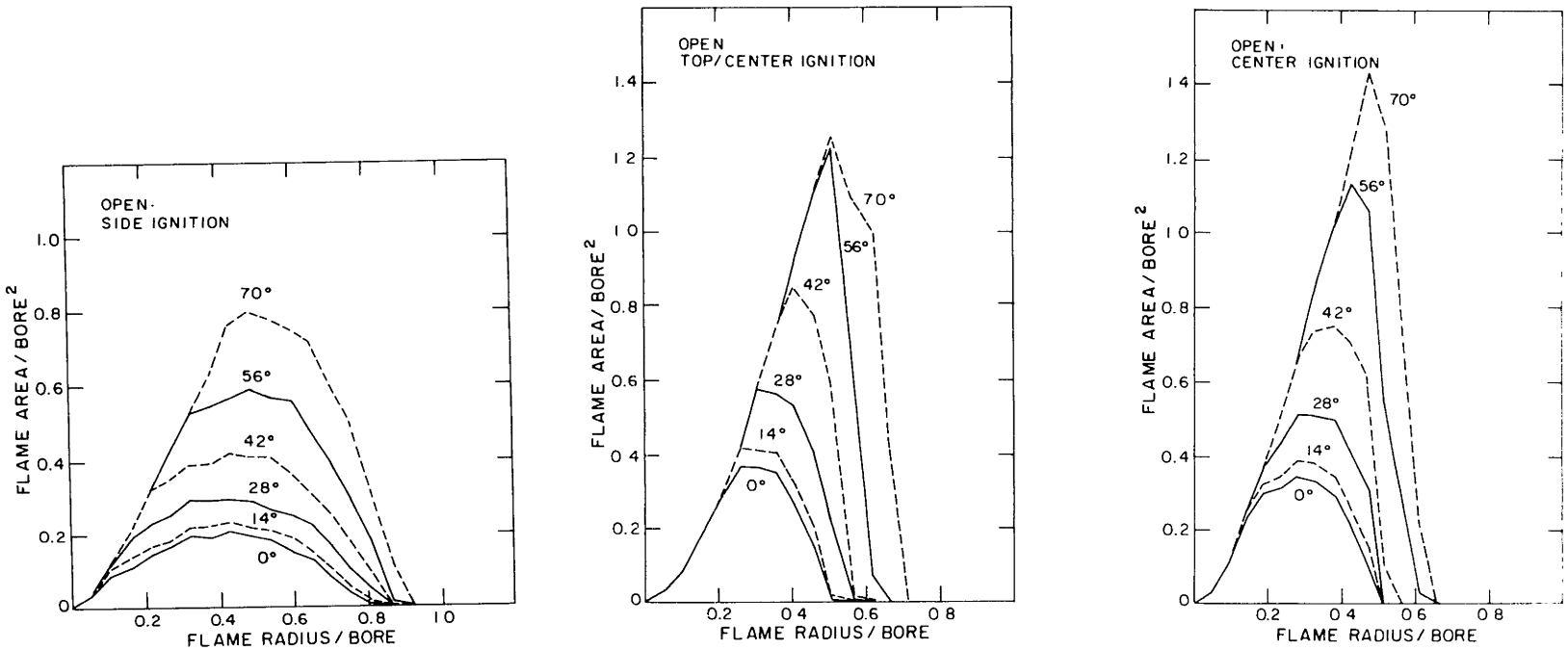


Figure 18: Flame area vs. flame radius and crank angle from top center for open chamber with side, top/center, and center ignition.

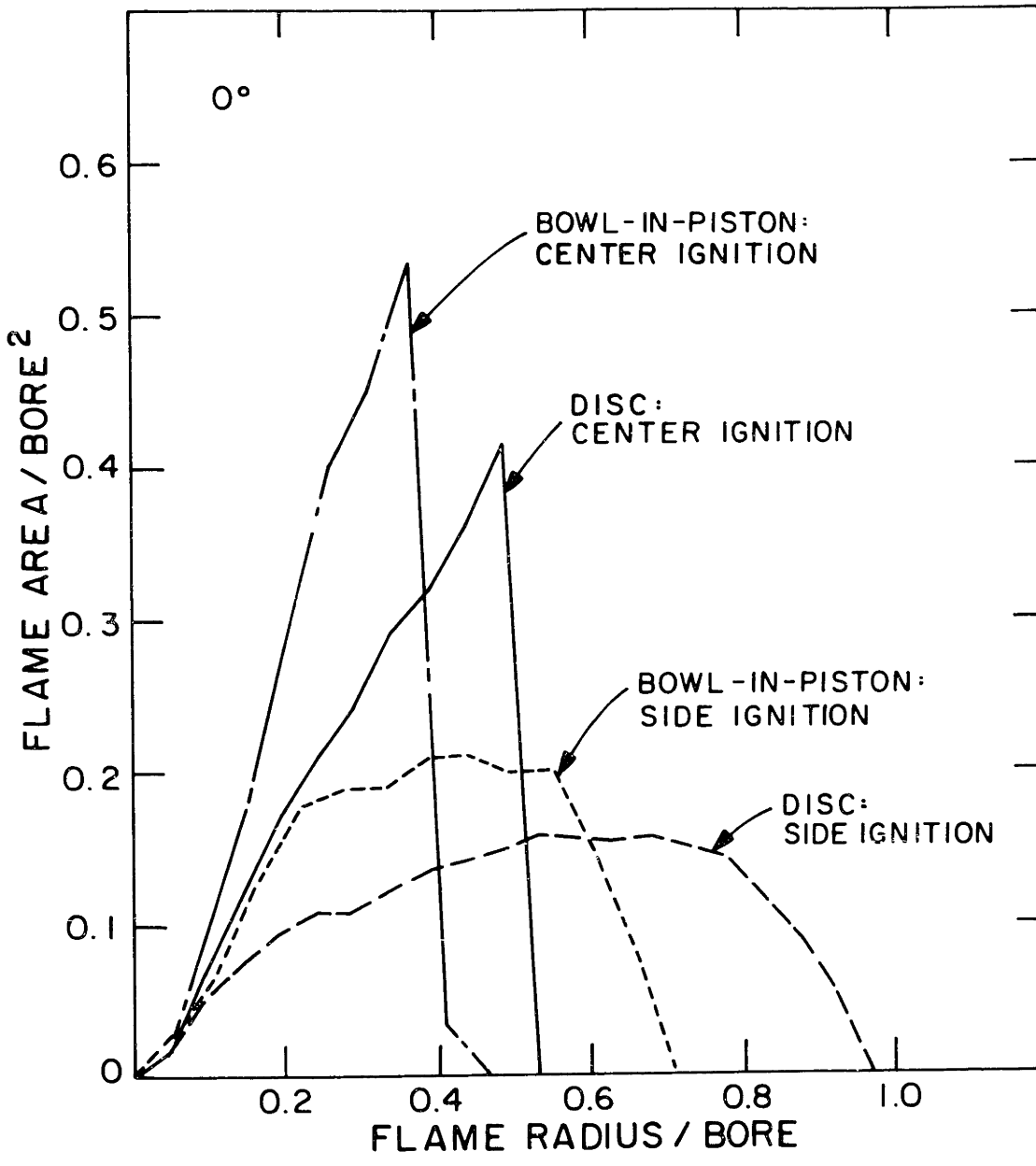
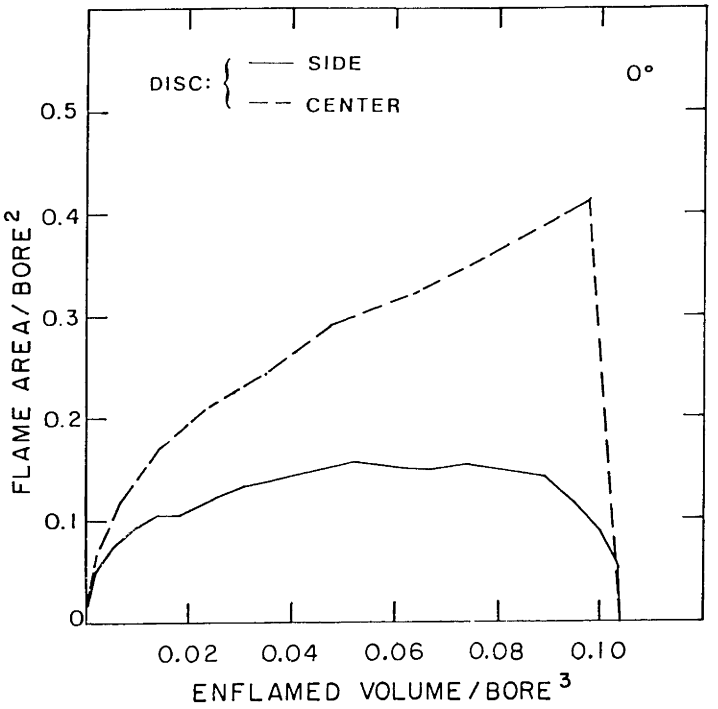


Figure 19. Flame area vs. flame radius at top center for bowl-in-piston and disc chambers with side and center ignition.



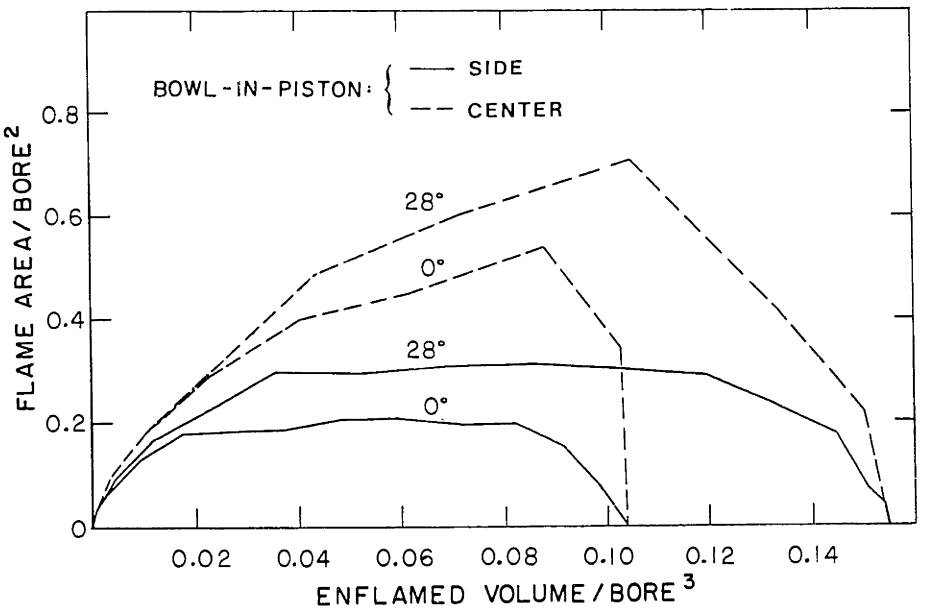


Figure 20. Flame area vs. enflamed volume near top center for disc and bowl-in-piston chambers with side and center ignition.

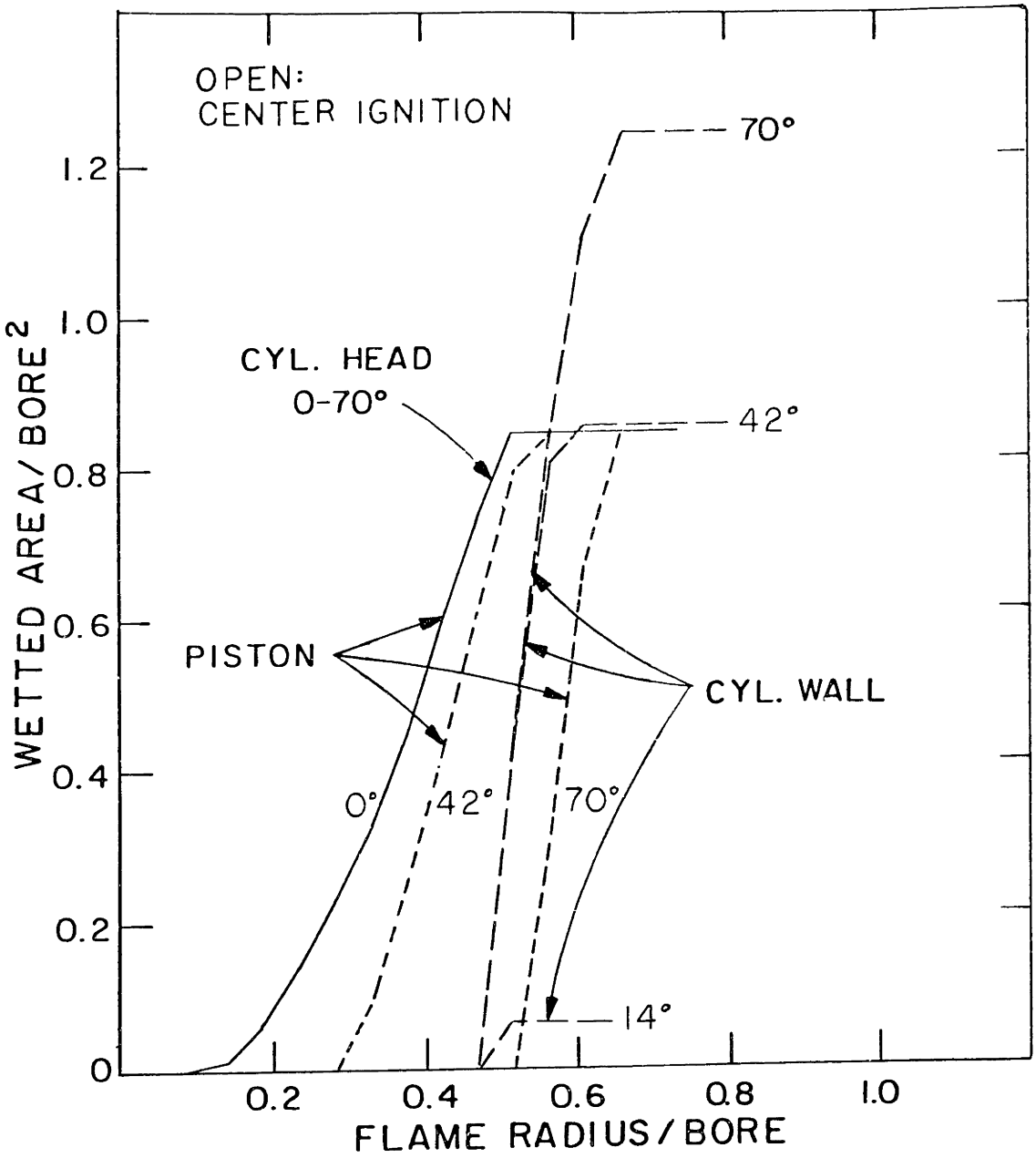


Figure 21. Wetted wall area vs. flame radius and crank angle from top center for open chamber with center ignition.

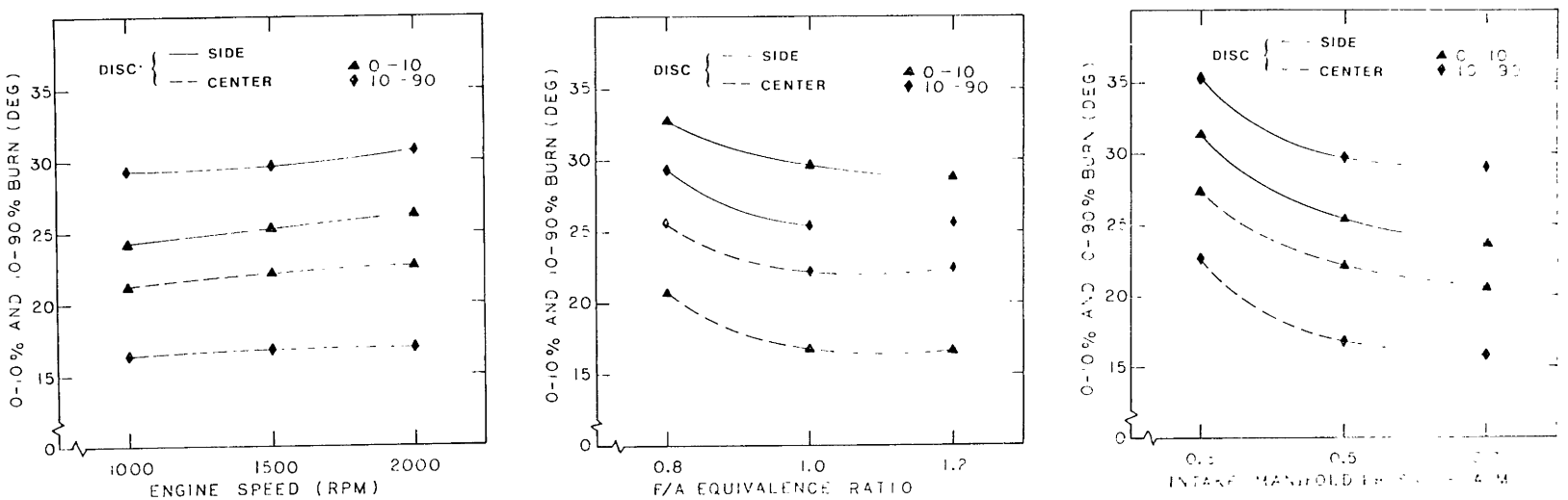


Figure 22. Model predictions of the effect of engine speed, fuel/air equivalence ratio, and intake manifold pressure on duration of early and main stages of combustion.

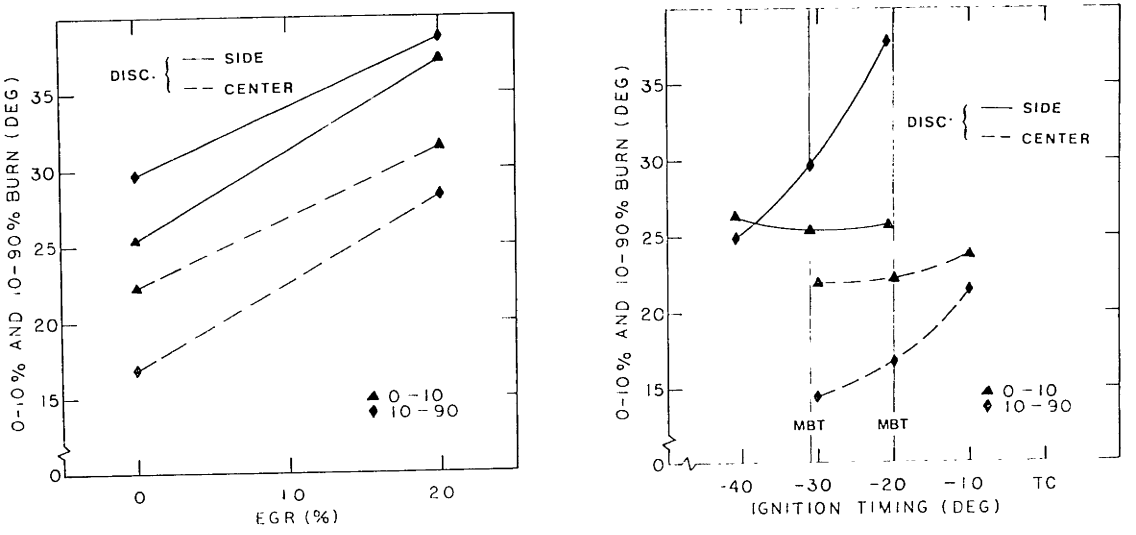


Figure 23. Model predictions of the effect of exhaust gas recirculation and spark timing on duration of early and main stages of combustion.

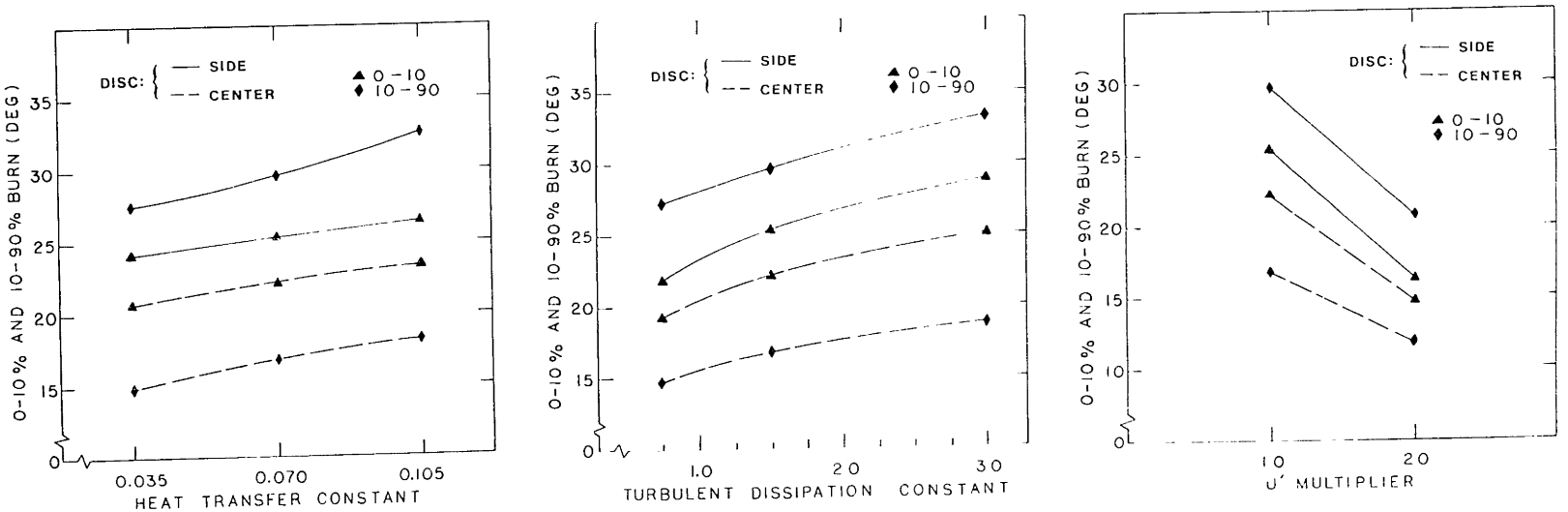
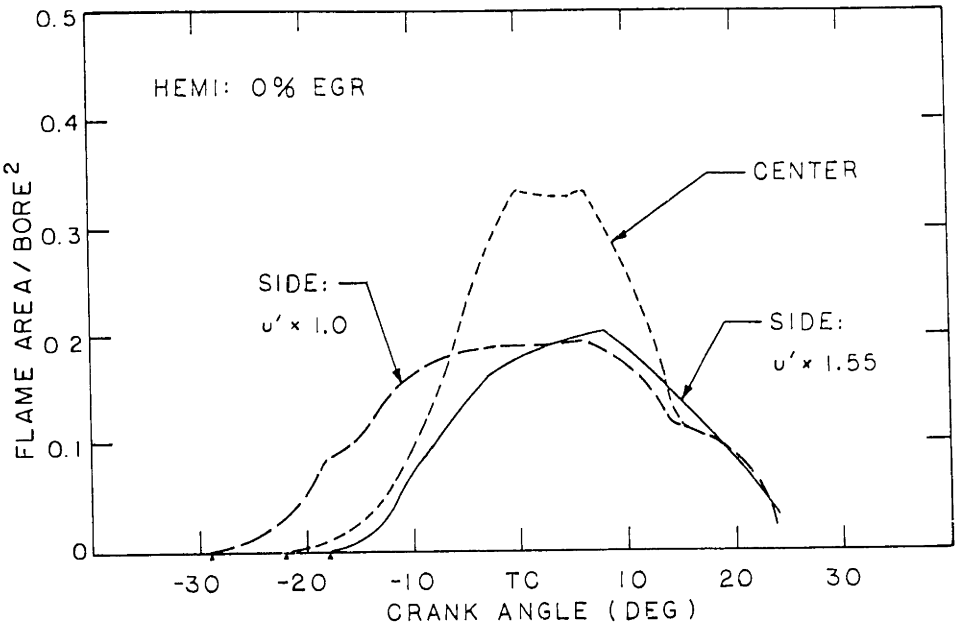


Figure 24. Model predictions of the effect of heat transfer constant, α, turbulent dissipation constant, c_β, and u' multiplier, c_{mult}, on duration of early and main stages of combustion.



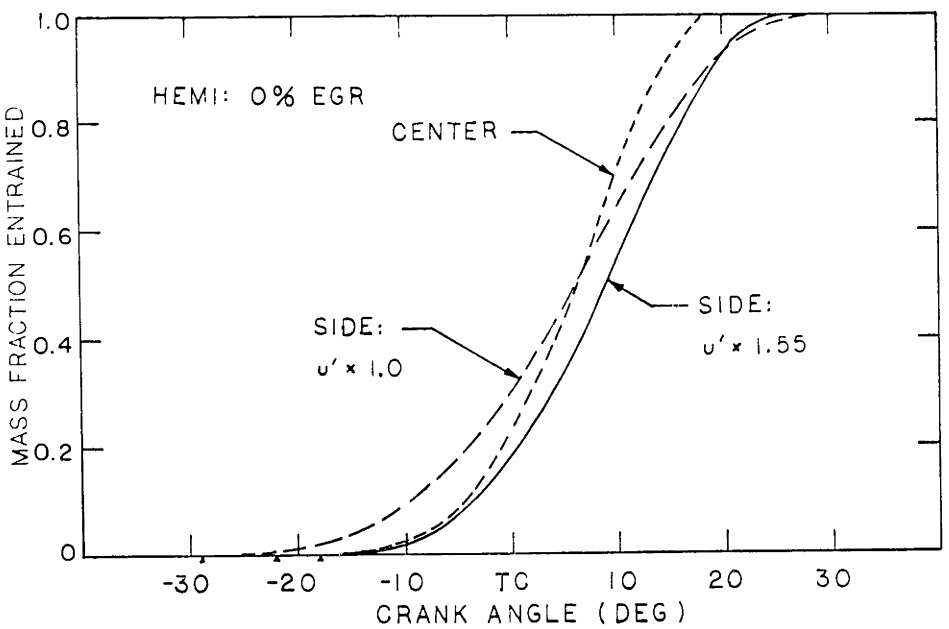


Figure 25. Flame area and mass fraction entrained vs. crank angle for hemi chamber with center ignition, side ignition with normal turbulence, and side ignition with amplified turbulence.

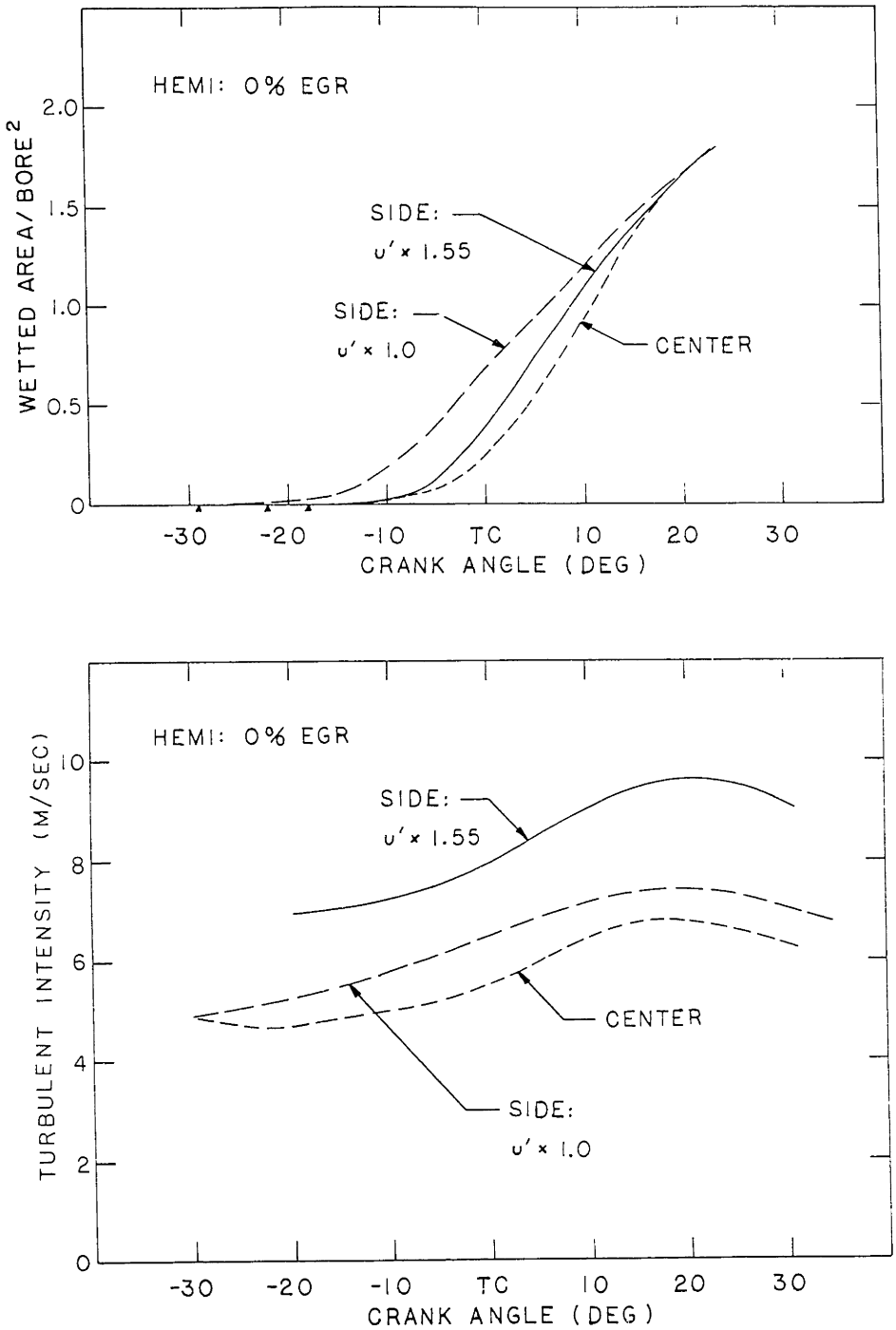


Figure 26. Wall area wetted by the flame and turbulent intensity vs. crank angle for hemi chamber with center ignition, side ignition with normal turbulence, and side ignition with amplified turbulence.

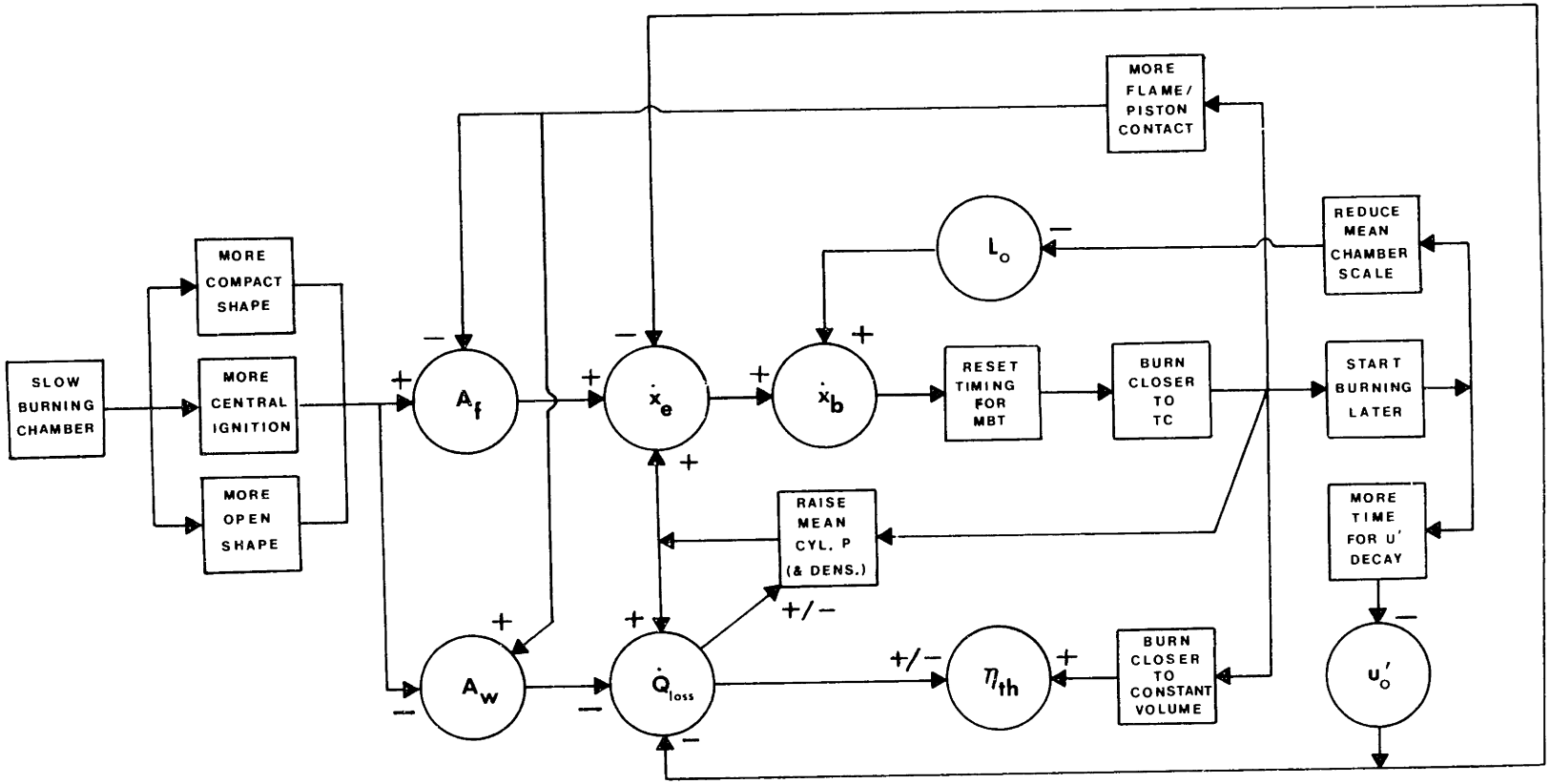


Figure 27. Model for the interaction between dominant effects which follow a change in combustion chamber geometry.

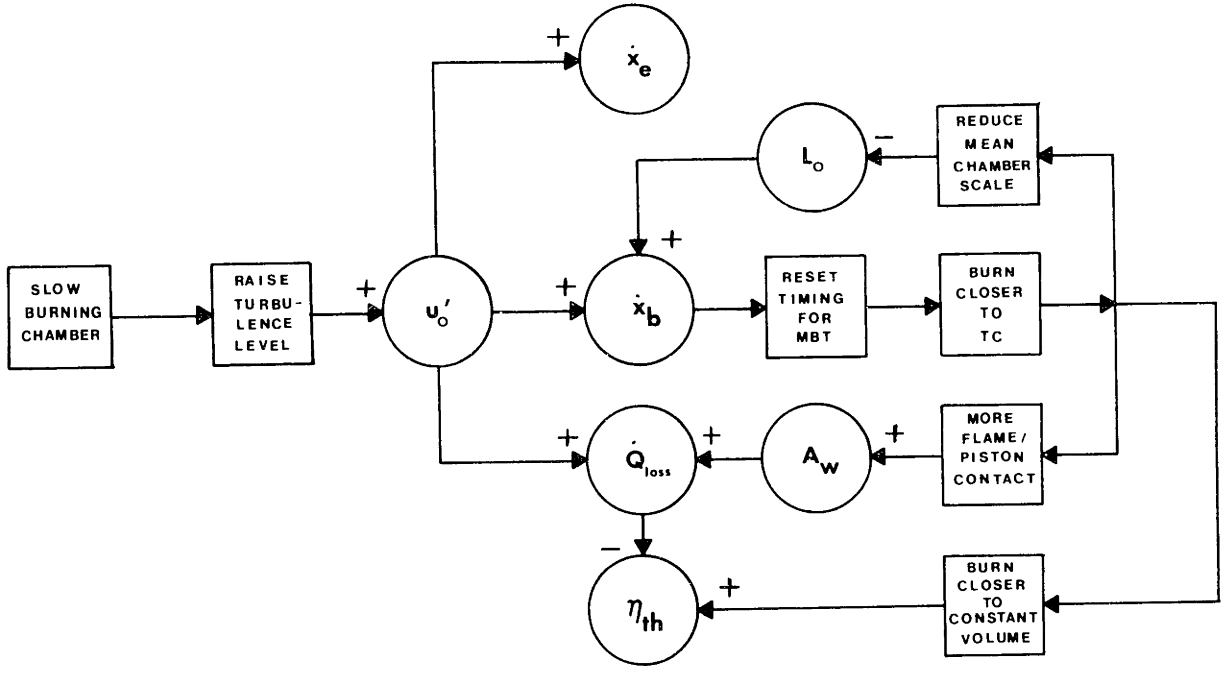


Figure 28. Model for the interaction between dominant effects which follow a scaled increase in turbulent intensity during combustion.

APPENDIX A

SI ENGINE CYCLE SIMULATION CODE

QUASI-DIMENSIONAL SIMULATION OF THE RECIPROCATING SPARK-IGNITION ENGINE CYCLE: A PERFORMANCE AND EMISSIONS PREDICTIVE MODEL

BY

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S. HOSSEIN MANSOURI

SLOAN AUTOMOTIVE LABORATORY

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

MARCH 1982

ADDRESS: PROF. JOHN B. HEYWOOD
ROOM 3-339, 77 MASS. AVE.
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
CAMBRIDGE, MASS 02139

```
C
C     PURPOSE
C
C        THIS PROGRAM IS A QUASI-DIMENSIONAL SIMULATION OF THE
C
C        OPERATING CYCLE OF RECIPROCATING SPARK-IGNITION ENGINES.
C
C        THE PROGRAM CALCULATES TEMPERATURE AND PRESSURE IN THE
C
C        COMBUSTION CHAMBER AS WELL AS PERFORMANCE AND EMISSIONS
C
C        AS A FUNCTION OF OPERATING CONDITIONS AND ENGINE DESIGN,
C
C        INCLUDING DETAIL CHANGES IN COMBUSTION CHAMBER GEOMETRY.
C
C
C     DESCRIPTION OF PARAMETERS:
C
C        PARAMETER  INPUT  OUTPUT   DESCRIPTION
C
C     1  GEOMETRICAL AND DESIGN PARAMETERS
C
C        BORE       YES    NO       ENGINE BORE (CM)
C        STROKE     YES    NO       ENGINE STROKE (CM)
C        CONRL      YES    NO       CONNECTING ROD LENGTH (CM)
C        CLVTDC     YES    NO       CYLINDER VOLUME AT TDC (CM**3)
C        TIVO       YES    NO       INTAKE VALVE OPENS (DEG)
C        TIVC       YES    NO       INTAKE VALVE CLOSES (DEG)
C        TEVO       YES    NO       EXHAUST VALVE OPENS (DEG)
C        TEVC       YES    NO       EXHAUST VALVE CLOSES (DEG)
C
C
C     2  OPERATING PARAMETERS
C
C        PIM        YES    NO       INTAKE PRESSURE (ATM)
C        PEM        YES    NO       EXHAUST PRESSURE (ATM)
C        TFRESH     YES    NO       FRESH CHARGE TEMPERATURE (K)
C        TEGR       YES    NO       EGR TEMPERATURE (K)
C        EGR        YES    NO       EXHAUST GAS RECIRCULATION (%)
C        TSPARK     YES    NO       IGNITION TIMING (DEG)
C        PATM       YES    NO       ATMOSPHERIC PRESSURE (ATM)
C        TATM       YES    NO       ATMOSPHERIC TEMPERATURE (K)
C
C
C     3  TURBULENCE SUB-MODEL CONSTANTS
C
C        CBETA      YES    NO       TURBULENT DISSIPATION CONSTANT
C        CMULT      YES    NO       CONSTANT WHICH MULTIPLIES TURBULENCE
C        ------     ---    --       INTENSITY--COMBUSTION/EXPANSION ONLY
C
C
C     4  HEAT TRANSFER CONSTANTS: NU = CONS'T * (REYNOLDS NO.)**EXP'NT
```

```
C
C     PURPOSE
C
C        THIS PROGRAM IS A QUASI-DIMENSIONAL SIMULATION OF THE
C
C        OPERATING CYCLE OF RECIPROCATING SPARK-IGNITION ENGINES.
C
C        THE PROGRAM CALCULATES TEMPERATURE AND PRESSURE IN THE
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C        COMBUSTION CHAMBER AS WELL AS PERFORMANCE AND EMISSIONS
C
C        AS A FUNCTION OF OPERATING CONDITIONS AND ENGINE DESIGN,
C
C        INCLUDING DETAIL CHANGES IN COMBUSTION CHAMBER GEOMETRY.
C
C
C     DESCRIPTION OF PARAMETERS:
C
C        PARAMETER  INPUT  OUTPUT   DESCRIPTION
C
C     1  GEOMETRICAL AND DESIGN PARAMETERS
C
C        BORE       YES    NO       ENGINE BORE (CM)
C        STROKE     YES    NO       ENGINE STROKE (CM)
C        CONRL      YES    NO       CONNECTING ROD LENGTH (CM)
C        CLVTDC     YES    NO       CYLINDER VOLUME AT TDC (CM**3)
C        TIVO       YES    NO       INTAKE VALVE OPENS (DEG)
C        TIVC       YES    NO       INTAKE VALVE CLOSES (DEG)
C        TEVO       YES    NO       EXHAUST VALVE OPENS (DEG)
C        TEVC       YES    NO       EXHAUST VALVE CLOSES (DEG)
C
C
C     2  OPERATING PARAMETERS
C
C        PIM        YES    NO       INTAKE PRESSURE (ATM)
C        PEM        YES    NO       EXHAUST PRESSURE (ATM)
C        TFRESH     YES    NO       FRESH CHARGE TEMPERATURE (K)
C        TEGR       YES    NO       EGR TEMPERATURE (K)
C        EGR        YES    NO       EXHAUST GAS RECIRCULATION (%)
C        TSPARK     YES    NO       IGNITION TIMING (DEG)
C        PATM       YES    NO       ATMOSPHERIC PRESSURE (ATM)
C        TATM       YES    NO       ATMOSPHERIC TEMPERATURE (K)
C
C
C     3  TURBULENCE SUB-MODEL CONSTANTS
C
C        CBETA      YES    NO       TURBULENT DISSIPATION CONSTANT
C        CMULT      YES    NO       CONSTANT WHICH MULTIPLIES TURBULENCE
C        ------     ---    --       INTENSITY--COMBUSTION/EXPANSION ONLY
C
C
C     4  HEAT TRANSFER CONSTANTS: NU = CONS'T * (REYNOLDS NO.)**EXP'NT
```

```
C
C        CONHT      YES    NO       CONS'T
C        EXPHT      YES    NO       EXP'NT
C
C
C     5  FUEL AND AIR SPECIFICATIONS
C
C        CX         YES    NO       NUMBER OF CARBON ATOMS IN THE
C        -----      ---    --       FUEL (8.0 FOR C8H18)
C        DEL        YES    NO       MOLAR C:H RATIO OF THE FUEL
C        PSI        YES    NO       MOLAR N:O RATIO OF AIR
C        QLOWER     YES    NO       LOWER HEATING VALUE OF FUEL (MJ/KG)
C
C
C     6  ERROR TOLERANCES
C
C        AREROT     YES    NO       ERROR TOLERANCE FOR CALCULATING
C        ------     ---    --       THE ROOT OF 'G' (SEE SUBROUTINE
C        ------     ---    --       ODERT).
C        CIINTG     YES    NO       ERROR TOLERANCE FOR INTEGRATION
C        ------     ---    --       DURING INTAKE PROCESS (SEE
C        ------     ---    --       SUBROUTINE ODERT).
C        CCINTG     YES    NO       SAME, DURING COMPRESSION PROCESS
C        CBINTG     YES    NO       SAME, DURING COMBUSTION PROCESS
C        CEINTG     YES    NO       SAME, DURING EXHAUST PROCESS
C        REL        YES    NO       RELATIVE ERROR TOLERANCE IN
C        ---        ---    --       REACHING TEND
C        MAXITS     YES    NO       MAXIMUM NUMBER OF ITERATIONS OF
C        ------     ---    --       COMPLETE CYCLE SIMULATION
C        MAXTRY     YES    NO       SEE SUBROUTINE ITRATE
C        MAXERR     YES    NO       SEE SUBROUTINE ITRATE
C
C
C     7  INITIAL GUESSES AT THE START OF INTAKE PROCESS
C
C        PSTART     NO     NO       INITIAL PRESSURE IN CYLINDER (ATM)
C        TSTART     NO     NO       INITIAL TEMPERATURE IN CYLINDER (K)
C        MKESTA     NO     NO       INITIAL MEAN K.E. (ERG)
C        TKESTA     NO     NO       INITIAL TURBULENT K.E. (ERG)
C
C
C     8  TIME INCREMENTS
C
C        TPRINT     YES    NO       PRINTING OUTPUT DURING INTAKE,
C        -----      ---    --       COMPRESSION, AND EXHAUST (DEG)
C        TPRINX     YES    NO       PRINTING OUTPUT DURING COMBUSTION
C        -----      ---    --       AND EXPANSION
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. FOR CALCULATED BURN RATE
C
C
C     REMARKS
C        ALL CRANK ANGLE DATA ARE REFERENCED TO 0.0 DEG @ TDC
C        OF THE INTAKE STROKE (START OF THE INTAKE STROKE)
C
C
C     SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED:
C
C     1  WORKING SUBROUTINES
C
C        INTAKE     CMPRES     CMBSTN     EXAUST
C        GINT1      GINT2      GCMP
C
C
C     2  SPECIAL UTILITY SUBROUTINES
C
C        IVACD      EVACD      CSAVDV
C
C
C     3  GENERAL UTILITY SUBROUTINES
C
C        UPROP      HPROD      CLDPRD     HELPHT     LAMFSP     RDGEOM
C        UTRANS     BTRANS     MFLRT      THERMO     PTCHEM
C        FUELDT     WRITE      ERRCHK     INTRP      ITRATE
C        ODERT      DERT1      ROOT       STEP1      FLAMEG
C
C
C     METHOD
C        SEE S. G. POULOS S.M. THESIS AND S. H. MANSOURI PH.D. THESIS,
C        M.I.T., 1982.
C
C     WRITTEN BY S. G. POULOS AND S. H. MANSOURI
C     EDITED BY S. G. POULOS
C
      LOGICAL FIRE, SPBURN, ENSTOP
      INTEGER FUELTP
      REAL*8 DT, DY(20), TOUT, RELERR, ABSERR, WORK, REROOT, AEROOT
      REAL MW, MWIM, MSTART, MACRSC, MICRSC, MASS, MKESTA, MACRSP,
     &     MAXERR, MWBL, MWAC, MFINAL
      DIMENSION Y(20), YP(20), WORK(520), IWORK(5)
      COMMON/EPARAM/ BORE, STROKE, CONRL, CYLCA, CSATDC, CMRTIO, CLVTDC
      COMMON/HTRC/ CONHT, EXPHT
      COMMON/TEMPS/ TPSTON, THEAD, TCW
      COMMON/BURN/ SPBURN, FIRE, RPM
      COMMON/DTDTH/ ESPDI
      COMMON/MANFP/ PIM, TIM, EGR, PEM, MSTART
      COMMON/TIMES/ TIVO, TEVC, TIVC, TSPARK, TEVO
      COMMON/IMTHP/ HIM, MWIM, GIM, RHOIM
```

```
C        ----        ---    --        = .FALSE. FOR MOTORING CASE
C        SPBURN      YES    NO        = .TRUE.  FOR SPECIFIED BURN RATE
C        ----        ---    --        = .FALSE. FOR CALCULATED BURN RATE
C
C
C     REMARKS
C        ALL CRANK ANGLE DATA ARE REFERENCED TO 0.0 DEG @ TDC
C        OF THE INTAKE STROKE (START OF THE INTAKE STROKE)
C
C
C     SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED:
C
C     1  WORKING SUBROUTINES
C
C        INTAKE      CMPRES      CMBSTN      EXAUST
C        GINT1       GINT2       GCMP
C
C
C     2  SPECIAL UTILITY SUBROUTINES
C
C        IVACD       EVACD       CSAVDV
C
C
C     3  GENERAL UTILITY SUBROUTINES
C
C        UPROP       HPROD       CLDPRD      HELPHT      LAMFSP      RDGEOM
C        UTRANS      BTRANS      MFLRT       THERMO      PTCHEM
C        FUELDT      WRITE       ERRCHK      INTRP       ITRATE
C        ODERT       DERT1       ROOT        STEP1       FLAMEG
C
C
C     METHOD
C        SEE S. G. POULOS S.M. THESIS AND S. H. MANSOURI PH.D. THESIS,
C        M.I.T., 1982.
C
C     WRITTEN BY S. G. POULOS AND S. H. MANSOURI
C     EDITED BY S. G. POULOS
C
      LOGICAL FIRE, SPBURN, ENSTOP
      INTEGER FUELTP
      REAL*8 DT, DY(20), TOUT, RELERR, ABSERR, WORK, REROOT, AEROOT
      REAL MW, MWIM, MSTART, MACRSC, MICRSC, MASS, MKESTA, MACRSP,
     &     MAXERR, MWBL, MWAC, MFINAL
      DIMENSION Y(20), YP(20), WORK(520), IWORK(5)
      COMMON/EPARAM/ BORE, STROKE, CONRL, CYLCA, CSATDC, CMRTIO, CLVTDC
      COMMON/HTRC/ CONHT, EXPHT
      COMMON/TEMPS/ TPSTON, THEAD, TCW
      COMMON/BURN/ SPBURN, FIRE, RPM
      COMMON/DTDTH/ ESPDI
      COMMON/MANFP/ PIM, TIM, EGR, PEM, MSTART
      COMMON/TIMES/ TIVO, TEVC, TIVC, TSPARK, TEVO
      COMMON/IMTHP/ HIM, MWIM, GIM, RHOIM
```

```
C
C        CONHT      YES    NO       CONS'T
C        EXPHT      YES    NO       EXP'NT
C
C
C     5  FUEL AND AIR SPECIFICATIONS
C
C        CX         YES    NO       NUMBER OF CARBON ATOMS IN THE
C        -----      ---    --       FUEL (8.0 FOR C8H18)
C        DEL        YES    NO       MOLAR C:H RATIO OF THE FUEL
C        PSI        YES    NO       MOLAR N:O RATIO OF AIR
C        QLOWER     YES    NO       LOWER HEATING VALUE OF FUEL (MJ/KG)
C
C
C     6  ERROR TOLERANCES
C
C        AREROT     YES    NO       ERROR TOLERANCE FOR CALCULATING
C        ------     ---    --       THE ROOT OF 'G' (SEE SUBROUTINE
C        ------     ---    --       ODERT).
C        CIINTG     YES    NO       ERROR TOLERANCE FOR INTEGRATION
C        ------     ---    --       DURING INTAKE PROCESS (SEE
C        ------     ---    --       SUBROUTINE ODERT).
C        CCINTG     YES    NO       SAME, DURING COMPRESSION PROCESS
C        CBINTG     YES    NO       SAME, DURING COMBUSTION PROCESS
C        CEINTG     YES    NO       SAME, DURING EXHAUST PROCESS
C        REL        YES    NO       RELATIVE ERROR TOLERANCE IN
C        ---        ---    --       REACHING TEND
C        MAXITS     YES    NO       MAXIMUM NUMBER OF ITERATIONS OF
C        ------     ---    --       COMPLETE CYCLE SIMULATION
C        MAXTRY     YES    NO       SEE SUBROUTINE ITRATE
C        MAXERR     YES    NO       SEE SUBROUTINE ITRATE
C
C
C     7  INITIAL GUESSES AT THE START OF INTAKE PROCESS
C
C        PSTART     NO     NO       INITIAL PRESSURE IN CYLINDER (ATM)
C        TSTART     NO     NO       INITIAL TEMPERATURE IN CYLINDER (K)
C        MKESTA     NO     NO       INITIAL MEAN K.E. (ERG)
C        TKESTA     NO     NO       INITIAL TURBULENT K.E. (ERG)
C
C
C     8  TIME INCREMENTS
C
C        TPRINT     YES    NO       PRINTING OUTPUT DURING INTAKE,
C        -----      ---    --       COMPRESSION, AND EXHAUST (DEG)
C        TPRINX     YES    NO       PRINTING OUTPUT DURING COMBUSTION
C        -----      ---    --       AND EXPANSION
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. FOR CALCULATED BURN RATE
C
C
C     REMARKS
C        ALL CRANK ANGLE DATA ARE REFERENCED TO 0.0 DEG @ TDC
C        OF THE INTAKE STROKE (START OF THE INTAKE STROKE)
C
C
C     SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED:
C
C     1  WORKING SUBROUTINES
C
C        INTAKE      CMPRES      CMBSTN      EXAUST
C        GINT1       GINT2       GCMP
C
C
C     2  SPECIAL UTILITY SUBROUTINES
C
C        IVACD       EVACD       CSAVDV
C
C
C     3  GENERAL UTILITY SUBROUTINES
C
C        UPROP       HPROD       CLDPRD      HELPHT      LAMFSP      RDGEOM
C        UTRANS      BTRANS      MFLRT       THERMO      PTCHEM
C        FUELDT      WRITE       ERRCHK      INTRP       ITRATE
C        ODERT       DERT1       ROOT        STEP1       FLAMEG
C
C
C     METHOD
C        SEE S. G. POULOS S.M. THESIS AND S. H. MANSOURI PH.D. THESIS,
C        M.I.T., 1982.
C
C     WRITTEN BY S. G. POULOS AND S. H. MANSOURI
C     EDITED BY S. G. POULOS
C
      LOGICAL FIRE, SPBURN, ENSTOP
      INTEGER FUELTP
      REAL*8 DT, DY(20), TOUT, RELERR, ABSERR, WORK, REROOT, AEROOT
      REAL MW, MWIM, MSTART, MACRSC, MICRSC, MASS, MKESTA, MACRSP,
     &     MAXERR, MWBL, MWAC, MFINAL
      DIMENSION Y(20), YP(20), WORK(520), IWORK(5)
      COMMON/EPARAM/ BORE, STROKE, CONRL, CYLCA, CSATDC, CMRTIO, CLVTDC
      COMMON/HTRC/ CONHT, EXPHT
      COMMON/TEMPS/ TPSTON, THEAD, TCW
      COMMON/BURN/ SPBURN, FIRE, RPM
      COMMON/DTDTH/ ESPDI
      COMMON/MANFP/ PIM, TIM, EGR, PEM, MSTART
      COMMON/TIMES/ TIVO, TEVC, TIVC, TSPARK, TEVO
      COMMON/IMTHP/ HIM, MWIM, GIM, RHOIM
```

```
      COMMON/FUEL/ FUELTP, ENW, CX, HY, OZ, DEL, PSI, PHI, QLOWER, FASTO
      COMMON/FLAG/ INFLAG
      COMMON/TURBU/ CBETA , MACRSC, UPRIME, VMKE
      COMMON/HEATS/ CVHTRN, HTRCOE, HTPAPI, HTPAHD, HTPACW, HTRAPI,
     &              HTRAHD, HTRACW, THTRAN, QFRPI, QFRHD, QFRCW
      COMMON/UBHEAT/ UHTRCO, BHTRCO
      COMMON/VALVE/ VIV, VEV
      COMMON/ITRLIM/ MAXTRY, MAXERR
      COMMON/RHMAS/ RHO, MASS, VOLUME, H, GAMMA
      COMMON/KINET/ TURBKE, MICRSC, SSUBL, BTIMSC
      COMMON/SPARK/ UPRISP, RHOUSP, MACRSP, CMULT
      COMMON/SPECB/ DTBRN, CONSPB, EXSPB
      COMMON/NOX/ YAC, YNO, XNOAC, XNOBL, XNO, PPMAC, PPMBL, PPMNO
      COMMON/ACBL/ VACONV, VBLONV, DBLONB, TWALLB, TAC, TBLAYR
      COMMON/FLPRO/ VENONV, VBRONV, AFLONB, APUONB, APBONB, AHUONB,
     &              AHBONB, ACUONB, ACBONB, DFLONB
      COMMON/XSTOP/ XESTOP, XBSTOP, ENSTOP, IFCNT
      COMMON/RADS/ RENTRA, RBURND
C
      NAMELIST/INPUT/ FIRE, SPBURN, RPM, FUELTP, PHI, CMRTIO, EGR, PIM,
     & PEM, TFRESH, TEGR, TPSTON, THEAD, TCW, XBZERO, TIVO, TIVC, TEVO,
     & TEVC, TSPARK, BORE, CLVTDC, TATM, PATM, DTBRN, CONSPB, EXSPB,
     & CBETA, CMULT, CONHT, EXPHT, CIINTG, CCINTG, CBINTG, CEINTG, REL,
     & AREROT, MAXITS, MAXERR, MAXTRY, TPRINT, TPRINX
C
      EXTERNAL INTAKE, CMPRES, CMBSTN, EXAUST, GINT1, GINT2, GCMP
C
C@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
C
C        STANDARD DATA SET -- OVERRIDE BY USING NAMELIST INPUT
C
C--------------------
      FIRE   = .TRUE.
      SPBURN = .TRUE.
      FUELTP = 1
      PHI    = 1.00
      BORE   = 10.3
      CLVTDC = 53.3333
      RPM    = 1500.
C--------------------
      TIVO   = -16.0
      TIVC   = 218.0
      TEVO   = 476.0
      TEVC   = 737.0
      TSPARK = 350.
C--------------------
      XBZERO = 0.0001
      XESTOP = 0.995
      XBSTOP = 0.995
      DTBRN  = 40.
      CONSPB = 5.
      EXSPB  = 1.
```

```
C--------------------
      PATM   = 1.0
      TATM   = 300.0
      PIM    = 0.9959
      TFRESH = 300.0
      TEGR   = 300.0
      EGR    = 0.0
      PEM    = 0.9876
C--------------------
      TPSTON = 462.
      THEAD  = 462.
      TCW    = 462.
      CONHT  = .035
      EXPHT  = .8
C--------------------
      CBETA = 1.5
      CMULT  = 1.0
C--------------------
      TPRINT = 10.0
      TPRINX = 1.0
C--------------------
      AREROT = .0002
      CIINTG = 0.0001
      CCINTG = 0.0001
      CBINTG = 0.00005
      CEINTG = 0.0001
      REL    = .0002
      MAXITS = 2
      MAXERR = 0.03
      MAXTRY = 5
C--------------------
C
C        READ NAMELIST INPUT
C
      READ (8,INPUT)
C
C        READ IN CHAMBER GEOMETRY DATA AND CALCULATE BASIC
C        GEOMETRIC ENGINE PARAMETERS AND CONSTANTS
C
      CALL RDGEOM
C
      DVOLUM = 3.141593 * BORE * BORE * STROKE/4.
      CMRTIO = (CLVTDC + DVOLUM)/CLVTDC
      CYLCA  = .7853982 * BORE * BORE
      ESPDI  = 1./(6. * RPM)
C
C        CALCULATE ALL FUEL-RELATED PARAMETERS
C
      IF ((.NOT. FIRE) .OR. (PHI .LE. 0.0)) PHI = 0.00001
      CALL FUELDT
C
C        FIND THERMODYNAMIC STATE OF INTAKE CHARGE
```

```
C
      CALL THERMO (TIVO, TFRESH, PIM, 0.0, HFRESH, XXA, XXB, XXC,
     &             XXD, XXE, XXF, XXG, XXH, XXI, XXJ, XXK)
      CALL THERMO (TIVO, TEGR, PIM, 1.0, HEGR, XXA, XXB, XXC,
     &             XXD, XXE, XXF, XXG, XXH, XXI, XXJ, XXK)
      HIM = (1. - EGR/100.)*HFRESH + (EGR/100.)*HEGR
      RESFIM = EGR/100.
      TGUESS = (1. - EGR/100.)*TFRESH + (EGR/100.)*TEGR
      CALL ITRATE (TIVO, TGUESS, PIM, RESFIM, HIM, CSUBPI, CSUBTI,
     &             RHOIM, DRODTI, DRODPI, GIM, MWIM, XXA, XXB, XXC, XXD)
      TIM = TGUESS
C
C        MAKE INITIAL GUESSES FOR FIRST CYCLE ITERATION
C
      MKESTA = 25000.
      TKESTA = 11000.
      PSTART = 1.25
      TSTART = 330.
      IF (FIRE) PSTART = 1.015
      IF (FIRE) TSTART = 1000.
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 (TIVO, TSTART, PSTART, RESFRK, HSTART, XXA, XXB,
     &       RHO, XXC, XXD, XXE, XXF, XXG, XXH, XXI, XXJ)
      CALL CSAVDV (TIVO, XXA, XXB, XXC, VOLUME, XXD)
      MSTART = RHO * VOLUME
C
C        PREPARE ALL OUTPUT FILES FOR OUTPUT FROM THIS ITERATION
C
    5 REWIND  6
      REWIND 11
      REWIND 12
      REWIND 13
      REWIND 14
      REWIND 15
      REWIND 16
C
C        WRITE MAIN HEADINGS AND ECHO INPUT PARAMETERS
```

```
C
      WRITE  (6,3333)
      WRITE  (6,3333)
      WRITE  (6,2901)
      WRITE  (6,3333)
      WRITE  (6,3333)
      WRITE  (6,77)
      WRITE  (6,3333)
      WRITE  (6,2902)
      IF (FIRE) WRITE (6,2903)
      IF (.NOT. FIRE) WRITE (6,2904)
      IF (SPBURN .AND. FIRE) WRITE (6,2905)
      IF (SPBURN .AND. FIRE) WRITE (6,2906) DTBRN, CONSPB, EXSPB
      IF (.NOT. SPBURN .AND. FIRE) WRITE (6,2907)
      WRITE  (6,3333)
      WRITE  (6,2908)
      IF (FIRE .AND. FUELTP .EQ. 1) WRITE (6,2909)
      IF (FIRE .AND. FUELTP .EQ. 2) WRITE (6,2910)
      IF (FIRE) WRITE (6,2911) PHI
      IF (FIRE .AND. ((PHI .GT. 1.3) .OR. (PHI .LT. 0.7))) WRITE (6,999)
      IF (FIRE .AND. ((PHI .GT. 1.3) .OR. (PHI .LT. 0.7))) WRITE (7,999)
      IF (FIRE) WRITE  (6,2912) TSPARK
      WRITE (6,2913) RPM
      WRITE  (6,3333)
      WRITE  (6,2914)
      WRITE  (6,2915) PIM, PEM, TFRESH, EGR, TEGR, TIM, PATM, TATM
      WRITE  (6,3333)
      WRITE  (6,2916)
      WRITE  (6,2917) CONHT, EXPHT, TPSTON, THEAD, TCW, CBETA, CMULT
      WRITE  (6,3333)
      WRITE  (6,2918)
      WRITE  (6,2919) BORE, STROKE, CONRL, CMRTIO, DVOLUM,
     &                CLVTDC, TIVO, TIVC, TEVO, TEVC
      WRITE  (6,3333)
      WRITE  (6,2920)
      WRITE  (6,2921) MAXITS, ITERAS, TPRINT, TPRINX, XBZERO, XESTOP,
     &                XBSTOP, CIINTG, CCINTG, CBINTG, CEINTG, AREROT,
     &                REL, MAXERR, MAXTRY
      WRITE  (6,3333)
      WRITE  (6,3333)
      WRITE  (6,2225)
      WRITE (11,2225)
      WRITE (12,2225)
      WRITE (13,2225)
      WRITE (14,2225)
      WRITE (15,2225)
      WRITE (16,2225)
C
      WRITE  (6,4595)
      WRITE  (6,4596)
      WRITE  (6,3333)
      WRITE (13,7111)
```

```
      WRITE (13,4592)
      WRITE (13,3333)
      WRITE (12,6111)
      WRITE (12,4594)
      WRITE (12,3333)
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
      Y(6)  = MKESTA
      Y(7)  = TKESTA
      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
C
      HEATI = 0.0
      WORKI = 0.0
      VIV = 0.0
C
      DO 10 I = 1, 20
           DY(I) = Y(I)
   10 CONTINUE
      WRITE (6,1277) TIVO, DY(12), DY(11), DY(1), DY(2), VIV,
     &               DY(5), DY(16)
      AEROOT = AREROT
      REROOT = AREROT
C
C##################################################################
C
C        START OF INTAKE PROCESS (TIVO - TIVC)
C
C##################################################################
C
   20 I = 0
      NEQN = 20
      IFLAG = 1
      T = TIVO
```

```
      TEND = 180.
      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 CYLINDER OF NEW CHARGE
C        ( FRESH AIR/FUEL MIXTURE + EGR ); SET INFLAG = 1
C
   40 INFLAG = 1
C
C        TPRINT:  CRANK ANGLE INCREMENT AT WHICH SOLUTION
C                 IS TO BE PRINTED
C
      NCALL = IFIX( ABS(TEND - T)/TPRINT )
      IF (NCALL .LE. 0) GO TO 70
C
C        NCALL:  NO. OF TIMES INTEGRATING SUBROUTINE IS CALLED
C
      DO 60 NC = 1, NCALL
           TOUT = T + TPRINT
   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
           UPRIME = DSQRT(.66667 * DY(7)/MASS)
           WRITE  (7,881)  DT, DY(12), INFLAG, IFLAG
           WRITE  (6,1210) DT, DY(12), DY(11), DY(1), DY(2), VIV,
     &                     VEV, DY(5), THTRAN, DY(16), INFLAG, IFLAG
           WRITE (12,3210) DT, DY(6), DY(7), VMKE, UPRIME,
     &                     MACRSC, MICRSC, SSUBL, BTIMSC
           WRITE (13,4210) DT, CVHTRN, HTPAPI, HTPAHD, HTPACW,
     &                     QFRPI, QFRHD, QFRCW
C
           IF (ABS(T/TEND - 1.0) .LE. REL) GO TO 190
           IF (IFLAG .EQ. 8) GO TO 90
C
C             I.E. REVERSE FLOW ACROSS INTAKE VALVE.
C
           IF (IFLAG .NE. 2) GO TO 50
   60 CONTINUE
C
C        NO ROOT FOR GINT1; COMPLETE INTAKE PROCESS.
C
   70 TOUT = TEND
```

```
   80 ABSERR = CIINTG
      RELERR = CIINTG
C
      CALL ODERT (INTAKE, NEQN, DY, DT, TOUT, RELERR, ABSERR,
     &            IFLAG, WORK, IWORK, GINT1, REROOT, AEROOT)
      CALL HELPHT (DT, DY, 1)
C
      T = DT
      UPRIME = DSQRT(.66667 * DY(7)/MASS)
      WRITE  (7,881)  DT, DY(12), INFLAG, IFLAG
      WRITE  (6,1210) DT, DY(12), DY(11), DY(1), DY(2), VIV,
     &                VEV, DY(5), THTRAN, DY(16), INFLAG, IFLAG
      WRITE (12,3210) DT, DY(6), DY(7), VMKE, UPRIME,
     &                MACRSC, MICRSC, SSUBL, BTIMSC
      WRITE (13,4210) DT, CVHTRN, HTPAPI, HTPAHD, HTPACW,
     &                QFRPI, QFRHD, QFRCW
C
      IF (ABS(T/TEND - 1.0) .LE. REL) GO TO 190
      IF (IFLAG .EQ. 8) GO TO 90
      IF (IFLAG .NE. 2) GO TO 80
C
C        ROOT FOUND FOR GINT1; FLOW ACROSS INTAKE VALVE
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)/TPRINT )
      IF (NCALL .LE. 0) GO TO 120
      DO 110 NC = 1, NCALL
           TOUT = T + TPRINT
  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
           UPRIME = DSQRT(.66667 * DY(7)/MASS)
           WRITE  (7,881)  DT, DY(12), INFLAG, IFLAG
           WRITE  (6,1210) DT, DY(12), DY(11), DY(1), DY(2), VIV,
     &                     VEV, DY(5), THTRAN, DY(16), INFLAG, IFLAG
           WRITE (12,3210) DT, DY(6), DY(7), VMKE, UPRIME,
     &                     MACRSC, MICRSC, SSUBL, BTIMSC
           WRITE (13,4210) DT, CVHTRN, HTPAPI, HTPAHD, HTPACW,
     &                     QFRPI, QFRHD, QFRCW
C
           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
      UPRIME = DSQRT(.66667 * DY(7)/MASS)
      WRITE  (7,881)  DT, DY(12), INFLAG, IFLAG
      WRITE  (6,1210) DT, DY(12), DY(11), DY(1), DY(2), VIV,
     &                VEV, DY(5), THTRAN, DY(16), INFLAG, IFLAG
      WRITE (12,3210) DT, DY(6), DY(7), VMKE, UPRIME,
     &                MACRSC, MICRSC, SSUBL, BTIMSC
      WRITE (13,4210) DT, CVHTRN, HTPAPI, HTPAHD, HTPACW,
     &                QFRPI, QFRHD, QFRCW
C
      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 VALVE 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)/TPRINT )
      IF (NCALL .LE. 0) GO TO 170
      DO 160 NC = 1, NCALL
           TOUT = T + TPRINT
  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
           T = DT
           UPRIME = DSQRT(.66667 * DY(7)/MASS)
           WRITE  (7,881)  DT, DY(12), INFLAG, IFLAG
           WRITE  (6,1210) DT, DY(12), DY(11), DY(1), DY(2), VIV,
     &                     VEV, DY(5), THTRAN, DY(16), INFLAG, IFLAG
           WRITE (12,3210) DT, DY(6), DY(7), VMKE, UPRIME,
     &                     MACRSC, MICRSC, SSUBL, BTIMSC
           WRITE (13,4210) DT, CVHTRN, HTPAPI, HTPAHD, HTPACW,
     &                     QFRPI, QFRHD, QFRCW
C
           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
      T = DT
      UPRIME = DSQRT(.66667 * DY(7)/MASS)
      WRITE  (7,881)  DT, DY(12), INFLAG, IFLAG
      WRITE  (6,1210) DT, DY(12), DY(11), DY(1), DY(2), VIV,
     &                VEV, DY(5), THTRAN, DY(16), INFLAG, IFLAG
      WRITE (12,3210) DT, DY(6), DY(7), VMKE, UPRIME,
     &                MACRSC, MICRSC, SSUBL, BTIMSC
      WRITE (13,4210) DT, CVHTRN, HTPAPI, HTPAHD, HTPACW,
     &                QFRPI, QFRHD, QFRCW
C
      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 = TIVC
      GO TO 30
C
C        CALCULATE TOTAL MASS OF FUEL INDUCTED IN THIS CYCLE (FMIN)
C
  200 ZMAST = MSTART + DY(1) - DY(2)
      FMIN = DY(1) * (1. - EGR/100.) * PHI * FASTO/(PHI*FASTO + 1.)
      IF (.NOT. FIRE) FMIN = 0.0
C
C        CALCULATE TOTAL MASS OF AIR INDUCTED IN THIS CYCLE (AMIN)
C
      AMIN = DY(1) * (1. - EGR/100.) - FMIN
C
C        CALCULATE RESIDUAL FRACTION AT TIVC
C
      RESIDL = 1. - DY(5)
C
C        CALCULATE VOLUMETRIC EFFICIENCY RELATIVE TO INTAKE MANIFOLD
C        CONDITIONS (VOLEFI) AND ATMOSPHERIC CONDITIONS (VOLEFA)
C
      VOLEFI = 100. * AMIN / ( DVOLUM * RHOIM * (1. + PHI*FASTO) )
      VOLEFA = VOLEFI * (PIM/PATM) * (TATM/TIM)
```

```
      WRITE (7,1281) VOLEFI
      WRITE (6,3333)
      WRITE (6,1110)
      WRITE (6,2225)
      WRITE (6,4597)
      WRITE (6,3333)
      QREL = 0.0
      QIVC = DY(8) + DY(9) + DY(10)
      WRITE (6,1211) TIVC, DY(12), DY(11), QREL, THTRAN,
     &               DY(16), IFLAG
C
C#######################################################################
C
C        START OF COMPRESSION PROCESS (FIRING CASE) (TIVC - TSPARK)
C        START OF COMPRESSION AND EXPANSION PROCESSES
C        (MOTORING CASE) (TIVC - TEVO)
C
C#######################################################################
C
      TID = TSPARK
      TBD = TSPARK
      NEQN = 20
      IFLAG = 1
      T = TIVC
      TEND = TEVO
      IF (FIRE) TEND = TSPARK
      DT = T
      NCALL = IFIX( ABS(TEND - T)/TPRINT )
      IF (NCALL .LE. 0) GO TO 230
      DO 220 NC = 1, NCALL
           TOUT = T + TPRINT
  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
           T = DT
           UPRIME = DSQRT(.66667 * DY(7)/MASS)
           IF (FIRE) QREL = -( DY(8) + DY(9) + DY(10) - QIVC )/
     &                     (FMIN * QLOWER)
           WRITE  (7,882)  DT, DY(12), IFLAG
           WRITE  (6,1211) DT, DY(12), DY(11), QREL, THTRAN,
     &                     DY(16), IFLAG
           WRITE (12,3210) DT, DY(6), DY(7), VMKE, UPRIME,
     &                     MACRSC, MICRSC, SSUBL, BTIMSC
           WRITE (13,4210) DT, CVHTRN, HTPAPI, HTPAHD, HTPACW,
     &                     QFRPI, QFRHD, QFRCW
C
           IF (ABS(T/TEND - 1.0) .LE. REL) GO TO 250
           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
      T = DT
      UPRIME = DSQRT(.66667 * DY(7)/MASS)
      IF (FIRE) QREL = -( DY(8) + DY(9) + DY(10) - QIVC )/
     &                  (FMIN * QLOWER)
      WRITE  (7,882)  DT, DY(12), IFLAG
      WRITE  (6,1211) DT, DY(12), DY(11), QREL, THTRAN,
     &                DY(16), IFLAG
      WRITE (12,3210) DT, DY(6), DY(7), VMKE, UPRIME,
     &                MACRSC, MICRSC, SSUBL, BTIMSC
      WRITE (13,4210) DT, CVHTRN, HTPAPI, HTPAHD, HTPACW,
     &                QFRPI, QFRHD, QFRCW
C
      IF (ABS(T/TEND - 1.0) .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 (TEVO - TIVO)
C
C#######################################################################
C
  250 WRITE (6,3333)
      IF (FIRE) GO TO 330
      WRITE (6,2225)
      WRITE (6,1111)
      WRITE (6,4599)
      WRITE (6,3333)
      VEV = 0.0
      WRITE (6,1213) TEVO, DY(12), DY(11), DY(2), VEV,
     &               THTRAN, DY(16), IFLAG
C
      I = 0
      NEQN = 20
      IFLAG = 1
      T = TEVO
      TEND = 540.
      DT = T
  260 I = I + 1
      IFLAG = 1
      NCALL = IFIX( ABS(TEND - T)/TPRINT )
      IF (NCALL .LE. 0) GO TO 290
      DO 280 NC = 1, NCALL
```

```
          TOUT = T + TPRINT
  270     ABSERR = CEINTG
          RELERR = CEINTG
C
          CALL ODERT (EXAUST, NEQN, DY, DT, TOUT, RELERR, ABSERR,
     &                IFLAG, WORK, IWORK, GCMP, REROOT, AEROOT)
          CALL HELPHT (DT, DY, 4)
C
          T = DT
          UPRIME = DSQRT(.66667 * DY(7)/MASS)
          WRITE  (7,882)  DT, DY(12), IFLAG
          WRITE  (6,1213) DT, DY(12), DY(11), DY(2), VEV,
     &                    THTRAN, DY(16), IFLAG
          WRITE (12,3210) DT, DY(6), DY(7), VMKE, UPRIME,
     &                    MACRSC, MICRSC, SSUBL, BTIMSC
          WRITE (13,4210) DT, CVHTRN, HTPAPI, HTPAHD, HTPACW,
     &                    QFRPI, QFRHD, QFRCW
C
          IF (ABS(T/TEND - 1.0) .LE. REL) GO TO 310
          IF (IFLAG .NE. 2) GO TO 270
  280 CONTINUE
  290 TOUT = TEND
  300 ABSERR = CEINTG
      RELERR = CEINTG
C
      CALL ODERT (EXAUST,NEQN,DY,DT,TOUT,RELERR,ABSERR,IFLAG,
     &            WORK,IWORK,GCMP,REROOT,AEROOT)
      CALL HELPHT (DT, DY, 4)
C
      T = DT
      UPRIME = DSQRT(.66667 * DY(7)/MASS)
      WRITE  (7,882)  DT, DY(12), IFLAG
      WRITE  (6,1213) DT, DY(12), DY(11), DY(2), VEV,
     &                THTRAN, DY(16), IFLAG
      WRITE (12,3210) DT, DY(6), DY(7), VMKE, UPRIME,
     &                MACRSC, MICRSC, SSUBL, BTIMSC
      WRITE (13,4210) DT, CVHTRN, HTPAPI, HTPAHD, HTPACW,
     &                QFRPI, QFRHD, QFRCW
C
      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 = TIVO + 720.
      GO TO 260
C
  320 HEATE = DY(8) + DY(9) + DY(10) - HEATCE - HEATI
      WORKE = DY(16) - WORKCE - WORKI
      WRITE (6,3333)
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 (6,2225)
      WRITE (6,1112)
      WRITE (6,4598)
      WRITE (6,3333)
C
C        REINITIALIZE 'ODERT' FOR START OF COMBUSTION
C
C        CALCULATE PRESSURE RISE DUE TO INITIAL HEAT RELEASE
C
      MASS = MSTART + DY(1) - DY(2)
      PZERO = DY(12) + 9.8692326 * MASS * XBZERO * QLOWER *
     &        (GAMMA - 1.)/VOLUME
C
C        CALCULATE INITIAL BURNED ZONE TEMPERATURE
C
      HB = H
      TGUESB = 2400.
      CALL ITRATE (TSPARK, TGUESB, PZERO, 1.0, HB, XXA, XXB,
     &             RHOB, XXC, XXD, XXE, XXF, XXG, XXH, XXI, XXJ)
C
C        CALCULATE INITIAL UNBURNED ZONE TEMPERATURE
C
      RHOUEX = (1. - XBZERO)/( VOLUME/MASS - XBZERO/RHOB )
      TGUESU = DY(11)
      RESFRK = 1. - DY(5)
      DO 335 I = 1, 30
         CALL THERMO (TSPARK, TGUESU, PZERO, RESFRK, XXA, XXB, XXC,
     &                RHOUG, DRDTUG, XXD, XXE, XXF, XXG, XXH, XXI, XXJ)
         IF ( ABS( (RHOUG - RHOUEX)/RHOUEX ) .LE. 0.00001 ) GO TO 337
         TGUESU = TGUESU + (RHOUEX - RHOUG)/DRDTUG
  335 CONTINUE
  337 CALL THERMO (TSPARK, TGUESU, PZERO, RESFRK, HU, XXB, XXC,
     &             RHOU, DRDTU, XXD, XXE, XXF, XXG, XXH, XXI, XXJ)
C
C        INITIALIZE 'ODERT' FOR START OF COMBUSTION
C
      DY(3)  = XBZERO
      DY(4)  = XBZERO
      DY(12) = PZERO
      DY(13) = TGUESU
      DY(14) = VOLUME - ( DY(4)*MASS/RHOB )
```

```
      DY(15) = TGUESB
      IF (CONHT .GT. 0.0) DY(20) = XBZERO/50.
C
C        STORE TURBULENCE PARAMETERS AT TSPARK
C
      UPRISP = UPRIME
      RHOUSP = RHOU
      MACRSP = MACRSC
      RENTRA = 0.00001
      RBURND = RENTRA
C
      WRITE  (6,1212) TSPARK, DY(12), DY(15), DY(13), DY(3),
     &                DY(4), QREL, THTRAN, DY(16), IFLAG
      WRITE (14,4111)
      WRITE (14,4222)
      WRITE (14,3333)
      WRITE (15,5111)
      WRITE (15,5222)
      WRITE (15,3333)
      WRITE (16,3111)
      WRITE (16,3222)
      WRITE (16,3333)
      DT = TSPARK
      ENSTOP = .FALSE.
      CALL HELPHT (DT, DY, 3)
      WRITE (13,4210) TSPARK, CVHTRN, HTPAPI, HTPAHD, HTPACW,
     &                QFRPI, QFRHD, QFRCW
      WRITE (14,6444) TSPARK, VENONV, VBRONV, DFLONB, AFLONB, AHUONB,
     &                AHBONB, APUONB, APBONB, ACUONB, ACBONB
      WRITE (15,5444) TSPARK, YAC, DY(20), VACONV, VBLONV, DBLONB,
     &                TWALLB, DY(15), TAC, TBLAYR
      WRITE (16,3444) TSPARK, YAC, DY(20), DY(18), DY(19), YNO, XNOAC,
     &                XNOBL, XNO, PPMAC, PPMBL, PPMNO
C
C#######################################################################
C
C        START OF COMBUSTION PROCESS (TSPARK - TEVO)
C
C#######################################################################
C
      IFCNT = 0
      IDCNT = 0
      IBCNT = 0
      NEQN = 20
      IFLAG = 1
      T = TSPARK
      TEND = TEVO
      DT = T
      NCALL = AFIX( ABS(TEND - T)/TPRINX )
      IF (NCALL .LE. 0) GO TO 360
      DO 350 NC = 1, NCALL
           TOUT = T + TPRINX
```

```
 340      ABSERR = CBINTG
          RELERR = CBINTG
          TOLDXB = T
          XBOLD = DY(4)
C
          CALL ODERT (CMBSTN,NEQN,DY,DT,TOUT,RELERR,ABSERR,IFLAG,
     &                WORK,IWORK,GCMP,REROOT,AEROOT)
          CALL HELPHT (DT, DY, 3)
          BTIMSC = 1.0E+03 * BTIMSC
C
C            RESTART IF X-BURNED OR X-ENTRAINED EXCEED 1.0
C
          IF ((DY(3) .LE. 1.0) .AND. (DY(4) .LE. 1.0)) GO TO 341
          IF (DY(3) .GT. 1.0) XESTOP = XESTOP - 0.002
          IF (DY(4) .GT. 1.0) XBSTOP = XBSTOP - 0.002
          GO TO 5
C
 341      T = DT
C
C            CHECK FOR XBURNED = 0.1 OR XBURNED = 0.9
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
C
 347      QREL = DY(4) - ( DY(8) + DY(9) + DY(10) - QIVC )/
     &           (FMIN * QLOWER)
          WRITE  (7,883)  DT, DY(12), DY(4), IFLAG
          WRITE  (6,1212) DT, DY(12), DY(15), DY(13), DY(3),
     &                    DY(4), QREL, THTRAN, DY(16), IFLAG
          WRITE (12,3210) DT, DY(6), DY(7), VMKE, UPRIME,
     &                    MACRSC, MICRSC, SSUBL, BTIMSC
          WRITE (13,4210) DT, CVHTRN, HTPAPI, HTPAHD, HTPACW,
     &                    QFRPI, QFRHD, QFRCW
C
          WRITE (14,6444) DT, VENONV, VBRONV, DFLONB, AFLONB, AHUONB,
     &                    AHBONB, APUONB, APBONB, ACUONB, ACBONB
          WRITE (15,5444) DT, YAC, DY(20), VACONV, VBLONV, DBLONB,
     &                    TWALLB, DY(15), TAC, TBLAYR
          WRITE (16,3444) DT, YAC, DY(20), DY(18), DY(19), YNO,
     &                    XNOAC, XNOBL, XNO, PPMAC, PPMBL, PPMNO
          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,GCMP,REROOT,AEROOT)
      CALL HELPHT (DT, DY, 3)
      BTIMSC = 1.0E+03 * BTIMSC
      IF ((DY(3) .LE. 1.0) .AND. (DY(4) .LE. 1.0)) GO TO 371
      IF (DY(3) .GT. 1.0) XESTOP = XESTOP - 0.02
      IF (DY(4) .GT. 1.0) XBSTOP = XBSTOP - 0.02
      GO TO 5
C
  371 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
  377 QREL = DY(4) - ( DY(8) + DY(9) + DY(10) - QIVC )/
     &       (FMIN * QLOWER)
C
      WRITE  (7,883)  DT, DY(12), DY(4), IFLAG
      WRITE  (6,1212) DT, DY(12), DY(15), DY(13), DY(3),
     &                DY(4), QREL, THTRAN, DY(16), IFLAG
      WRITE (12,3210) DT, DY(6), DY(7), VMKE, UPRIME,
     &                MACRSC, MICRSC, SSUBL, BTIMSC
      WRITE (13,4210) DT, CVHTRN, HTPAPI, HTPAHD, HTPACW,
     &                QFRPI, QFRHD, QFRCW
      WRITE (14,6444) DT, VENONV, VBRONV, DFLONB, AFLONB, AHUONB,
     &                AHBONB, APUONB, APBONB, ACUONB, ACBONB
C
      WRITE (15,5444) DT, YAC, DY(20), VACONV, VBLONV, DBLONB,
     &                TWALLB, DY(15), TAC, TBLAYR
      WRITE (16,3444) DT, YAC, DY(20), DY(18), DY(19), YNO, XNOAC,
     &                XNOBL, XNO, PPMAC, PPMBL, PPMNO
      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) (TEVO - TIVO)
C
C##################################################################
C
  380 WRITE (6,3333)
      WRITE (6,2225)
      WRITE (6,1111)
      WRITE (6,4599)
      WRITE (6,3333)
      MICRSC = 0.0
      SSUBL = 0.0
      BTIMSC = 0.0
```

```
      VEV = 0.0
      WRITE (6,1213) TEVO, DY(12), DY(15), DY(2), VEV,
     &               THTRAN, DY(16), IFLAG
C
C        REINITIALIZE 'ODERT' FOR START OF EXHAUST
C
      DY(7) = TURBKE
      DY(11) = DY(15)
C
      I = 0
      NEQN = 20
      IFLAG = 1
      T = TEVO
      TEND = 540.
      DT = T
  390 I = I + 1
      NCALL = IFIX( ABS(TEND - T)/TPRINT )
      IF (NCALL .LE. 0) GO TO 420
      DO 410 NC = 1, NCALL
           TOUT = T + TPRINT
  400      ABSERR = CEINTG
           RELERR = CEINTG
C
           CALL ODERT (EXAUST,NEQN,DY,DT,TOUT,RELERR,ABSERR,IFLAG,
     &                WORK,IWORK,GCMP,REROOT,AEROOT)
           CALL HELPHT (DT, DY, 4)
C
           T = DT
           UPRIME = DSQRT(.66667 * DY(7)/MASS)
           WRITE  (7,882)  DT, DY(12), IFLAG
           WRITE  (6,1213) DT, DY(12), DY(11), DY(2), VEV,
     &                     THTRAN, DY(16), IFLAG
           WRITE (12,3210) DT, DY(6), DY(7), VMKE, UPRIME,
     &                     MACRSC, MICRSC, SSUBL, BTIMSC
           WRITE (13,4210) DT, CVHTRN, HTPAPI, HTPAHD, HTPACW,
     &                     QFRPI, QFRHD, QFRCW
C
           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,GCMP,REROOT,AEROOT)
      CALL HELPHT (DT, DY, 4)
C
      T = DT
      UPRIME = DSQRT(.66667 * DY(7)/MASS)
      WRITE  (7,882)  DT, DY(12), IFLAG
      WRITE  (6,1213) DT, DY(12), DY(11), DY(2), VEV,
```

```
     &                THTRAN, DY(16), IFLAG
      WRITE (12,3210) DT, DY(6), DY(7), VMKE, UPRIME,
     &                MACRSC, MICRSC, SSUBL, BTIMSC
      WRITE (13,4210) DT, CVHTRN, HTPAPI, HTPAHD, HTPACW,
     &                QFRPI, QFRHD, QFRCW
C
      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 = TIVO + 720.
      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 (6,3333)
C
C        CONVERGENCE CHECK
C
  455 Y(6) = DY(6)
      Y(7) = DY(7)
      Y(12) = DY(12)
      Y(11) = DY(11)
      Y(1) = DY(1)
      Y(2) = DY(2)
      IF (ABS( (Y(6) - MKESTA)/MKESTA ) .GT. 0.10) GO TO 460
      IF (ABS( (Y(7) - TKESTA)/TKESTA ) .GT. 0.10) GO TO 460
      IF (ABS( (Y(12) - PSTART)/PSTART ) .GT. 0.01) GO TO 460
      IF (ABS( (Y(11) - TSTART)/TSTART ) .GT. 0.01) GO TO 460
      IF (ABS( (Y(1) - Y(2))/MSTART )    .GT. 0.02) GO TO 460
      GO TO 480
  460 MKESTA = DY(6)
      TKESTA = DY(7)
      PSTART = DY(12)
      TSTART = DY(11)
C
  470 CONTINUE
C
C*****************************************************************
C
C        END OF CURRENT CYCLE ITERATION
C
C*****************************************************************
C
```

```
C        CALCULATION RESULTS FOR THIS CYCLE
C
C        CALCULATE MASS REMAINING IN CYLINDER
C
  480 RESFRK = 0.0
      IF (FIRE) RESFRK = 1.0
      CALL THERMO (TEVO, Y(11), Y(12), RESFRK, HFINAL, CSUBP, CSUBT,
     &       RHO, DRHODT, DRHODP, GAMMA, MW, ADUMY, BDUMY, GDUMY, HDUMY)
      CALL CSAVDV (TIVO, AHEAD, APSTON, ACW, VOLUME, DVDT)
      MFINAL = RHO * VOLUME
C
      THREFN = 0.0
      THREFG = 0.0
      HEATX  = 0.0
      IF (.NOT. FIRE) GO TO 490
C
C        CALCULATE NET AND GROSS THERMAL EFFICIENCIES
C
      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
      ZISNOX = XNO * ZMAST * 3600./WORKCE
C
      AVREXH = DY(17)/DY(2)
      TGUESS = 500.
      IF (FIRE) TGUESS = 1300.
      CALL ITRATE (T, TGUESS, PEM, RESFRK, AVREXH, XXA, XXB, XXC,
     &             XXD, XXE, XXF, XXG, XXH, XXI, XXJ, XXK)
      AVREXT = TGUESS
C
C        CALCULATE IGNITION DELAY AND BURN DURATION PERIODS
C
      DTHIGD = TID - TSPARK
      DTIGD  = DTHIGD * ESPDI * 1.0E+3
      DTHBRN = TBD - TID
      DTBRN  = DTHBRN * ESPDI * 1.0E+3
C
C        ENERGY BALANCE
C
      TOHSTA = 1.0E-10 * HSTART * MSTART
      TOHIN  = 1.0E-10 * HIM * DY(1)
      TOHEX  = 1.0E-10 * DY(17)
      TOHEAT = HEATI + HEATCE + HEATE
      TOWORK = WORKI + WORKCE + WORKE
      TOHFIN = 1.0E-10 * HFINAL * MFINAL
      DECYCL = TOHFIN + TOHEX + TOHEAT + TOWORK - TOHIN - TOHSTA
      DEONHI = 100.0 * DECYCL/(TOHIN + TOHSTA)
      DEONQ  = 0.0
      IF (FIRE) DEONQ = 100.0 * DECYCL/(FMIN * QLOWER)
```

```
      WRITE (6,2225)
      WRITE (6,5910)
      WRITE (6,3333)
      WRITE (6,5920) VOLEFI, VOLEFA, ZPMEP, ZIMEP, ZISFC, THREFG,
     &               THREFN, HEATX
      WRITE (6,5921) DTHIGD, DTIGD, DTHBRN, DTBRN, PPMNO, ZISNOX, AVREXT
      WRITE (6,3333)
      WRITE (6,9876) MSTART, ZMAST, AMIN, FMIN, RESIDL
      WRITE (6,3333)
      WRITE (6,1261) HEATI, WORKI
      IF (FIRE) WRITE (6,1264) HEATC, WORKC
      IF (FIRE) WRITE (6,1262) HEATCE, WORKCE
      IF (.NOT. FIRE) WRITE (6,1262) HEATCE, WORKCE
      WRITE (6,1263) HEATE, WORKE
      WRITE (6,3333)
      WRITE (6,1890) TOHSTA, TOHIN, TOHEX, TOHEAT, TOWORK, TOHFIN,
     &               DECYCL, DEONHI, DEONQ
      WRITE (6,3333)
C
      CALL WRITE
C
C@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
C
C         FORMAT STATEMENTS
C
 2225 FORMAT (1H1)
C
  881 FORMAT (1H ,2X,'CA = ',F6.2,10X,'P = ',F10.5,9X,'INFLAG = ',I2,
     &        8X,'IFG = ',I2)
C
  882 FORMAT (1H ,2X,'CA = ',F6.2,10X,'P = ',F10.5,28X,'IFG = ',I2)
C
  883 FORMAT (1H ,2X,'CA = ',F6.2,10X,'P = ',F10.5,9X,'XB = ',F9.6,
     &        5X,'IFG = ',I2)
C
  449 FORMAT (////,1H ,18X,'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,
     &        ' (M/SEC)',2X,' (M/SEC)',6X,'(-)',7X,'(J/DEG)',8X,
     &        '(KJ)'))
C
 4597 FORMAT ((4X,'CA',7X,'P',9X,'TEMP',48X,'QREL',9X,
     &        'Q DOT',9X,'WORK',14X,'IFG')/
     &        (2X,'(DEG)',4X,'(ATM)',7X,'(K)',49X,'(-)',9X,
     &        '(J/DEG)',8X,
     &        '(KJ)'))
```

```
C
 4598 FORMAT ((4X,'CA',7X,'P',22X,'TB ',7X,'TU ',4X,'XENTRA',4X,
     &        'XBURND',6X,'QREL',9X,'Q DOT',9X,'WORK',14X,'IFG')/
     &        (2X,'(DEG)',4X,'(ATM)',20X,'(K)',7X,'(K)',5X,
     &        '(-)',7X,'(-)',8X,'(-)',9X,'(J/DEG)',8X,
     &        '(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,'(J/DEG)',8X,
     &        '(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,
     &        F9.5,2X,1F10.5,4X,1F10.6,3X,1I4,1I6)
C
 1211 FORMAT (1F7.1,2X,F9.4,2X,F9.2,44X,F10.6,2X,
     &        1F10.5,4X,1F10.6,9X,1I4)
C
 1212 FORMAT (1F7.1,2X,F9.4,13X,2F10.2,2X,F8.5,2X,F8.5,2X,F10.6,2X,
     &        1F10.5,4X,1F10.6,9X,1I4)
C
 1213 FORMAT (1F7.1,2X,F9.4,2X,F9.2,12X,1F10.5,12X,F8.1,14X,
     &        1F10.5,4X,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 AIR INDUCTED     = ',F8.5,' G')//
     &          ('     MASS OF FUEL INDUCTED    = ',F8.5,' G')//
     &          ('     RESIDUAL FRACTION        = ',F8.5)/)
C
 1890 FORMAT ( /('     INITIAL ENTHALPY / CYCLE    = ',F9.5,' KJ')//
     &          ('     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')//
     &          ('     RESIDUAL ENTHALPY / CYCLE   = ',F9.5,' KJ')//
     &          ('     NET ENERGY GAIN / CYCLE     = ',F9.5,' KJ')//
     &          ('     (ENERGY GAIN)/(H @ IVC)     = ',F9.5,' %')//
     &          ('     (ENERGY GAIN)/(MFUEL*LHV)   = ',F9.5,' %')/)
C
 1261 FORMAT ( /('     HEATI   =  ',F10.6,' KJ','  (TIVO   -    180)')/
     &          ('     WORKI   =  ',F10.6,' KJ')/ )
C
 1281 FORMAT (///('  VOLUMETRIC EFFICIENCY = ',1F5.1,' %')//)
```

```
C
 1262 FORMAT (  /('      HEATCE  =  ',F10.6,' KJ','  (180    -    540)')/
     &           ('      WORKCE  =  ',F10.6,' KJ')/ )
C
 1263 FORMAT (  /('      HEATE   =  ',F10.6,' KJ','  (540    -   TIVO)')/
     &           ('      WORKE   =  ',F10.6,' KJ')/ )
C
 1264 FORMAT (  /('      HEATC   =  ',F10.6,' KJ','  (180    - TSPARK)')/
     &           ('      WORKC   =  ',F10.6,' KJ')/ )
C
 3210 FORMAT (5X,1F7.1,2X,2(1F12.1,2X),2(1F12.2,2X),
     &       2X,F10.3,4X,F10.5,4X,F10.3,4X,F9.4)
C
 4210 FORMAT (5X,1F7.1,2X,F10.1,3X,3(F11.3,3X),4X,3(F12.3,5X))
C
 1112 FORMAT (///(1X,' >>>>> START OF COMBUSTION AND EXPANSION PROCESSES
     &         ')///)
C
 4592 FORMAT (//(9X,'CA',7X,'CVHTRN',7X,'HTPAPI',8X,'HTPAHD',8X,
     &         'HTPACW',13X,'Q% PI',12X,'Q% HD',12X,'Q% CW')/
     &         (8X,'(DEG)',4X,'(CM/SEC)',5X,'(KW/M**2)',5X,'(KW/M**2)',
     &         5X,'(KW/M**2)',12X,'(%)',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
 3111 FORMAT (///,1H ,59X,'NOX FORMATION')
C
 5111 FORMAT (///,1H ,48X,'ADIABATIC CORE / BOUNDARY LAYER DATA')
C
 4111 FORMAT (///,1H ,54X,'FLAME PROPAGATION DATA')
C
 6111 FORMAT (///,1H ,55X,'TURBULENT FLOW MODEL')
C
 7111 FORMAT (///,1H ,56X,'HEAT TRANSFER DATA')
C
 3222 FORMAT (//,1H ,6X,'CA',7X,'YAC',7X,'YBL',7X,'YNOAC',5X,'YNOBL',5X,
     &        'YNO',6X,'XNOAC',6X,'XNOBL',5X,'XNO',8X,'PPMAC',6X,
     &        'PPMBL',6X,'PPMNO')
C
 4222 FORMAT (//,1H ,6X,'CA',5X,'VENONV',5X,'VBRONV',5X,'DFLONB',5X,
     &        'AFLONB',5X,'AHUONB',5X,'AHBONB',5X,'APUONB',5X,'APBONB',
     &        5X,'ACUONB',5X,'ACBONB')
C
 5222 FORMAT (//,1H ,6X,'CA',8X,'YAC',8X,'YBL',8X,'VACONV',6X,'VBLONV',
     &        6X,'DBLONB',10X,'TWALLB',7X,'TB',9X,'TAC',8X,'TBLAYR')
C
 3333 FORMAT (1H ,1X,'____________________________________________',
     &         '____________________________________________',
     &         '________________________',/)
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C
 3444 FORMAT (1H ,3X,F8.1,8(2X,F8.6),3(2X,F9.2))
C
 5444 FORMAT (1H ,2X,F8.1,5(4X,F8.6),2X,4(3X,F9.1))
C
 6444 FORMAT (1H ,2X,F8.1,10(3X,F8.5))
C
 5910 FORMAT (///(46X,'>--------------+--------------<')/
     &          (46X,'>                              <')/
     &          (46X,'>     CALCULATION RESULTS      <')/
     &          (46X,'>                              <')/
     &          (46X,'>--------------+--------------<')///)
C
 5920 FORMAT (/(33X,' -->  VOLUMETRIC EFFICIENCY; (%) ')/
     & (33X,'      BASED ON: INTAKE / ATM            ----> ',2(F8.1))///
     & (33X,' -->  PUMPING MEAN EFFECTIVE  ')/
     & (33X,'      PRESSURE; (KPA) : PEMP            ----> ',1F7.1)///
     & (33X,' -->  GROSS INDICATED MEAN EFFECTIVE ')/
     & (33X,'      PRESSURE; (KPA) : IMEP            ----> ',1F7.1)///
     & (33X,' -->  GROSS INDICATED SPECIFIC FUEL  ')/
     & (33X,'      CONSUMPTION; (G/IKW-HR) : ISFC    ----> ',1F7.1)///
     & (33X,' -->  GROSS INDICATED THERMAL      ')/
     & (33X,'      EFFICIENCY; (%)                   ----> ',1F7.1)///
     & (33X,' -->  NET INDICATED THERMAL        ')/
     & (33X,'      EFFICIENCY; (%)                   ----> ',1F7.1)///
     & (33X,' -->  (HEAT TRANSFER PER CYCLE)/   ')/
     & (33X,'      (MASS OF FUEL TIMES LHV); (%)     ----> ',1F7.1)//)
 5921 FORMAT ((33X,' -->  IGNITION DELAY (0 - 10%)     ')/
     & (33X,'      (CRANK ANGLE) / (MS)              ----> ',2(F8.2))///
     & (33X,' -->  BURN DURATION (10 - 90%)     ')/
     & (33X,'      (CRANK ANGLE) / (MS)              ----> ',2(F8.2))///
     & (33X,' -->  NOX EMISSIONS; (PPM) : NOX        ----> ',1F6.0)///
     & (33X,' -->  GROSS INDICATED SPECIFIC            ')/
     & (33X,'      NOX; (G/IKW-HR) : ISNO            ----> ',1F7.1)///
     & (33X,' -->  MEAN EXHAUST                 ')/
     & (33X,'      TEMPERATURE; (K)                  ----> ',1F7.1)/)
 2901 FORMAT (/////,1H ,39X,'M.I.T. QUASI-DIMENSIONAL SI 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,'BURN DURATION    = ',F8.3,' DEG CA',
     &        /,1H ,30X,'WIEBE CONSTANT   = ',F8.3,
     &        /,1H ,30X,'WIEBE EXPONENT   = ',F8.3,/)
 2907 FORMAT (/,1H ,25X,'PREDICTED BURN RATE',/)
 2908 FORMAT (/,1H ,10X,'>>>>> OPERATING CONDITIONS',/)
 2909 FORMAT (/,1H ,25X,'FUEL USED IS ISOOCTANE')
 2910 FORMAT (/,1H ,25X,'FUEL USED IS PROPANE')
 2911 FORMAT (/,1H ,25X,'F/A EQUIVALENCE RATIO = ',F9.3)
 2912 FORMAT (/,1H ,25X,'SPARK TIMING          = ',F8.2,' DEG CA')
 2913 FORMAT (/,1H ,25X,'ENGINE SPEED          = ',F7.1,' RPM',/)
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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,'PISTON TEMPERATURE              =',F9.2,'   K',/
    &        /,1H ,25X,'CYLINDER HEAD TEMPERATURE       =',F9.2,'   K',/
    &        /,1H ,25X,'CYLINDER WALL TEMPERATURE       =',F9.2,'   K',/
    &        /,1H ,25X,'TURBULENT DISSIPATION CONSTANT = ',F10.4,/
    &        /,1H ,25X,'UPRIME MULTIPLYER               = ',F10.4,/)
2918 FORMAT (/,1H ,10X,'>>>>> ENGINE DESIGN PARAMETERS',/)
2919 FORMAT (/,1H ,25X,'CYLINDER BORE            = ',F9.3,' CM',/
    &        /,1H ,25X,'CRANKSHAFT STROKE        = ',F9.3,' CM',/
    &        /,1H ,25X,'CONNECTING ROD LENGTH    = ',F9.3,' CM',/
    &        /,1H ,25X,'COMPRESSION RATIO        = ',F9.3,/
    &        /,1H ,25X,'DISPLACED VOLUME         = ',F9.3,' CC',/
    &        /,1H ,25X,'CLEARANCE VOLUME         = ',F9.3,' CC',/
    &        /,1H ,25X,'INTAKE VALVE OPENS       = ',F7.1,'   DEG CA',/
    &        /,1H ,25X,'INTAKE VALVE CLOSES      = ',F7.1,'   DEG CA',/
    &        /,1H ,25X,'EXHAUST VALVE OPENS      = ',F7.1,'   DEG CA',/
    &        /,1H ,25X,'EXHAUST VALVE CLOSES     = ',F7.1,'   DEG CA',/)
2920 FORMAT (/,1H ,10X,'>>>>> COMPUTATIONAL PARAMETERS',/)
2921 FORMAT (/,1H ,25X,'MAXIMUN # OF ITERATIONS =   ',I4,/
    &        /,1H ,25X,'OUTPUT AT ITERATION #   =   ',I4,/
    &        /,1H ,25X,'TPRINT                  = ',F9.2,
    &        /,1H ,25X,'TPRINX                  = ',F9.2,
    &        /,1H ,25X,'XBZERO                  = ',F12.5,
    &        /,1H ,25X,'XESTOP                  = ',F12.5,
    &        /,1H ,25X,'XBSTOP                  = ',F12.5,
    &        /,1H ,25X,'CIINTG                  = ',F13.6,
    &        /,1H ,25X,'CCINTG                  = ',F13.6,
    &        /,1H ,25X,'CBINTG                  = ',F13.6,
    &        /,1H ,25X,'CEINTG                  = ',F13.6,
    &        /,1H ,25X,'AREROT                  = ',F13.6,
    &        /,1H ,25X,'REL                     = ',F13.6,
    &        /,1H ,25X,'MAXERR                  = ',F13.6,
    &        /,1H ,25X,'MAXTRY                  = ',I6,/)
 999 FORMAT (///,1H ,15X,
    &        'WARNING!!  RESULTS FROM THIS CYCLE SIMULATION',/,16X,
    &        'MAY NOT BE ACCURATE FOR PHI > 1.3 OR PHI < 0.7',///)
C
      STOP
      END
```

```
C_____________________________________________________________________
C
C     SUBROUTINE INTAKE
C
C     PURPOSE
C        CALCULATES THE TIME RATE OF CHANGE OF PRESSURE, TEMPERATURE,
C        MASS, HEAT TRANSFER, WORK TRANSFER, MEAN KINETIC ENERGY, AND
C        TURBULENT KINETIC ENERGY IN THE CYLINDER DURING INTAKE.
C
C     USAGE
C        CALL INTAKE (DT, DY, DYP)
C
C     DESCRIPTION OF PARAMETERS
C
C        PARAMETER  INPUT  OUTPUT   DESCRIPTION
C
C        DT         YES    NO       TIME (DEG)
C        DY(1)      YES    NO       MASS INDUCTED INTO CHAMBER THROUGH
C        -----      ---    --       INTAKE VALVE (G)
C        DY(2)      YES    NO       MASS EXHAUSTED FROM CHAMBER THROUGH
C        -----      ---    --       EXHAUST VALVE (G)
C        DY(5)      YES    NO       MASS FRACTION OF FRESH CHARGE (-)
C        DY(6)      YES    NO       MEAN KINETIC ENERGY IN CHAMBER (ERG)
C        DY(7)      YES    NO       TURBULENT KINETIC ENERGY IN
C        -----      ---    --       CHAMBER (ERG)
C        DY(8)      YES    NO       HEAT TRANSFER - PISTON TOP (KJ)
C        DY(9)      YES    NO       HEAT TRANSFER - CYLINDER HEAD (KJ)
C        DY(10)     YES    NO       HEAT TRANSFER - CYLINDER WALL (KJ)
C        DY(11)     YES    NO       CYLINDER TEMPERATURE (K)
C        DY(12)     YES    NO       CYLINDER PRESSURE (ATM)
C        DY(16)     YES    NO       TOTAL WORK TRANSFER (KJ)
C        DY(17)     YES    NO       TOTAL ENTHALPY EXHAUSTED (KJ)
C
C        ------------------------------------------------------------
C
C        DYP(1)     NO     YES      RATE AT WHICH MASS IS INDUCTED
C        ------     --     ---      THROUGH THE INTAKE VALVE  (G/DEG)
C        DYP(2)     NO     YES      RATE AT WHICH MASS IS EXHAUSTED
C        ------     --     ---      THROUGH THE EXHAUST VALVE (G/DEG)
C        DYP(5)     NO     YES      RATE OF CHANGE OF MASS FRACTION OF
C        ------     --     ---      FRESH CHARGE (1/DEG)
C        DYP(6)     NO     YES      RATE OF CHANGE OF MEAN KINETIC
C        ------     --     ---      ENERGY (KJ/DEG)
C        DYP(7)     NO     YES      RATE OF CHANGE OF TURBULENT KINETIC
C        ------     --     ---      ENERGY (KJ/DEG)
C        DYP(8)     NO     YES      RATE OF HEAT TRANSFER -
C        ------     --     ---      CYLINDER HEAD (KJ/DEG)
C        DYP(9)     NO     YES      RATE OF HEAT TRANSFER -
C        ------     --     ---      PISTON TOP (KJ/DEG)
C        DYP(10)    NO     YES      RATE OF HEAT TRANSFER -
C        ------     --     ---      CYLINDER WALL (KJ/DEG)
C        DYP(11)    NO     YES      RATE OF CHANGE OF CYLINDER
```

```
C        ------      --      ---       TEMPERATURE (K/DEG)
C        DYP(12)     NO      YES       RATE OF CHANGE OF CYLINDER
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
C
C     REMARKS
C        NONE
C
C     SUBROUTINE AND FUNCTION SUBPROGRAMS REQUIRED
C        UTHRMO      UTRANS      IVACD       MFLRT
C        CSAVDV      EVACD
C
C
C     METHOD
C        SEE REPORT
C
C     WRITTEN BY S. H. MANSOURI AND S. G. POULOS
C     EDITED BY S. G. POULOS
C
      SUBROUTINE INTAKE (DT, DY, DYP)
C
      REAL*8 DT, DY(20), DYP(20)
      REAL MW, MWIM, MWIMM, KINVIS, MASS, MDOT, MDOTFR, MSTART, MACRSC
      DIMENSION Y(20), YP(20)
      COMMON/EPARAM/ BORE, STROKE, CONRL, CYLCA, CSATDC, CMRTIO, CLVTDC
      COMMON/HTRC/ CONHT, EXPHT
      COMMON/TEMPS/ TPSTON, THEAD, TCW
      COMMON/DTDTH/ ESPDI
      COMMON/MANFP/ PIM, TIM, EGR, PEM, MSTART
      COMMON/TIMES/ TIVO, TEVC, TIVC, TSPARK, TEVO
      COMMON/IMTHP/ HIM, MWIM, GIM, RHOIM
      COMMON/FLAG/ INFLAG
      COMMON/HEATS/ CVHTRN, HTRCOE, HTPAPI, HTPAHD, HTPACW, HTRAPI,
     &              HTRAHD, HTRACW, THTRAN, QFRPI, QFRHD, QFRCW
      COMMON/TURBU/ CBETA, MACRSC, UPRIME, VMKE
      COMMON/VALVE/ VIV, VEV
      COMMON/RHMAS/ RHO, MASS, VOLUME, H, GAMMA
C
      VIV = 0.0
      VEV = 0.0
C
      DO 10  I = 1, 20
           Y(I) = DY(I)
   10 CONTINUE
      T = DT
      DO 20 I = 1, 20
           YP(I) = 0.0
   20 CONTINUE
C
```

```
C        FIND THERMODYNAMIC AND TRANSPORT PROPERTIES IN CYLINDER
C
      RESFRK = 1. - Y(5)
      CALL THERMO (T, Y(11), Y(12), RESFRK, H, CSUBP, CSUBT,
     & RHO, DRHODT, DRHODP, GAMMA, MW, ADUMY, BDUMY, GDUMY, HDUMY)
      CALL UTRANS (Y(11), DYNVIS, THRCON)
      KINVIS = DYNVIS/RHO
      MASS = MSTART + Y(1) - Y(2)
C
C        FIND OUT IF INTAKE VALVE IS OPEN.
C
      IF (T .GE. TIVC) GO TO 50
C
C        YES IT IS.
C        FIND OUT IF ANY MASS FLOWS ACROSS INTAKE VALVE.
C
      IF (PIM - Y(12)) 30, 50, 40
C
C        REVERSE FLOW PAST VALVE.
C        CALCULATE CD AND EFFECTIVE AREA.
C
   30 PR = Y(12)/PIM
      CALL IVACD (T, PR, AREA, CD)
C
C        CALCULATE MASS FLOW RATE FROM CYLINDER 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
      VIV = -FRAIV/(RHO * AREA)
   35 YP(6) = -FRAIV * (Y(6)/MASS)
      YP(7) = -FRAIV * (Y(7)/MASS)
      HIMM = H
      GO TO 50
C
C        FLOW INTO CYLINDER.
C        CALCULATE CD AND AREA.
C
   40 PR = PIM/Y(12)
      CALL IVACD (T, PR, AREA, CD)
C
C        CALCULATE THERMODYNAMIC PROPERTIES OF MATERIAL FLOWING
C        INTO CYLINDER.
C        INFLAG = 0; CYLINDER 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
      IF (AREA .LE. 0.0) GO TO 45
      VIV = FRAIV/(RHOIMM * AREA)
   45 YP(6) = .5 * FRAIV * VIV*VIV
C
C        IS EXHAUST VALVE STILL OPEN ?
C
   50 IF ((T + 720.) .GE. TEVC) GO TO 80
C
C        YES IT IS.
C        ANY FLOW ACROSS IT ?
C
      IF (Y(12) - PEM) 60, 80, 70
C
C        YES, FLOW INTO CYLINDER.
C        FIND CD AND AREA FOR EXHAUST VALVE.
C
   60 PR = PEM/Y(12)
      CALL EVACD (T, PR, 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 65
      VEV = -FRAEV/(RHO * AREA)
   65 YP(6) = YP(6) + .5 * FRAEV * VEV*VEV
      GO TO 80
C
C        FLOW FROM CYLINDER INTO EXHAUST MANIFOLD.
C        FIND AREA AND CD FOR EXHAUST VALVE.
C
   70 PR = Y(12)/PEM
      CALL EVACD (T, PR, AREA, CD)
C
C        FIND MASS FLOW RATE.
C
      CALL MFLRT (CD, AREA, Y(12), MW, Y(11), PEM, GAMMA, FRAEV)
C
C        CALCULATE RATES DUE TO THIS FLOW.
```

```
C
      YP(2) = FRAEV
      IF (AREA .LE. 0.0) GO TO 75
      VEV = FRAEV/(RHO * AREA)
   75 YP(6) = YP(6) - FRAEV * (Y(6)/MASS)
      YP(7) = YP(7) - FRAEV * (Y(7)/MASS)
C
C        FIND SURFACE AREAS AND VOLUME OF CHAMBER
C
   80 CALL CSAVDV (T, AHEAD, APSTON, ACW, VOLUME, DVDT)
      MACRSC = VOLUME/(3.1415 * BORE * BORE/4.)
      IF (MACRSC .GE. (BORE/2.)) MACRSC = BORE/2.
      YP(6) = YP(6) - .3307 * CBETA/MACRSC * Y(6) *
     &        SQRT( ABS(Y(7)/MASS) )
      YP(7) = YP(7) + .3307 * CBETA/MACRSC * Y(6) *
     &        SQRT( ABS(Y(7)/MASS) )
     &        - .5443 * Y(7)/MACRSC * SQRT( ABS(Y(7)/MASS) )
      MDOT = YP(1) - YP(2)
      MDOTFR = YP(1) * (1. - EGR/100.) * INFLAG - YP(2) * Y(5)
     &         + YP(1) * Y(5) * (1 - INFLAG)
      YP(5) = ( MDOTFR - Y(5)*MDOT )/MASS
C
C        CHARACTERISTIC VELOCITY IN CYLINDER; (CM/SEC).
C
      PI     = 3.141592654
      CONSTR = CONRL/STROKE
      SINTH  = SIN( T*PI/180. )
      COSTH  = COS( T*PI/180. )
      VONVPM = ABS( PI * SINTH * ( 1. + COSTH/SQRT( 4. * CONSTR*CONSTR
     &         - SINTH*SINTH ) )/2. )
      VPMEAN = STROKE/(180. * ESPDI)
      VPISTO = VPMEAN * VONVPM
      VMKE   = SQRT( 2. * Y(6)/MASS )
      UPRIME = SQRT( .666667 * Y(7)/MASS )
      CVHTRN = SQRT( 0.25*VPISTO*VPISTO + VMKE*VMKE + UPRIME*UPRIME )
C
C        CALCULATE HEAT TRANSFER RATES
C
      HTRCOE = CONHT*(ABS(CVHTRN*MACRSC/KINVIS))**EXPHT * THRCON/MACRSC
      HTPAPI = HTRCOE * ( Y(11) - TPSTON )
      HTPAHD = HTRCOE * ( Y(11) - THEAD )
      HTPACW = HTRCOE * ( Y(11) - TCW )
C
      HTRAPI = APSTON * HTPAPI
      HTRAHD = AHEAD * HTPAHD
      HTRACW = ACW * HTPACW
C
      THTRAN = HTRAPI + HTRAHD + HTRACW
      QFRPI = 0.0
      QFRHD = 0.0
      QFRCW = 0.0
      IF ((CONHT .LE. 0.0) .OR. (THTRAN .EQ. 0.0)) GO TO 90
```

```
      QFRPI = 100. * HTRAPI/THTRAN
      QFRHD = 100. * HTRAHD/THTRAN
      QFRCW = 100. * HTRACW/THTRAN
C
C        CALCULATE RATES OF CHANGE OF TEMPERATURE AND PRESSURE IN
C        THE CYLINDER.  THEN CALCULATE RATE OF DOING WORK.
C
   90 YP(11) = (BDUMY/ADUMY)*( YP(5)*HDUMY + (MDOT/MASS)*(1. -
     &          H/BDUMY) - DVDT/VOLUME + (YP(1)*HIMM - YP(2)*H -
     &          THTRAN)/(BDUMY*MASS) )
      YP(12) = (1./1.01325E+6)*RHO/DRHODP * ( GDUMY*YP(5) - DVDT/VOLUME
     &          - YP(11)*DRHODT/RHO + MDOT/MASS )
      YP(16) = Y(12) * DVDT * .101325E-3
C
      HTRCOE = HTRCOE * 1.E-6
      HTPAPI = HTPAPI * 1.E-6
      HTPAHD = HTPAHD * 1.E-6
      HTPACW = HTPACW * 1.E-6
      YP(8) = HTRAPI * 1.E-10
      YP(9) = HTRAHD * 1.E-10
      YP(10) = HTRACW * 1.E-10
      THTRAN = THTRAN * 1.E-7 * ESPDI
C
      YP(17) = YP(2) * H
      VIV = VIV/100.
      VEV = VEV/100.
C
C        CONVERT ALL TIME DERIVATIVES TO RATE PER CRANK
C        ANGLE DEGREE.
C
      DO 100 I = 1, 20
           DYP(I) = YP(I) * ESPDI
  100 CONTINUE
C
      RETURN
      END
```

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C_____________________________________________________________________
C
C     SUBROUTINE CMPRES
C
C     PURPOSE
C        CALCULATES THE TIME RATE OF CHANGE OF PRESSURE, TEMPERATURE,
C        MASS, HEAT TRANSFER, WORK TRANSFER, MEAN KINETIC ENERGY, AND
C        TURBULENT KINETIC ENERGY IN THE CYLINDER DURING 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(1)      YES    NO       MASS INDUCTED INTO CHAMBER THROUGH
C        -----      ---    --       INTAKE VALVE (G)
C        DY(2)      YES    NO       MASS EXHAUSTED FROM CHAMBER THROUGH
C        -----      ---    --       EXHAUST VALVE (G)
C        DY(5)      YES    NO       MASS FRACTION OF FRESH CHARGE (-)
C        DY(6)      YES    NO       MEAN KINETIC ENERGY IN CHAMBER (ERG)
C        DY(7)      YES    NO       TURBULENT KINETIC ENERGY IN
C        -----      ---    --       CHAMBER (ERG)
C        DY(8)      YES    NO       HEAT TRANSFER - PISTON TOP (KJ)
C        DY(9)      YES    NO       HEAT TRANSFER - CYLINDER HEAD (KJ)
C        DY(10)     YES    NO       HEAT TRANSFER - CYLINDER WALL (KJ)
C        DY(11)     YES    NO       CYLINDER TEMPERATURE (K)
C        DY(12)     YES    NO       CYLINDER PRESSURE (ATM)
C        DY(16)     YES    NO       TOTAL WORK TRANSFER (KJ)
C
C        ------------------------------------------------------------
C
C        DYP(1)     NO     YES      RATE AT WHICH MASS IS INDUCTED
C        ------     --     ---      THROUGH THE INTAKE VALVE  (G/DEG)
C        DYP(2)     NO     YES      RATE AT WHICH MASS IS EXHAUSTED
C        ------     --     ---      THROUGH THE EXHAUST VALVE (G/DEG)
C        DYP(5)     NO     YES      RATE OF CHANGE OF MASS FRACTION OF
C        ------     --     ---      FRESH CHARGE (1/DEG)
C        DYP(6)     NO     YES      RATE OF CHANGE OF MEAN KINETIC
C        ------     --     ---      ENERGY (KJ/DEG)
C        DYP(7)     NO     YES      RATE OF CHANGE OF TURBULENT KINETIC
C        ------     --     ---      ENERGY (KJ/DEG)
C        DYP(8)     NO     YES      RATE OF HEAT TRANSFER -
C        ------     --     ---      CYLINDER HEAD (KJ/DEG)
C        DYP(9)     NO     YES      RATE OF HEAT TRANSFER -
C        ------     --     ---      PISTON TOP (KJ/DEG)
C        DYP(10)    NO     YES      RATE OF HEAT TRANSFER -
C        ------     --     ---      CYLINDER WALL (KJ/DEG)
C        DYP(11)    NO     YES      RATE OF CHANGE OF CYLINDER
C        ------     --     ---      TEMPERATURE (K/DEG)
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C        DYP(12)     NO      YES       RATE OF CHANGE OF CYLINDER
C        ------      --      ---       PRESSURE (ATM/DEG)
C        DYP(16)     NO      YES       RATE OF TOTAL WORK TRANSFER (KJ/DEG)
C
C
C     REMARKS
C        NONE
C
C     SUBROUTINE AND FUNCTION SUBPROGRAMS REQUIRED
C        UTHRMO      UTRANS      CSAVDV
C
C
C     METHOD
C        SEE REPORT
C
C     WRITTEN BY S. H. MANSOURI AND S. G. POULOS
C     EDITED BY S. G. POULOS
C
      SUBROUTINE CMPRES (DT,DY,DYP)
C
      REAL*8 DT, DY(20), DYP(20)
      REAL MW, MWIM, MWIMM, KINVIS, MASS, MDOT, MDOTFR, MSTART, MACRSC
      DIMENSION Y(20), YP(20)
      COMMON/EPARAM/ BORE, STROKE, CONRL, CYLCA, CSATDC, CMRTIO, CLVTDC
      COMMON/HTRC/ CONHT, EXPHT
      COMMON/TEMPS/ TPSTON, THEAD, TCW
      COMMON/DTDTH/ ESPDI
      COMMON/MANFP/ PIM, TIM, EGR, PEM, MSTART
      COMMON/TIMES/ TIVO, TEVC, TIVC, TSPARK, TEVO
      COMMON/IMTHP/ HIM, MWIM, GIM, RHOIM
      COMMON/FLAG/ INFLAG
      COMMON/HEATS/ CVHTRN, HTRCOE, HTPAPI, HTPAHD, HTPACW, HTRAPI,
     &              HTRAHD, HTRACW, THTRAN, QFRPI, QFRHD, QFRCW
      COMMON/TURBU/ CBETA, MACRSC, UPRIME, VMKE
      COMMON/VALVE/ VIV, VEV
      COMMON/RHMAS/ RHO, MASS, VOLUME, H, GAMMA
C
      DO 10  I = 1, 20
           Y(I) = DY(I)
   10 CONTINUE
      T = DT
      DO 20 I = 1, 20
           YP(I) = 0.0
   20 CONTINUE
C
C        FIND THERMODYNAMIC AND TRANSPORT PROPERTIES IN CYLINDER
C
      RESFRK = 1. - Y(5)
      CALL THERMO (T, Y(11), Y(12), RESFRK, H, CSUBP, CSUBT,
     & RHO, DRHODT, DRHODP, GAMMA, MW, ADUMY, BDUMY, GDUMY, HDUMY)
      CALL UTRANS (Y(11), DYNVIS, THRCON)
      KINVIS = DYNVIS/RHO
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```
      MASS = MSTART + Y(1) - Y(2)
C
C        FIND SURFACE AREAS AND VOLUME OF CHAMBER
C
      CALL CSAVDV (T, AHEAD, APSTON, ACW, VOLUME, DVDT)
      MACRSC = VOLUME/(3.1415 * BORE * BORE/4.)
      IF (MACRSC.GE.(BORE/2.)) MACRSC = BORE/2.
      YP(6) = -.3307 * CBETA/MACRSC * Y(6) * SQRT(Y(7)/MASS)
      YP(7) =  .3307 * CBETA/MACRSC * Y(6) * SQRT(Y(7)/MASS)
     1        - .5443 * Y(7)/MACRSC * SQRT(Y(7)/MASS)
C
C        CHARACTERISTIC VELOCITY IN CYLINDER; (CM/SEC).
C
      PI     = 3.141592654
      CONSTR = CONRL/STROKE
      SINTH  = SIN( T*PI/180. )
      COSTH  = COS( T*PI/180. )
      VONVPM = ABS( PI * SINTH * ( 1. + COSTH/SQRT( 4. * CONSTR*CONSTR
     &         - SINTH*SINTH ) )/2. )
      VPMEAN = STROKE/(180. * ESPDI)
      VPISTO = VPMEAN * VONVPM
      VMKE   = SQRT( 2. * Y(6)/MASS )
      UPRIME = SQRT( .666667 * Y(7)/MASS )
      CVHTRN = SQRT( 0.25*VPISTO*VPISTO + VMKE*VMKE + UPRIME*UPRIME )
C
C        CALCULATE HEAT TRANSFER RATES
C
      HTRCOE = CONHT*( (CVHTRN*MACRSC/KINVIS)**EXPHT ) * THRCON/MACRSC
      HTPAPI = HTRCOE * ( Y(11) - TPSTON )
      HTPAHD = HTRCOE * ( Y(11) - THEAD )
      HTPACW = HTRCOE * ( Y(11) - TCW )
C
      HTRAPI = APSTON * HTPAPI
      HTRAHD = AHEAD * HTPAHD
      HTRACW = ACW * HTPACW
C
      THTRAN = HTRAPI + HTRAHD + HTRACW
      QFRPI = 0.0
      QFRHD = 0.0
      QFRCW = 0.0
      IF ((CONHT .LE. 0.0) .OR. (THTRAN .EQ. 0.0)) GO TO 30
      QFRPI = 100. * HTRAPI/THTRAN
      QFRHD = 100. * HTRAHD/THTRAN
      QFRCW = 100. * HTRACW/THTRAN
C
C        CALCULATE RATES OF CHANGE OF TEMPERATURE AND PRESSURE IN
C        THE CYLINDER.  THEN CALCULATE RATE OF DOING WORK.
C
   30 YP(11) = -(BDUMY/ADUMY)*( DVDT/VOLUME + THTRAN/(BDUMY*MASS) )
      YP(12) = RHO/DRHODP * ( -DVDT/VOLUME - YP(11)*DRHODT/RHO )
      YP(12) = YP(12)/1.01325E+6
      YP(16) = Y(12) * DVDT * .101325E-3
```

```
C
      HTRCOE = HTRCOE * 1.E-6
      HTPAPI = HTPAPI * 1.E-6
      HTPAHD = HTPAHD * 1.E-6
      HTPACW = HTPACW * 1.E-6
      YP(8) = HTRAPI * 1.E-10
      YP(9) = HTRAHD * 1.E-10
      YP(10) = HTRACW * 1.E-10
      THTRAN = THTRAN * 1.E-7 * ESPDI
C
C        CONVERT ALL TIME DERIVATIVES TO RATE PER CRANK
C        ANGLE DEGREE.
C
      DO 40 I = 1, 20
           DYP(I) = YP(I) * ESPDI
   40 CONTINUE
C
      RETURN
      END
```

```
C_____________________________________________________________________
C
C     SUBROUTINE CMBSTN
C
C     PURPOSE
C        CALCULATES THE TIME RATE OF CHANGE OF PRESSURE, TEMPERATURE,
C        MASS, HEAT TRANSFER, WORK TRANSFER, MEAN KINETIC ENERGY, AND
C        TURBULENT KINETIC ENERGY IN THE CYLINDER DURING COMBUSTION.
C
C     USAGE
C        CALL CMBSTN (DT, DY, DYP)
C
C     DESCRIPTION OF PARAMETERS
C
C        PARAMETER  INPUT  OUTPUT   DESCRIPTION
C
C        DT         YES    NO       TIME (DEG)
C        DY(1)      YES    NO       MASS INDUCTED INTO CHAMBER THROUGH
C        -----      ---    --       INTAKE VALVE (G)
C        DY(2)      YES    NO       MASS EXHAUSTED FROM CHAMBER THROUGH
C        -----      ---    --       EXHAUST VALVE (G)
C        DY(3)      YES    NO       MASS FRACTION ENTRAINED (-)
C        DY(4)      YES    NO       MASS FRACTION BURNED (-)
C        DY(5)      YES    NO       MASS FRACTION OF FRESH CHARGE (-)
C        DY(6)      YES    NO       MEAN KINETIC ENERGY IN CHAMBER (ERG)
C        DY(8)      YES    NO       HEAT TRANSFER - PISTON TOP (KJ)
C        DY(9)      YES    NO       HEAT TRANSFER - CYLINDER HEAD (KJ)
C        DY(10)     YES    NO       HEAT TRANSFER - CYLINDER WALL (KJ)
C        DY(12)     YES    NO       CYLINDER PRESSURE (ATM)
C        DY(13)     YES    NO       TEMPERATURE OF UNBURNED MIXTURE
C        ------     ---    --       DURING COMBUSTION (K)
C        DY(14)     YES    NO       VOLUME OF UNBURNED MIXTURE
C        ------     ---    --       DURING COMBUSTION (CM**3)
C        DY(15)     YES    NO       TEMPERATURE OF BURNED PRODUCTS
C        ------     ---    --       DURING COMBUSTION (K)
C        DY(16)     YES    NO       TOTAL WORK TRANSFER (KJ)
C        DY(18)     YES    NO       MASS FRACTION OF (NO) IN ADIABATIC
C        ------     ---    --       CORE ZONE (MNOAC/MAC)
C        DY(19)     YES    NO       MASS FRACTION OF (NO) IN BOUNDARY
C        ------     ---    --       LAYER ZONE (MNOBL/MBL)
C        DY(20)     YES    NO       MASS FRACTION IN BOUNDARY
C        ------     ---    --       LAYER ZONE (-)
C
C        ------------------------------------------------------------
C
C        DYP(1)     NO     YES      RATE AT WHICH MASS IS INDUCTED
C        ------     --     ---      THROUGH THE INTAKE VALVE  (G/DEG)
C        DYP(2)     NO     YES      RATE AT WHICH MASS IS EXHAUSTED
C        ------     --     ---      THROUGH THE EXHAUST VALVE (G/DEG)
C        DYP(3)     NO     YES      RATE OF CHANGE OF MASS FRACTION
C        ------     --     ---      ENTRAINED (1/DEG)
C        DYP(4)     NO     YES      RATE OF CHANGE OF MASS FRACTION
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```
C        ------     --     ---      BURNED (1/DEG)
C        DYP(5)     NO     YES      RATE OF CHANGE OF MASS FRACTION OF
C        ------     --     ---      FRESH CHARGE (1/DEG)
C        DYP(6)     NO     YES      RATE OF CHANGE OF MEAN KINETIC
C        ------     --     ---      ENERGY (KJ/DEG)
C        DYP(8)     NO     YES      RATE OF HEAT TRANSFER -
C        ------     --     ---      CYLINDER HEAD (KJ/DEG)
C        DYP(9)     NO     YES      RATE OF HEAT TRANSFER -
C        ------     --     ---      PISTON TOP (KJ/DEG)
C        DYP(10)    NO     YES      RATE OF HEAT TRANSFER -
C        ------     --     ---      CYLINDER WALL (KJ/DEG)
C        DYP(12)    NO     YES      RATE OF CHANGE OF CYLINDER
C        ------     --     ---      PRESSURE (ATM/DEG)
C        DYP(13)    NO     YES      RATE OF CHANGE OF UNBURNED MIXTURE
C        ------     --     ---      TEMPERATURE DURING COMBUSTION
C        ------     --     ---      (K/DEG)
C        DYP(14)    NO     YES      RATE OF CHANGE OF UNBURNED MIXTURE
C        -------    --     ---      VOLUME DURING COMBUSTION (CM**3/DEG)
C        DYP(15)    NO     YES      RATE OF CHANGE OF BURNED PRODUCTS
C        ------     --     ---      TEMPERATURE DURING COMBUSTION
C        ------     --     ---      (K/DEG)
C        DYP(16)    NO     YES      RATE OF TOTAL WORK TRANSFER (KJ/DEG)
C        DYP(18)    NO     YES      RATE OF CHANGE OF (NO) MASS FRACTION
C        -------    --     ---      IN ADIABATIC CORE ZONE (1/DEG)
C        DYP(19)    NO     YES      RATE OF CHANGE OF (NO) MASS FRACTION
C        -------    --     ---      IN BOUNDARY LAYER ZONE (1/DEG)
C        DYP(20)    NO     YES      RATE OF CHANGE OF MASS FRACTION
C        -------    --     ---      IN BOUNDARY LAYER ZONE (1/DEG)
C
C
C     REMARKS
C        NONE
C
C     SUBROUTINE AND FUNCTION SUBPROGRAMS REQUIRED
C        UTHRMO     UTRANS     CSAVDV
C
C
C     METHOD
C        SEE S. G. POULOS SM THESIS
C
C     WRITTEN BY S. H. MANSOURI AND S. G. POULOS
C     EDITED BY S. G. POULOS
C
      SUBROUTINE CMBSTN (DT, DY, DYP)
C
      LOGICAL SPBURN, ENSTOP
      REAL*8 DT, DY(20), DYP(20), D(4), XMOFR(14), TMP, PRS
      REAL MW,MWIM,MWIMM,KINVIS,MASS,MDOT,MDOTFR,MSTART,MACRSC,MACRSP,
     &     MICRSC,MASSU,MASSAC,MWBL,MWAC,MWNO,MWN,MWO2,MWOH,K,K1,K2,K3
      DIMENSION Y(20),YP(20)
      COMMON/EPARAM/ BORE, STROKE, CONRL, CYLCA, CSATDC, CMRTIO, CLVTDC
      COMMON/HTRC/ CONHT, EXPHT
```

```
      COMMON/TEMPS/ TPSTON, THEAD, TCW
      COMMON/BURN/ SPBURN, FIRE, RPM
      COMMON/DTDTH/ ESPDI
      COMMON/MANFP/ PIM, TIM, EGR, PEM, MSTART
      COMMON/TIMES/ TIVO, TEVC, TIVC, TSPARK, TEVO
      COMMON/IMTHP/ HIM, MWIM, GIM, RHOIM
      COMMON/FLAG/ INFLAG
      COMMON/HEATS/ CVHTRN, HTRCOE, HTPAPI, HTPAHD, HTPACW, HTRAPI,
     &              HTRAHD, HTRACW, THTRAN, QFRPI, QFRHD, QFRCW
      COMMON/UBHEAT/ UHTRCO, BHTRCO
      COMMON/TURBU/ CBETA, MACRSC, UPRIME, VMKE
      COMMON/VALVE/ VIV, VEV
      COMMON/KINET/ TURBKE, MICRSC, SSUBL, BTIMSC
      COMMON/SPARK/ UPRISP, RHOUSP, MACRSP, CMULT
      COMMON/CHEM/ D
      COMMON/SPECB/ DTBRN, CONSPB, EXSPB
      COMMON/NOX/ YAC, YNO, XNOAC, XNOBL, XNO, PPMAC, PPMBL, PPMNO
      COMMON/ACBL/ VACONV, VBLONV, DBLONB, TWALLB, TAC, TBLAYR
      COMMON/FLPRO/ VENONV, VBRONV, AFLONB, APUONB, APBONB, AHUONB,
     &              AHBONB, ACUONB, ACBONB, DFLONB
      COMMON/XSTOP/ XESTOP, XBSTOP, ENSTOP, IFCNT
      COMMON/RADS/ RENTRA, RBURND
C
      DO 10  I = 1, 20
           Y(I) = DY(I)
   10 CONTINUE
      T = DT
      DO 20 I = 1, 20
           YP(I) = 0.0
   20 CONTINUE
C
C        FIND THERMODYNAMIC AND TRANSPORT PROPERTIES IN CYLINDER
C
      RESFRK = 1. - Y(5)
      CALL THERMO (T, Y(13), Y(12), RESFRK, HU, CSUBPU, CSUBTU,
     & RHOU, DRODTU, DRODPU, XXA, XXB, ADUMU, BDUMU, XXC, XXD)
      CALL THERMO (T, Y(15), Y(12), 1., HB, CSUBPB, CSUBTB,
     & RHOB, DRODTB, DRODPB, GAMAB, XXB, ADUMB, BDUMB, XXC, XXD)
      CALL UTRANS (Y(13), UDYVIS, UTHRCN)
      CALL BTRANS (Y(15), GAMAB, CSUBPB, BDYVIS, BTHRCN)
      UKNVIS = UDYVIS/RHOU
      BKNVIS = BDYVIS/RHOB
C
C        CALCULATE TOTAL MASS AND UNBURNED MASS IN CYLINDER
C
      MASS = MSTART + Y(1) - Y(2)
      MASSU = MASS*( 1. - Y(4) )
C
      CALL CSAVDV (T, AHEAD, APSTON, ACW, VOLUME, DVDT)
      VENTRA = VOLUME - (MASS/RHOU)*( 1. - Y(3) )
      VBURND = VOLUME - Y(14)
C
```

```
C        IF ENTRAINMENT IS ALMOST COMPLETE, USE SIMPLE FLAME GEOMETRY
C
      IF (.NOT. ENSTOP) GO TO 25
   23 AFLAM  = AFSTOP * (TEVO - T)*(TEVO - T)/((TEVO - TSTOP)*
     &          (TEVO - TSTOP))
      APISU  = 0.0
      AHEADU = 0.0
      ACWU   = 0.0
      FLMDEL = 0.0
      APISB  = APSTON
      AHEADB = AHEAD
      ACWB   = ACW
      GO TO 27
C
C        CALCULATE GEOMETRIC INTERACTION BETWEEN FLAME AND CHAMBER
C
   25 CALL FLAMEG (T, VENTRA, VBURND, RENTRA, RBURND, AFLAM, APISU,
     &              APISB, AHEADU, AHEADB, ACWU, ACWB, FLMDEL)
   27 VENONV = VENTRA/VOLUME
      VBRONV = VBURND/VOLUME
      AFLONB = AFLAM/(BORE*BORE)
      APUONB = APISU/(BORE*BORE)
      APBONB = APISB/(BORE*BORE)
      AHUONB = AHEADU/(BORE*BORE)
      AHBONB = AHEADB/(BORE*BORE)
      ACUONB = ACWU/(BORE*BORE)
      ACBONB = ACWB/(BORE*BORE)
      DFLONB = FLMDEL/BORE
      IF ((Y(3) .GT. 0.99) .AND. (IFCNT .LE. 0)) GO TO 28
      IF ((AFLONB .GT. 1.0E-8) .OR. (T .LE. TSPARK) .OR.
     &   (IFCNT .GT. 0) .OR. (SPBURN)) GO TO 29
C
C        STORE FINAL FLAME AREA PRIOR TO USING SIMPLE FLAME GEOMETRY
C
   28 AFSTOP = AOLDF
      TSTOP = TOLDF
      ENSTOP = .TRUE.
      IFCNT = IFCNT + 1
      GO TO 23
   29 AOLDF = AFLAM
      TOLDF = T
C
C        CALCULATE TURBULENT FLOW AND COMBUSTION MODEL PARAMETERS
C
      MACRSC = MACRSP * ( RHOUSP/RHOU )**(1./3.)
      IF (MACRSC .GE. (BORE/2.)) MACRSC = BORE/2.
      CALL LAMFSP (Y(13), Y(12), RESFRK, SSUBL)
      UPRIME = CMULT * UPRISP * ( RHOU/RHOUSP )**(1./3.)
C
C        CMULT: ARTIFICIAL FACTOR WHICH MULTIPLIES U' DURING COMBUSTION
C
      MICRSC = MACRSC * SQRT( 15. * UKNVIS/( UPRIME * MACRSC ) )
```

```
      BTIMSC = MICRSC/SSUBL
      IF (SPBURN) GO TO 30
C
C        PREDICTED BURN RATE COMBUSTION MODEL
C        CALCULATE ENTRAINMENT AND BURN RATES
C
      YP(3) = RHOU * AFLAM * ( UPRIME + SSUBL )/MASS
      IF (Y(3) .GE. XESTOP) YP(3) = YP(3)/1.5
      IF (Y(3) .GE. 0.998)  YP(3) = YP(3)/1.5
      IF (Y(3) .GE. 0.999)  YP(3) = YP(3)/1.5
      IF (Y(3) .GE. 0.9999) YP(3) = 0.0
      YP(4) = ( Y(3) - Y(4) )/BTIMSC
      GO TO 40
C
C        SPECIFIED BURN RATE COMBUSTION MODEL
C
   30 TONDTB = (T - TSPARK)/DTBRN
      IF (TONDTB .GT. 1.0) TONDTB = 1.0
      YP(4) = CONSPB*(EXSPB + 1.)*(TONDTB**EXSPB)*EXP( -CONSPB*
     &        TONDTB**(EXSPB + 1.) )/(DTBRN*ESPDI)
      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
      YP(3) = YP(4)
C
   40 TURBKE = 1.5 * MASS * UPRIME**2.
      YP(6) = -.3307 * CBETA/MACRSC * Y(6) * SQRT( TURBKE/MASS )
C
C        CVHTRN: CHARACTERISTIC VELOCITY IN CYLINDER; (CM/SEC).
C
      PI     = 3.141592654
      CONSTR = CONRL/STROKE
      SINTH = SIN( T*PI/180. )
      COSTH = COS( T*PI/180. )
      VONVPM = ABS( PI * SINTH * ( 1. + COSTH/SQRT( 4. * CONSTR*CONSTR
     &         - SINTH*SINTH ) )/2. )
      VPMEAN = STROKE/(180. * ESPDI)
      VPISTO = VPMEAN * VONVPM
      VMKE = SQRT( 2. * Y(6)/MASS )
      CVHTRN = SQRT( 0.25*VPISTO*VPISTO + VMKE*VMKE + UPRIME*UPRIME )
C
C        CALCULATE HEAT TRANSFER RATE.
C
      UHTRCO = CONHT*( (CVHTRN*MACRSC/UKNVIS)**EXPHT ) * UTHRCN/MACRSC
      BHTRCO = CONHT*( (CVHTRN*MACRSC/BKNVIS)**EXPHT ) * BTHRCN/MACRSC
      UHPAPI = UHTRCO * ( Y(13) - TPSTON )
      BHPAPI = BHTRCO * ( Y(15) - TPSTON )
      UHPAHD = UHTRCO * ( Y(13) - THEAD )
      BHPAHD = BHTRCO * ( Y(15) - THEAD )
      UHPACW = UHTRCO * ( Y(13) - TCW )
      BHPACW = BHTRCO * ( Y(15) - TCW )
```

```
C
      UHTRPI = UHPAPI * APISU
      BHTRPI = BHPAPI * APISB
      UHTRHD = UHPAHD * AHEADU
      BHTRHD = BHPAHD * AHEADB
      UHTRCW = UHPACW * ACWU
      BHTRCW = BHPACW * ACWB
C
      HTPAPI = (UHTRPI + BHTRPI)/(APISU + APISB)
      HTPAHD = (UHTRHD + BHTRHD)/(AHEADU + AHEADB)
      HTPACW = 0.0
      IF (T .EQ. 360.) GO TO 50
      HTPACW = (UHTRCW + BHTRCW)/(ACWU + ACWB)
   50 CONTINUE
C
      UHTRAN = UHTRPI + UHTRHD + UHTRCW
      BHTRAN = BHTRPI + BHTRHD + BHTRCW
C
      YP(8) = 1.E-10 * (UHTRPI + BHTRPI)
      YP(9) = 1.E-10 * (UHTRHD + BHTRHD)
      YP(10) = 1.E-10 * (UHTRCW + BHTRCW)
C
C        CALCULATE RATES OF CHANGE OF TEMPERATURE AND PRESSURE IN
C        THE CYLINDER.  THEN CALCULATE RATE OF DOING WORK.
C
      CDUMU = 1. - ( DRODTU * BDUMU )/( RHOU * ADUMU )
      CDUMB = 1. - ( DRODTB * BDUMB )/( RHOB * ADUMB )
      DDUMY = YP(4)/(Y(4) - 1.) - (1. - 1./CDUMU)*UHTRAN/
     &          (BDUMU*MASSU)
      EDUMY = ( VBURND/Y(14) )*( DVDT/VBURND - YP(4)/Y(4) -
     &          (1. - 1./CDUMB)*( YP(4)*(HU - HB)/(Y(4)*BDUMB) -
     &          BHTRAN/(BDUMB*Y(4)*MASS) ) )
      FDUMY = VBURND*DRODPB/( Y(14)*CDUMB*RHOB ) + DRODPU/(CDUMU*RHOU)
      YP(12) = ( DDUMY - EDUMY )/FDUMY
      IF (MASSU .EQ. 0.0) MASSU = 0.00005 * MASS
      YP(14) = Y(14)*( DDUMY - DRODPU*YP(12)/( CDUMU*RHOU ) )
      YP(13) = (BDUMU/ADUMU)*( YP(4)/(Y(4) - 1.) - YP(14)/Y(14) -
     &          UHTRAN/( BDUMU*MASSU ) )
      DVDTB = DVDT - YP(14)
      YP(15) = (BDUMB/ADUMB)*( YP(4)*(1. + (HU - HB)/BDUMB )/Y(4) -
     &          DVDTB/VBURND - BHTRAN/( BDUMB*Y(4)*MASS ) )
      YP(16) = Y(12) * DVDT * .101325E-3
C
C        END OF PERFORMANCE CALCULATION
C
C-----------------------------------------------------------------------
C#######################################################################
C
C        START OF NOX CALCULATION;
C        BURNED ZONE IS DIVIDED INTO AN ADIABATIC
C        CORE AND A THERMAL BOUNDARY LAYER
C
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      IF ( (APISB + AHEADB + ACWB) .GT. 0.0 ) GO TO 53
      TWALLB = THEAD
      GO TO 55
   53 TWALLB = ( ( APISB*TPSTON ) + ( AHEADB*THEAD ) + ( ACWB*TCW ) )/
     &          ( APISB + AHEADB + ACWB )
C
C        FOR ADIABATIC ENGINE USE SINGLE ZONE MODEL (NO B. L.)
C
      IF (CONHT .LE. 0.0) GO TO 55
      TBLAYR = 0.5*( TWALLB + Y(15) )
      CALL THERMO (T, TBLAYR, Y(12), 1., HBL, XXA, XXB, RHOBL, DRDTBL,
     &             DRDPBL, MWBL, XXD, ADUMBL, BDUMBL, XXG, XXH)
      TDOTBL = 0.5*YP(15)
C
C        CALCULATE RATE OF CHANGE OF BOUNDARY LAYER MASS
C
      YP(20) = ( (1. - Y(20)/Y(4))*( ADUMBL*Y(20)*(TDOTBL - BDUMBL*
     &          (DRDTBL*TDOTBL + DRDPBL*YP(12))/(RHOBL*ADUMBL)) +
     &           BHTRAN/MASS ) )/(HB - HBL)
C
      GO TO 57
   55 YP(20) = 0.0
      YP(19) = 0.0
      TBLAYR = Y(15)
      RHOBL = RHOB
   57 VBLAYR = MASS*Y(20)/RHOBL
      VBLONV = VBLAYR/VOLUME
      DELTBL = 0.0
      IF ( (APISB + AHEADB + ACWB) .GT. 0.0 )
     &   DELTBL = VBLAYR/( APISB + AHEADB + ACWB )
      DBLONB = DELTBL/BORE
      VADIAC = VBURND - VBLAYR
      VACONV = VADIAC/VOLUME
      MASSAC = MASS*Y(4)*( 1. - Y(20)/Y(4) )
      HAC = ( Y(4)*HB - Y(20)*HBL )/( Y(4) - Y(20) )
      TAC = 1.03 * Y(15)
      IF (CONHT .LE. 0.0) TAC = Y(15)
C
C        CALCULATE ADIABATIC CORE TEMPERATURE
C
      CALL ITRATE (T, TAC, Y(12), 1.0, HAC, XXA, XXB, RHOAC,
     &             XXC, XXD, XXE, MWAC, XXF, XXG, XXH, XXI)
C
      MWNO = 30.
      MWN  = 14.
      MWO2 = 32.
      MWOH = 17.
      TMP = TAC
      PRS = Y(12)
C
C        OBTAIN EQUILIBRIUM MOLE FRACTIONS OF NO, N, O2, AND OH
C
```

```
      CALL PTCHEM (TMP, PRS, D, XMOFR, ISENT)
C
      IF (ISENT .EQ. 2) GO TO 60
      EQNO = XMOFR(9)*( MWNO/MWAC )
      EQN  = XMOFR(8)*( MWN/MWAC )
      EQO2 = XMOFR(14)*( MWO2/MWAC )
      EQOH = XMOFR(5)*( MWOH/MWAC )
C
      K1 = 7.6E+13 * DEXP( -38.0D+3/TMP )
      K2 = 1.5E+09 * TMP * DEXP( -19.5D+3/TMP )
      K3 = 4.1E+13
C
      R1 = K1 * EQN * EQNO
      R2 = K2 * EQN * EQO2
      R3 = K3 * EQN * EQOH
      K = R1/( R2 + R3 )
C
C        CALCULATE RATES OF CHANGE OF NO IN BOUNDARY LAYER
C        AND IN ADIABATIC CORE
C
      IF (CONHT .GT. 0.0) YP(19) = YP(20) * Y(18)/Y(20)
      YP(18) = (2.*MWNO/RHOAC)*( 1. - Y(18)*Y(18)/(EQNO*EQNO) )*R1/
     &         ( 1. + K*Y(18)/EQNO ) - MASS*YP(20)*Y(18)/MASSAC
C
      YAC = Y(4) - Y(20)
      YNO = Y(18)*YAC + Y(19)*Y(20)
C
      XNOAC = Y(18) * MWAC/MWNO
      XNOBL = Y(19) * MWBL/MWNO
      XNO = ( XNOAC*VADIAC/TAC + XNOBL*VBLAYR/TBLAYR )/
     &      ( VADIAC/TAC + VBLAYR/TBLAYR + Y(14)/Y(13) )
C
      PPMAC = 1.0E+06 * XNOAC
      PPMBL = 1.0E+06 * XNOBL
      PPMNO = 1.0E+06 * XNO
C
C        END OF NOX CALCULATION
C
C#######################################################################
C-----------------------------------------------------------------------
C
   60 YP(12) = YP(12)/1.01325E+6
      UHTRCO = UHTRCO * 1.E-6
      BHTRCO = BHTRCO * 1.E-6
      HTPAPI = HTPAPI * 1.E-6
      HTPAHD = HTPAHD * 1.E-6
      HTPACW = HTPACW * 1.E-6
      HTRAPI = YP(8)
      HTRAHD = YP(9)
      HTRACW = YP(10)
      THTRAN = HTRAPI + HTRAHD + HTRACW
      QFRPI = 0.0
```

```
      QFRHD = 0.0
      QFRCW = 0.0
      IF ((CONHT .LE. 0.0) .OR. (THTRAN .EQ. 0.0)) GO TO 70
      QFRPI = 100. * HTRAPI/THTRAN
      QFRHD = 100. * HTRAHD/THTRAN
      QFRCW = 100. * HTRACW/THTRAN
      THTRAN = 1000. * THTRAN * ESPDI
C
C        CONVERT ALL TIME DERIVATIVES TO RATE PER CRANK
C        ANGLE DEGREE.
C
   70 DO 80 I = 1, 20
         DYP(I) = YP(I) * ESPDI
   80 CONTINUE
C
      RETURN
      END
```

```
C_____________________________________________________________________
C
C     SUBROUTINE EXAUST
C
C     PURPOSE
C        CALCULATES THE TIME RATE OF CHANGE OF PRESSURE, TEMPERATURE,
C        MASS, HEAT TRANSFER, WORK TRANSFER, MEAN KINETIC ENERGY, AND
C        TURBULENT KINETIC ENERGY IN THE CYLINDER DURING EXAUST.
C
C     USAGE
C        CALL EXAUST (DT, DY, DYP)
C
C     DESCRIPTION OF PARAMETERS
C
C        PARAMETER  INPUT  OUTPUT   DESCRIPTION
C
C        DT         YES    NO       TIME (DEG)
C        DY(1)      YES    NO       MASS INDUCTED INTO CHAMBER THROUGH
C        -----      ---    --       INTAKE VALVE (G)
C        DY(2)      YES    NO       MASS EXHAUSTED FROM CHAMBER THROUGH
C        -----      ---    --       EXHAUST VALVE (G)
C        DY(6)      YES    NO       MEAN KINETIC ENERGY IN CHAMBER (ERG)
C        DY(7)      YES    NO       TURBULENT KINETIC ENERGY IN
C        -----      ---    --       CHAMBER (ERG)
C        DY(8)      YES    NO       HEAT TRANSFER - PISTON TOP (KJ)
C        DY(9)      YES    NO       HEAT TRANSFER - CYLINDER HEAD (KJ)
C        DY(10)     YES    NO       HEAT TRANSFER - CYLINDER WALL (KJ)
C        DY(11)     YES    NO       CYLINDER TEMPERATURE (K)
C        DY(12)     YES    NO       CYLINDER PRESSURE (ATM)
C        DY(16)     YES    NO       TOTAL WORK TRANSFER (KJ)
C        DY(17)     YES    NO       TOTAL ENTHALPY EXHAUSTED (KJ)
C
C        ------------------------------------------------------------
C
C        DYP(1)     NO     YES      RATE AT WHICH MASS IS INDUCTED
C        ------     --     ---      THROUGH THE INTAKE VALVE  (G/DEG)
C        DYP(2)     NO     YES      RATE AT WHICH MASS IS EXHAUSTED
C        ------     --     ---      THROUGH THE EXHAUST VALVE (G/DEG)
C        DYP(6)     NO     YES      RATE OF CHANGE OF MEAN KINETIC
C        ------     --     ---      ENERGY (KJ/DEG)
C        DYP(7)     NO     YES      RATE OF CHANGE OF TURBULENT KINETIC
C        ------     --     ---      ENERGY (KJ/DEG)
C        DYP(8)     NO     YES      RATE OF HEAT TRANSFER -
C        ------     --     ---      CYLINDER HEAD (KJ/DEG)
C        DYP(9)     NO     YES      RATE OF HEAT TRANSFER -
C        ------     --     ---      PISTON TOP (KJ/DEG)
C        DYP(10)    NO     YES      RATE OF HEAT TRANSFER -
C        ------     --     ---      CYLINDER WALL (KJ/DEG)
C        DYP(11)    NO     YES      RATE OF CHANGE OF CYLINDER
C        ------     --     ---      TEMPERATURE (K/DEG)
C        DYP(12)    NO     YES      RATE OF CHANGE OF CYLINDER
C        ------     --     ---      PRESSURE (ATM/DEG)
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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
C
C     REMARKS
C        NONE
C
C     SUBROUTINE AND FUNCTION SUBPROGRAMS REQUIRED
C        UTHRMO      BTRANS      MFLRT
C        CSAVDV      EVACD
C
C
C     METHOD
C        SEE REPORT
C
C     WRITTEN BY S. H. MANSOURI AND S. G. POULOS
C     EDITED BY S. G. POULOS
C
      SUBROUTINE EXAUST (DT, DY, DYP)
C
      LOGICAL FIRE
      REAL*8 DT, DY(20), DYP(20)
      REAL MW, MWIM, MWIMM, KINVIS, MASS, MDOT, MDOTFR, MSTART, MACRSC
      DIMENSION Y(20), YP(20)
      COMMON/EPARAM/ BORE, STROKE, CONRL, CYLCA, CSATDC, CMRTIO, CLVTDC
      COMMON/BURN/ SPBURN, FIRE, RPM
      COMMON/HTRC/ CONHT, EXPHT
      COMMON/TEMPS/ TPSTON, THEAD, TCW
      COMMON/DTDTH/ ESPDI
      COMMON/MANFP/ PIM, TIM, EGR, PEM, MSTART
      COMMON/TIMES/ TIVO, TEVC, TIVC, TSPARK, TEVO
      COMMON/IMTHP/ HIM, MWIM, GIM, RHOIM
      COMMON/FLAG/ INFLAG
      COMMON/HEATS/ CVHTRN, HTRCOE, HTPAPI, HTPAHD, HTPACW, HTRAPI,
     &              HTRAHD, HTRACW, THTRAN, QFRPI, QFRHD, QFRCW
      COMMON/TURBU/ CBETA, MACRSC, UPRIME, VMKE
      COMMON/VALVE/ VIV, VEV
      COMMON/RHMAS/ RHO, MASS, VOLUME, H, GAMMA
C
      VEV = 0.0
C
      DO 10  I = 1, 20
          Y(I) = DY(I)
   10 CONTINUE
      T = DT
      DO 20 I = 1, 20
          YP(I) = 0.0
   20 CONTINUE
C
C        FIND THERMODYNAMIC AND TRANSPORT PROPERTIES IN CYLINDER
C
```

```
      RESFRK = 1.
      IF (.NOT. FIRE) RESFRK = 0.0
      CALL THERMO (T, Y(11), Y(12), RESFRK, H, CSUBP, CSUBT,
     & RHO, DRHODT, DRHODP, GAMMA, MW, ADUMY, BDUMY, GDUMY, HDUMY)
      IF (FIRE) CALL BTRANS (Y(11), GAMMA, CSUBP, DYNVIS, THRCON)
      IF (.NOT. FIRE) CALL UTRANS (Y(11), DYNVIS, THRCON)
      KINVIS = DYNVIS/RHO
      MASS = MSTART + Y(1) - Y(2)
C
C        IS EXHAUST VALVE STILL OPEN ?
C
      IF (T .GE. TEVC) GO TO 50
C
C        YES IT IS.
C        ANY FLOW ACROSS IT ?
C
      IF (Y(12) - PEM) 30, 50, 40
C
C        YES, FLOW INTO CYLINDER.
C        FIND CD AND AREA FOR EXHAUST VALVE.
C
   30 PR = PEM/Y(12)
      CALL EVACD (T, PR, 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
      VEV = -FRAEV/(RHO * AREA)
   35 YP(6) = .5 * FRAEV * VEV*VEV
      GO TO 50
C
C        FLOW FROM CYLINDER INTO EXHAUST MANIFOLD.
C        FIND AREA AND CD FOR EXHAUST VALVE.
C
   40 PR = Y(12)/PEM
      CALL EVACD (T, PR, 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
      VEV = FRAEV/(RHO * AREA)
   45 YP(6) = -FRAEV * (Y(6)/MASS)
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      YP(7) = -FRAEV * (Y(7)/MASS)
C
C        FIND SURFACE AREAS AND VOLUME OF CHAMBER
C
   50 CALL CSAVDV (T, AHEAD, APSTON, ACW, VOLUME, DVDT)
      MACRSC = VOLUME/(3.1415 * BORE * BORE/4.)
      IF (MACRSC .GE. (BORE/2.)) MACRSC = BORE/2.
      YP(6) = YP(6) - .3307 * CBETA/MACRSC * Y(6) * SQRT(Y(7)/MASS)
      YP(7) = YP(7) + .3307 * CBETA/MACRSC * Y(6) * SQRT(Y(7)/MASS)
     1        - .5443 * Y(7)/MACRSC * SQRT(Y(7)/MASS)
      MDOT = -YP(2)
C
C        CHARACTERISTIC VELOCITY IN CYLINDER; (CM/SEC).
C
      PI     = 3.141592654
      CONSTR = CONRL/STROKE
      SINTH  = SIN( T*PI/180. )
      COSTH  = COS( T*PI/180. )
      VONVPM = ABS( PI * SINTH * ( 1. + COSTH/SQRT( 4. * CONSTR*CONSTR
     &         - SINTH*SINTH ) )/2. )
      VPMEAN = STROKE/(180. * ESPDI)
      VPISTO = VPMEAN * VONVPM
      VMKE   = SQRT( 2. * Y(6)/MASS )
      UPRIME = SQRT( .666667 * Y(7)/MASS )
C
C        ADD VELOCITY TERM DUE TO BLOWDOWN
C
      VBDOWN = 4 * YP(2)/( 3.1415925 * RHO * BORE * BORE )
      IF ( YP(2) .LT. 0.0 ) VBDOWN = 0.0
      CVHTRN = SQRT( 0.25*VPISTO*VPISTO + VMKE*VMKE + UPRIME*UPRIME +
     &         VBDOWN*VBDOWN )
C
C        CALCULATE HEAT TRANSFER RATES
C
      HTRCOE = CONHT*( (CVHTRN*MACRSC/KINVIS)**EXPHT ) * THRCON/MACRSC
      HTPAPI = HTRCOE * ( Y(11) - TPSTON )
      HTPAHD = HTRCOE * ( Y(11) - THEAD )
      HTPACW = HTRCOE * ( Y(11) - TCW )
C
      HTRAPI = APSTON * HTPAPI
      HTRAHD = AHEAD * HTPAHD
      HTRACW = ACW * HTPACW
C
      THTRAN = HTRAPI + HTRAHD + HTRACW
      QFRPI = 0.0
      QFRHD = 0.0
      QFRCW = 0.0
      IF ((CONHT .LE. 0.0) .OR. (THTRAN .EQ. 0.0)) GO TO 60
      QFRPI = 100. * HTRAPI/THTRAN
      QFRHD = 100. * HTRAHD/THTRAN
      QFRCW = 100. * HTRACW/THTRAN
C
```

```
C        CALCULATE RATES OF CHANGE OF TEMPERATURE AND PRESSURE IN
C        THE CYLINDER.  THEN CALCULATE RATE OF DOING WORK.
C
   60 YP(11) = -(BDUMY/ADUMY)*( YP(2)/MASS + DVDT/VOLUME +
     &            THTRAN/(BDUMY*MASS) )
      YP(12) = (1./1.01325E+6) * RHO/DRHODP * ( -DVDT/VOLUME
     &           - YP(11)*DRHODT/RHO + MDOT/MASS )
      YP(16) = Y(12) * DVDT * .101325E-3
C
      HTRCOE = HTRCOE * 1.E-6
      HTPAPI = HTPAPI * 1.E-6
      HTPAHD = HTPAHD * 1.E-6
      HTPACW = HTPACW * 1.E-6
      YP(8) = HTRAPI * 1.E-10
      YP(9) = HTRAHD * 1.E-10
      YP(10) = HTRACW * 1.E-10
      THTRAN = THTRAN * 1.E-7 * ESPDI
C
      YP(17) = YP(2) * H
      VEV = VEV/100.
C
C        CONVERT ALL TIME DERIVATIVES TO RATE PER CRANK
C        ANGLE DEGREE.
C
      DO 70 I = 1, 20
           DYP(I) = YP(I) * ESPDI
   70 CONTINUE
C
      RETURN
      END
```

```
C
C
C     FUNCTION GINT1
C
C        CALLED BY 'ODERT' TO CHECK FOR A ROOT OF: DM/DT)IN = 0.0
C
      FUNCTION GINT1 (DT, DY, DYP)
      REAL*8 DT,DY(20),DYP(20),GINT1
C
      GINT1 = DYP(1)
C
      RETURN
      END
C
C
C     FUNCTION GINT2
C
C        CALLED BY 'ODERT' TO CHECK FOR A ROOT OF: MASS INDUCTED = 0.0
C
      FUNCTION GINT2 (DT, DY, DYP)
      REAL*8 DT,DY(20),DYP(20),GINT2
C
      GINT2 = DY(1)
C
      RETURN
      END
C
C
C     FUNCTION GCMP
C
C        CALLED BY 'ODERT' TO CHECK FOR ROOTS DURING COMPRESSION,
C        COMBUSTION, AND EXHAUST. THIS A DUMMY FUNCTION (GCMP ALWAYS >0)
C
      FUNCTION GCMP (DT, DY, DYP)
      REAL*8 DT,DY(20),DYP(20),GCMP
C
      GCMP =10.D0
C
      RETURN
      END
```

```
C
C
C     SUBROUTINE HELPHT
C
C     PURPOSE
C        CALLS EITHER 'INTAKE', 'CMPRES', 'CMBSTN', OR 'EXAUST',
C        AFTER EVERY CALL TO 'ODERT'.  'ODERT' MAY OVERSHOOT IT'S
C        STOPPING POINT (TOUT) FOR IMPROVED ACCURACY.  IF THIS
C        OCCURS, 'ODERT' WILL RETURN WITH THE CORRECT VECTOR (DY),
C        BUT THE HEAT TRANSFER DATA CALCULATED BY THE EXTERNAL
C        FUNCTIONS WILL CORRESPOND TO THE LAST OVERSHOT VALUE
C        OF T AND NOT TO TOUT.  IT IS THEN NECESSARY TO CALL
C        THE EXTERNAL FUNCTIONS ONCE AFTER EACH CALL TO ODERT IF
C        THE CORRECT HEAT TRANSFER DATA IS TO BE AVAILABLE FOR
C        PRINTING OUT.  THIS PROCEDURE DOES NOT AFFECT THE NOR-
C        MAL CALCULATION PROCESS PERFORMED BY 'ODERT'.
C
C     USAGE
C        CALL HELPHT (DT, DY, IWHERE)
C
C     DESCRIPTION OF PARAMETERS
C        PARAMETER  INPUT  OUTPUT  DESCRIPTION
C
C        DT         YES    NO      CURRENT TIME (DEG)
C        DY         YES    NO      CURRENT SOLUTION VECTOR
C        IWHERE     YES    NO      1 = INTAKE; 2 = CMPRES;
C        ------     ---    --      3 = CMBSTN; 4 = EXAUST
C        XXX        NO     NO      DUMMY VARIABLE
C
C     REMARKS
C        NONE
C
C     SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED
C        INTAKE     CMPRES     CMBSTN     EXAUST
C
C     METHOD
C        SEE PURPOSE, ABOVE
C
C     WRITTEN BY S. G. POULOS
C     EDITED BY S. G. POULOS
C
      SUBROUTINE HELPHT (DT, DY, IWHERE)
      REAL*8 DT, DY(20), XXX(20)
C
      IF (IWHERE.EQ.1) CALL INTAKE (DT, DY, XXX)
      IF (IWHERE.EQ.2) CALL CMPRES (DT, DY, XXX)
      IF (IWHERE.EQ.3) CALL CMBSTN (DT, DY, XXX)
      IF (IWHERE.EQ.4) CALL EXAUST (DT, DY, XXX)
C
      RETURN
      END
```

```
C_____________________________________________________________________
C
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, AHEAD, APSTON, ACW, VOLUME, DVDT)
C
C     DESCRIPTION OF PARAMETERS
C
C        PARAMETER  INPUT  OUTPUT   DESCRIPTION
C
C        T          YES    NO       TIME (DEG)
C        SRFACE     NO     YES      SURFACE AREA OF CHAMBER (CM**2)
C        DVDT       NO     YES      TIME RATE OF CHANGE OF VOLUME OF
C        -----      --     ---      CHAMBER (CM**3/SEC)
C
C     REMARKS
C        NONE
C
C     SUBROUTINE AND FUNCTION SUBPROGRAMS REQUIRED
C        NONE
C
C     METHOD
C        SEE REPORT
C
C     WRITTEN BY S. H. MANSOURI AND K. RADHAKRISHNAN
C     EDITED BY S. H. MANSOURI AND S. G. POULOS
C
      SUBROUTINE CSAVDV (T, AHEAD, APSTON, ACW, VOLUME, DVDT)
C
      COMMON/EPARAM/ BORE, STROKE, CONRL, CYLCA, CSATDC, CMRTIO, CLVTDC
      COMMON/DTDTH/ ESPDI
      COMMON/AREAS/ AHEEE, APIII
C
      THETA = T * 0.0174533
      COSC  = 0.5 * STROKE * COS(THETA)
      SINC  = 0.5 * STROKE * SIN(THETA)
      CI    = SQRT( CONRL * CONRL - SINC * SINC )
C
C        CYLL: CYLINDER LENGTH FROM PISTON POSITION AT TDC
C
      CYLL   = CONRL + 0.5 * STROKE - COSC - CI
      IF (CYLL .LT. 0.0) CYLL = 0.0
      ACW    = 3.141593 * BORE * CYLL
      AHEAD  = AHEEE
      APSTON = APIII
      VOLUME = CLVTDC + CYLCA * CYLL
      DVDT   = CYLCA * SINC * (1.0 + COSC/CI) * .0174533/ESPDI
```

```
C
      RETURN
      END
```

```
C_____________________________________________________________________
C
C     SUBROUTINE RDGEOM
C
C     PURPOSE
C        THIS SUBROUTINE PROVIDES A LINK BETWEEN THE MAIN CYCLE
C        SIMULATION AND THE PROGRAM (ALLGEO) WHICH SIMULATES THE
C        INTERACTION BETWEEN A SPHERICAL PROPAGATING FLAME AND A
C        COMBUSTION CHAMBER OF ARBITRARY SHAPE.  THE TABLE OF DATA
C        GENERATED BY 'ALLGEO' AND STORED IN 'GEOX' IS READ BY THIS
C        SUBROUTINE AND THEN DENORMALIZED BY MULTIPLYING ALL DATA BY
C        APPROPRIATE FACTORS OF THE ENGINE BORE. THE BORE IS READ IN
C        BY THE MAIN PROGRAM AND TRANSFERED TO 'RDGEOM' VIA A COMMON
C        BLOCK.
C
C     USAGE
C        CALL RDGEOM
C
C     DESCRIPTION OF PARAMETERS
C        PARAMETER  INPUT  OUTPUT  DESCRIPTION
C
C        AFLAME     NO     YES     TOTAL FLAME AREA
C        AINH       NO     YES     AREA OF HEAD INSIDE FLAME
C        AOUTH      NO     YES     AREA OF HEAD OUTSIDE FLAME
C        AINP       NO     YES     AREA OF PISTON INSIDE FLAME
C        AOUTP      NO     YES     AREA OF PISTON OUTSIDE FLAME
C        AINCW      NO     YES     AREA OF CYL. WALL INSIDE FLAME
C        AOUTCW     NO     YES     AREA OF CYL. WALL OUTSIDE FLAME
C        VIN        NO     YES     VOLUME INSIDE THE FLAME
C        VOUT       NO     YES     VOLUME OUTSIDE THE FLAME
C        CSATDC     NO     YES     CHAMBER SURFACE AREA @ TDC
C        AHEEE      NO     YES     CYLINDER HEAD SURFACE AREA
C        APIII      NO     YES     PISTON TOP SURFACE AREA
C
C     REMARKS
C        ALL LENGTH DIMENSIONS ARE IN UNITS OF CM
C
C     SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED
C        ______     ______     ______     ______
C
C     METHOD
C        SEE PURPOSE, ABOVE
C
C     WRITTEN BY S. G. POULOS
C     EDITED BY S. G. POULOS
C
      SUBROUTINE RDGEOM
C
      REAL AFLAME(30,50), AINH(30,50), AOUTH(30,50), AINP(30,50),
     &     AOUTP(30,50), AINCW(30,50), AOUTCW(30,50), VIN(30,50),
     &     VOUT(30,50), MTHETA
      COMMON/EPARAM/ BORE, STROKE, CONRL, CYLCA, CSATDC, CMRTIO, CLVTDC
```

```
      COMMON/GEOM/ AFLAME, AINH, AOUTH, AINP, AOUTP, AINCW, AOUTCW,
     &             VIN, DTHETA, DELTAR, MTHETA
      COMMON/AREAS/ AHEEE, APIII
C
C        READ CRANK ANGLE STEP, MAXIMUM CRANK ANGLE, AND NORMALIZED
C        FLAME RADIUS STEP SIZE, STROKE, AND CONNECTING ROD LENGTH.
C
      READ (9,2111) DTHETA, MTHETA, DTBRAT, STBRAT, CTBRAT
C
      STROKE = BORE * STBRAT
      CONRL = BORE * CTBRAT
      DELTAR = BORE * DTBRAT
C
C        READ IN NORMALIZED GEOMETRIC TABLE
C
      DO 20 ITHETA = 1, 30
          DO 10 IRAD = 1, 50
              READ (9,333) RADIUS, AFLAME(ITHETA,IRAD),
     &                     AINH(ITHETA,IRAD), AOUTH(ITHETA,IRAD),
     &                     AINP(ITHETA,IRAD), AOUTP(ITHETA,IRAD),
     &                     AINCW(ITHETA,IRAD), AOUTCW(ITHETA,IRAD),
     &                     VIN(ITHETA,IRAD), VOUT(ITHETA,IRAD)
              IF (RADIUS .GE. 9999.) GO TO 30
   10     CONTINUE
   20 CONTINUE
C
C        DE-NORMALIZE TABLE OF GEOMETRIC PARAMETERS
C
   30 DO 50 ITHETA = 1, 30
          DO 40 IRAD = 1, 50
              AFLAME(ITHETA,IRAD) = AFLAME(ITHETA,IRAD) * BORE * BORE
              AINH(ITHETA,IRAD) = AINH(ITHETA,IRAD) * BORE * BORE
              AOUTH(ITHETA,IRAD) = AOUTH(ITHETA,IRAD) * BORE * BORE
              AINP(ITHETA,IRAD) = AINP(ITHETA,IRAD) * BORE * BORE
              AOUTP(ITHETA,IRAD) = AOUTP(ITHETA,IRAD) * BORE * BORE
              AINCW(ITHETA,IRAD) = AINCW(ITHETA,IRAD) * BORE * BORE
              AOUTCW(ITHETA,IRAD) = AOUTCW(ITHETA,IRAD) * BORE * BORE
              VIN(ITHETA,IRAD) = VIN(ITHETA,IRAD) * BORE * BORE * BORE
              VOUT(ITHETA,IRAD) = VOUT(ITHETA,IRAD) * BORE * BORE * BORE
   40     CONTINUE
   50 CONTINUE
C
C        CALCULATE CONSTANT CHAMBER SURFACE AREAS
C
      CSATDC = AOUTH(1,1) + AOUTP(1,1) + AOUTCW(1,1)
      AHEEE = AOUTH(1,1)
      APIII = AOUTP(1,1)
C
 2111 FORMAT (1H ,5(5X,F10.5))
  333 FORMAT (1H ,1X,10(3X,F10.6))
C
```

```
RETURN
END
```

```
C_____________________________________________________________________
C
C     SUBROUTINE FLAMEG
C
C     PURPOSE
C        'FLAMEG' IS CALLED BY 'CMBSTN' DURING COMBUSTION TO FIND
C        THE FLAME FRONT AREA AND THE HEAT TRANSFER AREAS ON EACH
C        SIDE OF THE FLAME.
C
C     USAGE
C        CALL FLAMEG (T, VENTRA, VBURND, RENTRA, RBURND, AFLAM,
C       &             APISU, APISB, AHEADU, AHEADB, ACWU, ACWB, FLMDEL)
C
C     DESCRIPTION OF PARAMETERS
C        PARAMETER  INPUT  OUTPUT  DESCRIPTION
C
C        T          YES    NO      TIME (DEG)
C        VENTRA     YES    NO      VOLUME ENTRAINED BY THE FLAME (CM**3)
C        VBURND     YES    NO      VOLUME BURNED (CM**3)
C        AFLAME     NO     YES     GROSS FRONTAL AREA OF FLAME (CM**2)
C        AINH       NO     YES     AREA OF HEAD INSIDE FLAME(CM**2)
C        AOUTH      NO     YES     AREA OF HEAD OUTSIDE FLAME(CM**2)
C        AINP       NO     YES     AREA OF PISTON INSIDE FLAME(CM**2)
C        AOUTP      NO     YES     AREA OF PISTON OUTSIDE FLAME(CM**2)
C        AINCW      NO     YES     AREA OF CYL. WALL INSIDE FLAME(")
C        AOUTCW     NO     YES     AREA OF CYL. WALL OUTSIDE FLAME  (")
C        VIN        NO     YES     VOLUME INSIDE THE FLAME (CM**3)
C        VOUT       NO     YES     VOLUME OUTSIDE THE FLAME (CM**3)
C
C     REMARKS
C        NONE
C
C     SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED
C        NONE
C
C     METHOD
C        THIS SUBROUTINE ACCESSES A TABLE OF DATA READ IN BY 'RDGEOM'.
C        'CMBSTN' SUPPLIES THE BURNED AND ENTRAINED VOLUMES AND
C        THE CRANK ANGLE.  'FLAMEG' THEN ITERATES IN THE TABLE TO
C        LOCATE THE FLAME RADIUS CORRESPONDING TO THE GIVEN VOLUME
C        AND CRANK ANGLE. ONCE THE FLAME RADIUS AND CRANK ANGLE ARE
C        KNOWN, THE FLAME AREA AND THE HEAT TRANSFER AREAS ARE FOUND
C        BY INTERPOLATION.  THE ENTRAINED VOLUME IS USED IN CALCULA-
C        TING THE FLAME FRONT AREA AND THE BURNED VOLUME IS USED IN
C        CALCULATING THE HEAT TRANSFER AREAS.
C
C        SEE PURPOSE, ABOVE
C
C     WRITTEN BY S. G. POULOS
C     EDITED BY S. G. POULOS
C
      SUBROUTINE FLAMEG (T, VENTRA, VBURND, RENTRA, RBURND, AFLAM,
```

```
     &                APISU, APISB, AHEADU, AHEADB, ACWU, ACWB, FLMDEL)
C
      LOGICAL SPBURN
      REAL AFLAME(30,50), AINH(30,50), AOUTH(30,50), AINP(30,50),
     &     AOUTP(30,50), AINCW(30,50), AOUTCW(30,50), VIN(30,50),
     &     MTHETA
C
      COMMON/BURN/ SPBURN, FIRE, RPM
      COMMON/GEOM/ AFLAME, AINH, AOUTH, AINP, AOUTP, AINCW, AOUTCW,
     &             VIN, DTHETA, DELTAR, MTHETA
C
      ITERS = 25
      RMAX = 50. * DELTAR
      VENEXA = VENTRA
      VBREXA = VBURND
C
C        CONVERT FROM CRANK ANGLE TO CRANK ANGLE FROM TDC
C
      THETA = ABS(T - 360.)
C
C        IF THETA IS TOO LARGE, USE LARGEST VALUE AVAILABLE
C
      IF (THETA .LE. MTHETA) GO TO 10
      WRITE (6,80) THETA, MTHETA
      THETA = MTHETA
C
C        INTERPOLATE BETWEEN THETA VALUES
C
   10 ITHT1 = IFIX( THETA/DTHETA ) + 1
      IF ( THETA .GE. (29.*DTHETA) ) ITHT1 = 29
      ITHT2 = ITHT1 + 1
C
      THT1 = FLOAT(ITHT1 - 1)*DTHETA
      THT2 = FLOAT(ITHT2 - 1)*DTHETA
C
      S = ( 2.*THETA - THT1 - THT2 )/( THT2 - THT1 )
      IF (SPBURN) GO TO 45
      IF (VENEXA .LE. 0.0) WRITE (7,*) VENEXA
      IF (VENEXA .LE. 0.0) VENEXA = 0.0001 * VIN(1,1)
      RNEW = RENTRA
      IF (RENTRA .LE. 0.0) RNEW = 0.1 * DELTAR
      IF (RENTRA .GT. RMAX) RNEW = 0.99 * RMAX
      XMAX = 15. * (3.*VENEXA/(4.*3.141593))**.333333
      IF (XMAX .GT. RMAX) XMAX = 0.99 * RMAX
      XMIN = 0.8 * RENTRA
      IF (XMIN .GE. XMAX) XMIN = 0.0
      IF (RENTRA .LE. 0.0) XMIN = 0.0
      RNEW = 1.2 * RNEW
C
C        ENTER LOOP TO ITERATE ON FLAME RADIUS UNTIL ENFLAMED
C        VOLUME MATCHES ENTRAINED VOLUME
C
```

```
      DO 30 ITER = 1, ITERS
C
C           NEW GUESS FOR RADIUS: BISECT NEW ITERATION INTERVAL
C
         RTEST = 0.5 * (XMAX + XMIN)
         IF (ITER .EQ. 1) RTEST = RNEW
         IF (RTEST .LE. 0.0) RTEST = 0.01  * DELTAR
         IF (RTEST .GT. XMAX) RTEST = 0.99 * XMAX
C
C           INTERPOLATE BETWEEN RADIUS VALUES
C
         IRD1 = IFIX( RTEST/DELTAR ) + 1
         IF (IRD1 .LE. 0) IRD1 = 1
         IRD2 = IRD1 + 1
C
         RAD1 = FLOAT(IRD1 - 1)*DELTAR
         RAD2 = FLOAT(IRD2 - 1)*DELTAR
C
         R = ( 2.*RTEST - RAD1 - RAD2 )/( RAD2 - RAD1 )
C
         FINT1 = (1. + R)*(1. + S)/4.
         FINT2 = (1. - R)*(1. + S)/4.
         FINT3 = (1. - R)*(1. - S)/4.
         FINT4 = (1. + R)*(1. - S)/4.
C
C           CALCULATE CORRESPONDING ENFLAMED VOLUME AND FLAME AREA
C
         VTRY = FINT3*VIN(ITHT1,IRD1) + FINT4*VIN(ITHT1,IRD2) +
     &          FINT1*VIN(ITHT2,IRD2) + FINT2*VIN(ITHT2,IRD1)
         AFLAM = FINT3*AFLAME(ITHT1,IRD1) + FINT4*AFLAME(ITHT1,IRD2) +
     &           FINT1*AFLAME(ITHT2,IRD2) + FINT2*AFLAME(ITHT2,IRD1)
C
C           CHECK FOR CONVERGENCE
C
         IF  ( (ABS(VTRY - VENEXA)/VENEXA) .LE. 0.001 ) GO TO 40
C
C           RESET OUTER LIMITS FOR NEXT ITERATION
C
         IF ((VTRY .GT. VENEXA) .AND. (RTEST .LT. XMAX)) XMAX = RTEST
         IF (XMAX .GT. RMAX) XMAX = 0.99 * RMAX
         IF ((VTRY .LT. VENEXA) .AND. (RTEST .GT. XMIN)) XMIN = RTEST
   30 CONTINUE
C
   40 RENTRA = RTEST
   45 IF (VBREXA .LE. 0.0) WRITE (7,*) VBREXA
      IF (VBREXA .LE. 0.0) VBREXA = 0.0001 * VIN(1,1)
C
C        REPEAT CALCULATION, BUT NOW MATCH BURNED VOLUME
C
      RNEW = RBURND
      IF (RBURND .LE. 0.0) RNEW = 0.1 * DELTAR
      IF (RBURND .GT. RMAX) RNEW = 0.99 * RMAX
```

```
      XMAX = 15. * (3.*VBREXA/(4.*3.141593))**.333333
      IF (XMAX .GT. RMAX) XMAX = 0.99 * RMAX
      XMIN = 0.8 * RBURND
      IF (XMIN .GE. XMAX) XMIN = 0.0
      IF (RBURND .LE. 0.0) XMIN = 0.0
      RNEW = 1.2 * RNEW
C
      DO 60 ITER = 1, ITERS
          RTEST = 0.5 * (XMAX + XMIN)
          IF (ITER .EQ. 1) RTEST = RNEW
          IF (RTEST .LE. 0.0) RTEST = 0.01  * DELTAR
          IF (RTEST .GT. XMAX) RTEST = 0.99 * XMAX
          IRD1 = IFIX( RTEST/DELTAR ) + 1
          IF (IRD1 .LE. 0) IRD1 = 1
          IRD2 = IRD1 + 1
C
          RAD1 = FLOAT(IRD1 - 1)*DELTAR
          RAD2 = FLOAT(IRD2 - 1)*DELTAR
C
          R = ( 2.*RTEST - RAD1 - RAD2 )/( RAD2 - RAD1 )
C
          FINT1 = (1. + R)*(1. + S)/4.
          FINT2 = (1. - R)*(1. + S)/4.
          FINT3 = (1. - R)*(1. - S)/4.
          FINT4 = (1. + R)*(1. - S)/4.
C
          VTRY = FINT3*VIN(ITHT1,IRD1) + FINT4*VIN(ITHT1,IRD2) +
     &           FINT1*VIN(ITHT2,IRD2) + FINT2*VIN(ITHT2,IRD1)
C
          IF  ( (ABS(VTRY - VBREXA)/VBREXA) .LE. 0.001 ) GO TO 70
          IF ((VTRY .GT. VBREXA) .AND. (RTEST .LT. XMAX)) XMAX = RTEST
          IF (XMAX .GT. RMAX) XMAX = 0.99 * RMAX
          IF ((VTRY .LT. VBREXA) .AND. (RTEST .GT. XMIN)) XMIN = RTEST
   60 CONTINUE
C
   70 RBURND = RTEST
      IF (SPBURN) GO TO 75
      FLMDEL = RENTRA - RBURND
C
C        CALCULATE HEAT TRANSFER AREAS ONCE BURNED RADIUS IS FOUND
C
   75 AHEADB = FINT3*AINH(ITHT1,IRD1) + FINT4*AINH(ITHT1,IRD2) +
     &         FINT1*AINH(ITHT2,IRD2) + FINT2*AINH(ITHT2,IRD1)
      AHEADU = FINT3*AOUTH(ITHT1,IRD1) + FINT4*AOUTH(ITHT1,IRD2) +
     &         FINT1*AOUTH(ITHT2,IRD2) + FINT2*AOUTH(ITHT2,IRD1)
      APISB = FINT3*AINP(ITHT1,IRD1) + FINT4*AINP(ITHT1,IRD2) +
     &        FINT1*AINP(ITHT2,IRD2) + FINT2*AINP(ITHT2,IRD1)
      APISU = FINT3*AOUTP(ITHT1,IRD1) + FINT4*AOUTP(ITHT1,IRD2) +
     &       FINT1*AOUTP(ITHT2,IRD2) + FINT2*AOUTP(ITHT2,IRD1)
      ACWB = FINT3*AINCW(ITHT1,IRD1) + FINT4*AINCW(ITHT1,IRD2) +
     &       FINT1*AINCW(ITHT2,IRD2) + FINT2*AINCW(ITHT2,IRD1)
      ACWU = FINT3*AOUTCW(ITHT1,IRD1) + FINT4*AOUTCW(ITHT1,IRD2) +
```

```
     &        FINT1*AOU1CW(ITHT2,IRD2) + FINT2*AOUTCW(ITHT2,IRD1)
C
   80 FORMAT (1H1,/,5X,19HWARNING!!, THETA = ,F8.3,16H IS GREATER THAN,
     &         10H MTHETA = ,F8.3,23H  -- THETA SET = MTHETA)
C
      RETURN
      END
```

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

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

```
C_____________________________________________________________________
C
C     SUBROUTINE IVACD
C
C     PURPOSE
C        CALCULATES AREA AND DISCHARGE COEFFICIENT
C        OF INTAKE VALVE
C
C     USAGE
C        CALL IVACD  (T, PR, AREA, CD)
C
C     DESCRIPTION OF PARAMETERS
C
C        PARAMETER  INPUT  OUTPUT   DESCRIPTION
C
C        T          YES    NO       TIME (DEG)
C        PR         YES    NO       PRESSURE RATIO ACROSS INTAKE
C        --         ---    --       VALVE (ALWAYS >1) I.E. PR=PRESSURE
C        --         ---    --       UPSTREAM/PRESSURE DOWNSTREAM
C        AREA       NO     YES      EFFECTIVE AREA OF INTAKE
C        ----       --     ---      VALVE (CM**2)
C        CD         NO     YES      DISCHARGE COEFFICIENT
C
C
C     REMARKS
C
C        PHIT                       PHI TABLE
C        ICCODT                     INTAKE CAM CONTOUR OPENING
C        ------                     DATA TABLE (IN)
C        ICCDT                      INTAKE CAM CONTOUR CLOSING
C        -----                      DATA TABLE (IN)
C        THIVO                      INTAKE VALVE OPENING TIME (DEG)
C        THIMAX                     INTAKE CAM CONTOUR MAXIMUM
C        ------                     OPENING TIME (DEG)
C        THIVC                      INTAKE VALVE CLOSING TIME (DEG)
C        DIV                        DIAMETER OF INTAKE VALVE (IN)
C        SAIV                       SEAT ANGLE OF INTAKE VALVE (DEG)
C        RARM                       ROCKER ARM RATIO
C        DPORT                      DIAMETER OF INTAKE PORT (IN)
C        APORT                      AREA OF INTAKE PORT (CM**2)
C        DIVDP                      DIV/DPORT
C        VTDP                       EVATH/DPORT
C        EVATH                      EFFECTIVE VALVE HEAD THICKNESS (IN)
C        SSA                        SIN(SAIV)
C        CSA                        COS(SAIV)
C        SS2A                       SIN(2*SAIV)
C        R2                         (1.-DIVDP)/SS2A
C        R3                         VTDP/(SSA*SSA)
C
C     SUBROUTINE AND FUNCTION SUBPROGRAMS REQUIRED
C        NONE
C
```

```
C     METHOD
C        SEE REPORT
C
C     WRITTEN BY S. H. MANSOURI AND K. RADHAKRISHNAN
C     EDITED BY S. H. MANSOURI AND S. G. POULOS
C
      SUBROUTINE IVACD (T, PR, AREA, CD)
C
      REAL ICCODT, ICCDT
      DIMENSION PHIT(79), ICCODT(79), ICCDT(79)
      DATA PHIT/1., 2., 3.0, 4.0, 5.0, 6.0, 7.0, 8.0, 9.0, 10.,
     &11., 12., 13., 14., 15., 16., 17., 18., 19., 20., 21., 22.,
     &23., 24., 25., 26., 27., 28., 29., 30., 31., 32., 33., 34.,
     &35., 36., 37., 38., 39., 40., 41., 42., 43., 44., 45., 46.,
     &47., 48., 49., 50., 51., 52., 53., 54., 55., 56., 57., 58.,
     &59., 60., 61., 62., 63., 64., 65., 66., 67., 68., 69., 70.,
     &71., 72., 73., 74., 75., 76., 77., 78., 79./
      DATA ICCODT/.2345, .23438, .23404, .23347, .23266, .23163,
     &.23037, .22888, .22716, .22522, .22305, .22065, .21803, .21519,
     &.21212, .20883, .20533, .20160, .19766, .19351, .18914, .18457,
     &.17979, .17482, .16966, .16431, .15878, .15308,
     &.14721, .14120, .13504, .12875, .12234, .11582, .10921, .10253,
     &.09579, .08902, .08225, .07551, .06887, .06235, .05600, .04989,
     &.04404, .03852, .03337, .02863, .02433, .02051, .01717, .01433,
     &.01196, .01004, .00851, .00730, .00634, .00556, .00490, .00431,
     &.00377, .00325, .00275, .00225, .00175, .00126, .00082, .00047,
     &.00022, .00007, .00001, .00000, .00000, .00000, .00000, .00000,
     &.00000, .00000, .00000/
      DATA ICCDT/.2345, .23438, .23404, .23347, .23266, .23163,
     &.23037, .22888, .22716, .22522, .22305, .22065, .21803, .21519,
     &.21212, .20883, .20533, .20160, .19766, .19351, .18914, .18457,
     &.17979, .17482, .16966, .16431, .15878, .15308,
     &.14721, .14120, .13504, .12875, .12234, .11582, .10921, .10253,
     &.09579, .08902, .08225, .07552, .06889, .06240, .05610, .05006,
     &.04432, .03898, .03394, .02937, .02525, .02156, .01833, .01554,
     &.01318, .01125, .00970, .00849, .00756, .00682, .00622, .00572,
     &.00528, .00488, .00451, .00414, .00378, .00342, .00306, .00270,
     &.00234, .00198, .00162, .00126, .00091, .00059, .00034, .00016,
     &.00005, .00001, .00000/
      DATA TIMAX /100.0/
      DATA RARMR/1.60/
      DATA DPORT,APORT,DIVDP,VTDP/1.6904,14.4789,.964269,.07099/
      DATA SSA,CSA,SS2A,R2,R3/.70711,.70711,1.0,.03573,.141978/
      DATA REFIO, REFIC/0.00490,.00572/
C
C        CALCULATE VALVE LIFT
C
      IF (T .GE. TIMAX) GO TO 10
      PHI   = 0.5 * (TIMAX - T) + 1.0
      IT    = IFIX( 0.5 * (TIMAX + 2.9999 - T) )
      IF (IT .LE. 1) IT = 2
      VLIFT = (ICCODT(IT) + (PHIT(IT) - PHI)*(ICCODT(IT-1) - ICCODT(IT))
```

```
     &          - REFIO) * RARMR
      GO TO 20
   10 PHI   = 0.5 * (T - TIMAX) + 1.0
      IT    = IFIX( 0.5 * (T + 1.9999 - TIMAX) )
      IF (IT .LE. 0) IT = 1
      VLIFT = (ICCDT(IT) + (PHIT(IT) - PHI)*( ICCDT(IT) - ICCDT(IT+1) )
     &          - REFIC) * RARMR
   20 RISE  = VLIFT/DPORT
      IF (RISE .LE. 0.0) RISE = 0.0
C
C        CALCULATE CD
C
      CDI  = 0.96 - 5.47 * RISE * RISE
C
C        EFFECT OF PRESSURE RATIO ON DISCHARGE COEFFICIENT
C
      CD   = CDI + 0.8 * (1. - CDI) * (CDI - 0.1) * (PR - 1.)
      IF ((RISE .LE. R3) .AND. (RISE .GE. R2)) GO TO 30
      IF (RISE .GT. R3) GO TO 40
      ATAP = 4.0 * (1.0 - .5 * RISE * SS2A) * RISE * CSA
      GO TO 50
   30 ATAP = 4.0 * (DIVDP + .5 * RISE * SS2A) * RISE * CSA
      GO TO 50
   40 ATAP = 4.0 * (DIVDP + VTDP*CSA/SSA) * SQRT( RISE*RISE - 2.0*RISE*
     &       VTDP + VTDP * VTDP/(SSA * SSA) )
C
C        CALCULATE EFFECTIVE VALVE OPEN AREA (CM**2).
C
   50 AREA = ATAP * APORT
C
      RETURN
      END
```

```
C_____________________________________________________________________
C
C     SUBROUTINE EVACD
C
C     PURPOSE
C        CALCULATES AREA AND DISCHARGE COEFFICIENT
C        OF EXHAUST VALVE
C
C     USAGE
C        CALL EVACD  (T, PR, AREA, CD)
C
C     DESCRIPTION OF PARAMETERS
C
C        PARAMETER  INPUT  OUTPUT   DESCRIPTION
C
C        T          YES    NO       TIME (DEG)
C        PR         YES    NO       PRESSURE RATIO ACROSS EXHAUST
C        --         ---    --       VALVE (ALWAYS >1) I.E. PR=PRESSURE
C        --         ---    --       UPSTREAM/PRESSURE DOWNSTREAM
C        AREA       NO     YES      EFFECTIVE AREA OF EXHAUST
C        ----       --     ---      VALVE (CM**2)
C        CD         NO     YES      DISCHARGE COEFFICIENT
C
C     REMARKS
C
C        PHIT                       PHI TABLE
C        ECCODT                     EXHAUST CAM CONTOUR OPENING
C        ------                     DATA TABLE (IN)
C        ECCDT                      EXHAUST CAM CONTOUR CLOSING
C        -----                      DATA TABLE (IN)
C        THEVO                      EXHAUST VALVE OPENING TIME (DEG)
C        THEMAX                     EXHAUST CAM CONTOUR MAXIMUM
C        ------                     OPENING TIME (DEG)
C        THEVC                      EXHAUST VALVE CLOSING TIME (DEG)
C        DEV                        DIAMETER OF EXHAUST VALVE (IN)
C        SAEV                       SEAT ANGLE OF EXHAUST VALVE (DEG)
C        RARM                       ROCKER ARM RATIO
C        DPORT                      DIAMETER OF EXHAUST PORT (IN)
C        APORT                      AREA OF EXHAUST PORT (CM**2)
C        DEVDP                      DEV/DPORT
C        VTDP                       EVATH/DPORT
C        EVATH                      EFFECTIVE VALVE HEAD THICKNESS (IN)
C        SSA                        SIN(SAEV)
C        CSA                        COS(SAEV)
C        SS2A                       SIN(2*SAEV)
C        R2                         (1.-DEVDP)/SS2A
C        R3                         VTDP/(SSA*SSA)
C
C     SUBROUTINE AND FUNCTION SUBPROGRAMS REQUIRED
C        NONE
C
C     METHOD
```

```
C        SEE REPORT
C
C     WRITTEN BY S. H. MANSOURI AND K. RADHAKRISHNAN
C     EDITED BY S. H. MANSOURI AND S. G. POULOS
C
      SUBROUTINE EVACD (T, PR, AREA, CD)
C
      DIMENSION PHIT(88), ECCODT(88), ECCDT(88)
      DATA PHIT/1., 2., 3.0, 4.0, 5.0, 6.0, 7.0, 8.0, 9.0, 10.,
     &11., 12., 13., 14., 15., 16., 17., 18., 19., 20., 21., 22.,
     &23., 24., 25., 26., 27., 28., 29., 30., 31., 32., 33., 34.,
     &35., 36., 37., 38., 39., 40., 41., 42., 43., 44., 45., 46.,
     &47., 48., 49., 50., 51., 52., 53., 54., 55., 56., 57., 58.,
     &59., 60., 61., 62., 63., 64., 65., 66., 67., 68., 69., 70.,
     &71., 72., 73., 74., 75., 76., 77., 78., 79., 80., 81., 82.,
     &83., 84., 85., 86., 87., 88./
      DATA ECCODT/.23500, .23491, .23466, .23423, .23364, .23287,
     &.23194, .23083, .22956, .22811, .22650, .22471, .22276, .22063,
     &.21834, .21587, .21324, .21043, .20746, .20431, .20100, .19751,
     &.19386, .19003, .18604, .18187, .17754, .17303,
     &.16836, .16352, .15850, .15332, .14798, .14248, .13682, .13102,
     &.12509, .11903, .11286, .10660, .10027, .09388, .08747, .08106,
     &.07468, .06839, .06222, .05622, .05044, .04492, .03971, .03484,
     &.03036, .02626, .02258, .01931, .01645, .01399, .01193, .01023,
     &.00888, .00782, .00700, .00637, .00588, .00547, .00512, .00481,
     &.00320, .00280, .00240, .00200, .00160, .00121, .00084, .00054,
     &.00030, .00014, .00004, .00001, .00000, .00000, .00000, .00000,
     &.00000, .00000, .00000, .00000/
      DATA ECCDT/.23500, .23491, .23466, .23423, .23364, .23287, .23194,
     &.23083, .22956, .22811, .22650, .22471, .22276, .22063, .21834,
     &.21587, .21324, .21043, .20746, .20431, .20100, .19751, .19386,
     &.19008, .18604, .18187, .17754, .17303, .16836,
     &.16352, .15850, .15332, .14798, .14248, .13682, .13102, .12509,
     &.11903, .11286, .10660, .10027, .09888, .08747, .08106, .07468,
     &.06839, .06222, .05622, .05044, .04492, .03971, .03484, .03036,
     &.02626, .02258, .01931, .01645, .01399, .01193, .01023, .00888,
     &.00782, .00700, .00637, .00588, .00547, .00512, .00481, .00450,
     &.00420, .00390, .00360, .00330, .00300, .00270, .00240, .00210,
     &.00180, .00150, .00120, .00091, .00068, .00040, .00022, .00010,
     &.00003, .00001, .00000/
      DATA TEMAX/606.0 /
      DATA RARMR/1.60/
      DATA DPORT,APORT,DEVDP,VTDP/1.4257,10.2995,.93848,.084169/
      DATA SSA,CSA,SS2A,R2,R3/.51504,.85717,.88295,.06152,.33664/
      DATA REFEO, REFEC/0.00547, .00670/
C
      TAT   = T
      IF (TAT .LT. 360.0) TAT = TAT + 720.0
C
C        CALCULATE VALVE LIFT
C
      IF (TAT .GE. TEMAX) GO TO 10
```

```
      PHI    = 0.5 * (TEMAX - TAT) + 1.0
      IT     = IFIX( 0.5 * (TEMAX + 2.9999 - TAT) )
      IF (IT .LE. 1) IT = 2
      VLIFT = (ECCODT(IT) + (PHIT(IT) - PHI)*(ECCODT(IT-1) - ECCODT(IT))
     &          - REFEO) * RARMR
      GO TO 20
C
   10 PHI    = 0.5 * (TAT - TEMAX) + 1.0
      IT     = IFIX( 0.5 * (TAT + 1.9999 - TEMAX) )
      IF (IT .LE. 0) IT = 1
      VLIFT = (ECCDT(IT) + (PHIT(IT) - PHI)*(ECCDT(IT) - ECCDT(IT+1))-
     &          REFEC) * RARMR
   20 RISE  = VLIFT/DPORT
      IF (RISE .LE. 0.0) RISE = 0.0
C
C        CALCULATE CD
C
   30 CDI    = 1.05 - 9.30 * RISE * RISE
   40 IF (PR .GT. 1.86) GO TO 50
C
C        EFFECT OF PRESSURE RATIO ON DISCHARGE COEFFICIENT
C
      CD     = CDI + 0.8 * (1. - CDI) * (CDI - 0.1) * (PR - 1.)
      GO TO 60
   50 CD     = CDI + 0.7 * (1. - CDI) * (CDI - 0.1) + (1. - CDI) *
     &          (0.27 - 0.1 * CDI) * ( 1. -3.46/(PR * PR) )
   60 IF ((RISE .LE. R3) .AND. (RISE .GE. R2)) GO TO 70
      IF (RISE .GT. R3) GO TO 80
      ATAP  = 4.0 * (1.0 - .5 * RISE * SS2A) * RISE * CSA
      GO TO 90
   70 ATAP  = 4.0 * (DEVDP + .5 * RISE * SS2A) * RISE * CSA
      GO TO 90
   80 ATAP  = 4.0 * (DEVDP + VTDP*CSA/SSA) * SQRT( RISE*RISE - 2.0*RISE*
     &        VTDP + VTDP * VTDP/(SSA * SSA) )
C
C        CALCULATE EFFECTIVE VALVE OPEN AREA ( CM**2 ).
C
   90 AREA  = ATAP * APORT
C
      RETURN
      END
```

```
C_______________________________________________________________________
C
C     SUBROUTINE THERMO
C
C     PURPOSE
C        'THERMO' IS CALLED BY THE THE 4 PROCESS ROUTINES AND BY
C        'MAIN' AND RETURNS WITH THE REQUIRED THERMODYNAMIC PROPER-
C        TIES IN EACH CASE.  IT CALLS 'UPROP' AND OR 'BPROP' AS
C        REQUIRED FOR EACH PROCESS, AND THEN CALCULATES FROM THE
C        RETURNED DATA ANY ADDITIONAL PROPERTIES OR COMBINATIONS
C        OF PROPERTIES OF INTEREST.  'THERMO' ALSO CONVERTS ALL
C        VALUES TO UNITS THAT ARE CONSISTENT WITH THOSE USED IN
C        THE REST OF THE PROGRAM.
C
C     USAGE
C        CALL THERMO ( T, TEMP, P, RESFRK, ENTHLP, CSUBP, CSUBT, RHO,
C              DRHODT, DRHODP, GAMMA, MW, ADUMY, BDUMY, GDUMY, HDUMY)
C
C     DESCRIPTION OF PARAMETERS
C        PARAMETER  INPUT  OUTPUT  DESCRIPTION
C
C        T          YES    NO      CRANK ANGLE (DEG)
C        TEMP       YES    NO      TEMPERATURE (K)
C        P          YES    NO      PRESSURE (ATM)
C        RESFRK     YES    NO      MASS BURNED / TOTAL MASS
C        ------     ---    --      ( <1. FOR UNBURNED ZONE ONLY )
C        ENTHLP     NO     YES     ENTHALPY  (ERG)
C        CSUBP      NO     YES     PARTIAL OF H WITH RESPECT TO T
C        CSUBT      NO     YES     PARTIAL OF H WITH RESPECT TO P
C        RHO        NO     YES     DENSITY
C        DRHODT     NO     YES     PARTIAL OF RHO WITH RESPECT TO T
C        DRHODP     NO     YES     PARTIAL OF RHO WITH RESPECT TO P
C        MW         NO     YES     MOLECULAR WEIGHT
C        GAMMA      NO     YES     RATIO OF SPECIFIC HEATS
C        ADUMY      NO     YES     SEE ASSIGNMENT STATEMENTS BELOW
C        BDUMY      NO     YES     SEE ASSIGNMENT STATEMENTS BELOW
C        GDUMY      NO     YES     SEE ASSIGNMENT STATEMENTS BELOW
C        HDUMY      NO     YES     SEE ASSIGNMENT STATEMENTS BELOW
C
C     REMARKS
C        NONE
C
C     SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED
C        UPROP      HPROD      CLDPRD
C
C     METHOD
C        SEE PURPOSE, ABOVE
C
C     WRITTEN BY S. G. POULOS
C     EDITED BY S. G. POULOS
C
C
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```
      SUBROUTINE THERMO (T, TEMP, P, RESFRK, ENTHLP, CSUBP, CSUBT, RHO,
     &            DRHODT, DRHODP, GAMMA, MW, ADUMY, BDUMY, GDUMY, HDUMY)
C
      REAL MW
      LOGICAL XXC, XXG
      COMMON/TIMES/ TIVO, TEVC, TIVC, TSPARK, TEVO
C
      IF (RESFRK .GT. .99) GO TO 10
C
      CALL UPROP (P, TEMP, RESFRK, ENTHLP, CSUBP, CSUBT, RHO,
     &                DRHODT, DRHODP, XXA)
C
      DRHODP = DRHODP/1.01325E+6
      BDUMY  = (1. - RHO*CSUBT)/DRHODP
      R      = 1.01325E+6 * P/( RHO * TEMP )
C
C        IF COMPRESSION OR COMBUSTION PROCESS, PREPARE TO RETURN
C
      IF (T .GE. TIVC) GO TO 20
C
C        SUBSCRIPTS 1 AND 2 REFFER TO FRESH CHARGE AND
C        RESIDUAL GAS, RESPECTIVELY
C
      CALL UPROP (P, TEMP, 0.0, H1, XXA, XXB, RHO1,
     &            XXC, XXD, XXE)
      H1 = H1 * 4.184E+10
      CALL UPROP (P, TEMP, 1.0, H2, XXA, XXB, RHO2,
     &            XXC, XXD, XXE)
      H2 = H2 * 4.184E+10
      R1 = 1.01325E+6 * P/( RHO1 * TEMP )
      R2 = 1.01325E+6 * P/( RHO2 * TEMP )
      GDUMY = (R1 - R2)/R
      HDUMY = GDUMY + (H2 - H1)/BDUMY
      GO TO 20
C
   10 CALL HPROD (P, TEMP, ENTHLP, CSUBP, CSUBT, RHO, DRHODT, DRHODP)
      R = 1.01325E+6 * P/( RHO * TEMP )
      DRHODP = DRHODP/1.01325E+6
      BDUMY = (1. - RHO*CSUBT)/DRHODP
C
C        CONVERT TO UNITS NEEDED IN MAIN PROGRAM
C
   20 CONTINUE
      CSUBP = CSUBP * 4.184E+7
      ADUMY = CSUBP + ( DRHODT/DRHODP )*( 1./RHO - CSUBT )
      ENTHLP = ENTHLP * 4.184E+10
      MW = 8.3145E+7/R
      GAMMA = CSUBP/( CSUBP - R )
C
      RETURN
      END
```

```
C_____________________________________________________________________
C
C     SUBROUTINE ITRATE
C
C     PURPOSE
C        THIS SUBROUTINE IS CALLED TO OBTAIN T GIVEN P, H, RESFRK,
C        AND A GUESS FOR T.  'ITRATE' CALLS 'THERMO' WITH TGUESS.
C        'THERMO' RETURNS WITH THE ENTHALPY CORRESPONDING TO THE
C        GIVEN TGUESS.  THEN A NEW CORRECTED VALUE FOR TGUESS
C        IS CALCULATED BY USING THE DEFINITION OF CSUBP AND THE
C        KNOWN VALUES OF CORRECT H AND RETURNED HGUESS.  THIS PRO-
C        CEDURE IS REPEATED AT MOST MAXTRY TIMES, OR FEWER TIMES
C        IF ACCURACY MAXERR IS ACHIEVED.
C
C     USAGE
C        CALL ITRATE (T, TGUESS, P, RESFRK, ENTHLP, CSUBP, CSUBT,
C       &             RHO, DRHODT, DRHODP, GAMMA, MW, ADUMY, BDUMY,
C       &             GDUMY, HDUMY)
C
C     DESCRIPTION OF PARAMETERS
C        PARAMETER  INPUT  OUTPUT  DESCRIPTION
C
C        T          YES    NO      CRANK ANGLE (DEG)
C        TGUESS     YES    YES     TEMPERATURE GUESS (K)
C        ------     ---    --      (CORRECTED VALUE IS RETURNED)
C        P          YES    NO      PRESSURE (ATM)
C        RESFRK     YES    NO      MASS BURNED / TOTAL MASS
C        ------     ---    --      ( <1. FOR UNBURNED ZONE ONLY )
C        ENTHLP     YES    NO      ENTHALPY ON WHICH TO ITERATE (ERG)
C        HGUESS     NO     NO      ENTHALPY GUESS (ERG)
C        CSUBP      NO     YES     DH/DT @ CONSTANT P (ERG/K)
C        CSUBT      NO     YES     DH/DP @ CONSTANT T (ERG/ATM)
C        RHO        NO     YES     DENSITY
C        DRHODT     NO     YES     PARTIAL OF RHO WITH RESPECT TO T
C        DRHODP     NO     YES     PARTIAL OF RHO WITH RESPECT TO P
C        MW         NO     YES     MOLECULAR WEIGHT
C        GAMMA      NO     YES     RATIO OF SPECIFIC HEATS
C        ADUMY      NO     YES     SEE ASSIGNMENT STATEMENTS BELOW
C        BDUMY      NO     YES     SEE ASSIGNMENT STATEMENTS BELOW
C        GDUMY      NO     YES     SEE ASSIGNMENT STATEMENTS BELOW
C        HDUMY      NO     YES     SEE ASSIGNMENT STATEMENTS BELOW
C
C     REMARKS
C        NONE
C
C     SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED
C        THERMO
C
C     METHOD
C        SEE PURPOSE, ABOVE
C
C     WRITTEN BY S. G. POULOS
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C     EDITED BY S. G. POULOS
C
      SUBROUTINE ITRATE (T, TGUESS, P, RESFRK, ENTHLP, CSUBP, CSUBT,
     &                   RHO, DRHODT, DRHODP, GAMMA, MW, ADUMY, BDUMY,
     &                   GDUMY, HDUMY)
C
      REAL MW, MAXERR
      COMMON/ITRLIM/ MAXTRY, MAXERR
C
      DO 10 I = 1, MAXTRY
         CALL THERMO (T, TGUESS, P, RESFRK, HGUESS, CSUBP, CSUBT, RHO,
     &           DRHODT, DRHODP, GAMMA, MW, ADUMY, BDUMY, GDUMY, HDUMY)
         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, HGUESS, CSUBP, CSUBT, RHO,
     &        DRHODT, DRHODP, GAMMA, MW, ADUMY, BDUMY, GDUMY, HDUMY)
C
      RETURN
      END
```

```
C_________________ VERSION 2.1 ___ 2/12/82 ____________________________
C
C       SUBROUTINE UPROP
C
C       PURPOSE
C          TO CALCULATE THE ENTHALPY AND DENSITY OF A HOMOGENEOUS
C          MIXTURE OF AIR, RESIDUAL GAS, AND FUEL AS A FUNCTION OF
C          EQUIVALENCE RATIO, TEMPERATURE, AND PRESSURE
C
C       USAGE
C          CALL UPROP (P, T, RESFRK, ENTHLP, CSUBP, CSUBT, RHO,
C         &            DRHODT, DRHODP, CHI)
C
C       DESCRIPTION OF PARAMETERS
C         GIVEN:
C         P      : ABSOLUTE PRESSURE (ATM)
C         T      : ABSOLUTE TEMPERATURE (DEG K)
C         RESFRK: RESIDUAL GAS FRACTION
C         PHI    : EQUIVALENCE RATIO
C       GIVEN IN COMMON AREA /FUEL/:
C         AF(I) : 6 DIMENSIONAL VECTOR OF ENTHALPY COEFFICIENTS SUCH
C                 THAT THE ENTHALPY OF FUEL VAPOR AS A FUNCTION
C                 OF TEMPERATURE (T DEG K) IS GIVEN BY:
C                  H(T) = AF(1)*ST + (AF(2)*ST**2)/2 + (AF(3)*ST**3)/3
C                        + (AF(4)*ST**4)/4 - AF(5)/ST +AF(6)
C                  WHERE ST = T/1000 AND H(T) = <KCAL/MOLE>
C                 FOR MOST APPLICATIONS, ENTHALPY FUNCTION H(T) SHOULD
C                 BE VALID AT LEAST OVER THE TEMPERATURE RANGE:
C                                  300 K < T < 1500 K
C
C                 ENTHALPY DATUM STATE IS AT T = 0 ABSOLUTE WITH
C                 O2, N2, AND H2 GASEOUS AND C SOLID GRAPHITE.
C       ENW     : AVERAGE NUMBER OF NITROGEN ATOMS PER FUEL MOLECULE
C       CX      : AVERAGE NUMBER OF CARBON ATOMS PER FUEL MOLECULE
C       HY      : AVERAGE NUMBER OF HYDROGEN ATOMS PER FUEL MOLECULE
C       OZ      : AVERAGE NUMBER OF OXYGEN ATOMS PER FUEL MOLECULE
C
C       REMARKS
C          EXACTLY THE SAME LOGIC AS VERSION 2.0 (1/10/76) BUT CLEANED
C          UP CODING AND DOCUMENTATION BY S. POULOS. 2/12/82
C
C       SUBROUTINES AND FUNCTION SUBPROGRAMS NEEDED
C          NONE
C
C       METHOD
C          DESCRIBED IN APPENDIX A OF HIRES ET AL, SAE PAPER #760161
C
C
      SUBROUTINE UPROP (P, T, RESFRK, ENTHLP, CSUBP, CSUBT, RHO,
     &                  DRHODT, DRHODP, CHI)
C
      LOGICAL RICH, LEAN
```

```
      INTEGER FUELTP
      REAL*4 MBAR,K
      REAL A(6,7,2), A1(42), A2(42), AF(6), X(7)
      COMMON/OXDANT/ XI
      COMMON/FUEL/ FUELTP, ENW, CX, HY, OZ, DEL, PSI, PHI, QLOWER, FASTO
      COMMON/FUPRP/ AF
      EQUIVALENCE (A1(1), A(1,1,1)), (A2(1), A(1,1,2))
C
C        INITIALIZE PARAMETERS, AND CHECK TO SEE IN WHAT TEMPERATURE
C        RANGE WE ARE SO THAT THE CORRECT FITTED COEFFICIENTS WILL BE
C        USED. FLAG TEMPERATURES TOO HIGH OR TOO LOW.
C
      DATA A1/11.94033,2.088581,-0.47029,0.037363,-0.589447,-97.1418,
     1   6.139094,4.60783,-0.9356009,6.669498E-02,0.0335801,-56.62588,
     2   7.099556,1.275957,-0.2877457,0.022356,-0.1598696,-27.73464,
     3   5.555680,1.787191,-0.2881342,1.951547E-02,0.1611828,0.76498,
     4   7.865847,0.6883719,-0.031944,-2.68708E-03,-0.2013873,
     5   -0.893455,6.807771,1.453404,-0.328985,2.561035E-02,
     6   -0.1189462,-0.331835,6*0.0/
      DATA A2/4.737305,16.65283,-11.23249,2.828001,6.76702E-03,
     1   -93.75793,7.809672,-0.2023519,3.418708,-1.179013,1.43629E-03,
     2   -57.08004,6.97393,-0.8238319,2.942042,-1.176239,4.132409E-04,
     3   -27.19597,6.991878,0.1617044,-0.2182071,0.2968197,
     4   -1.625234E-02,-0.118189,6.295715,2.388387,-0.0314788,
     5   -0.3267433,4.35925E-03,0.103637,7.092199,-1.295825,3.20688,
     6   -1.202212,-3.457938E-04,-0.013967,6*0.0/
C
C        ENTER THE FUEL PARAMETERS INTO ARRAYS A1 AND A2
C
      DO 5 I = 1, 6
         A1(I + 36) = AF(I)
         A2(I + 36) = AF(I)
    5 CONTINUE
      RICH = PHI .GT. 1.0
      LEAN = .NOT. RICH
      W    = ENW/CX
      Z    = CZ/CX
      DEL  = CX/HY
      EPS  = 4.*DEL/(1. + 4.*DEL - 2.*DEL*Z)
      IER  = 0
      IF (T .LT. 100.)  IER = 1
      IF (T .GT. 6000.) IER = 2
      IR = 1
      IF (T .LT. 500.)  IR  = 2
C
C        GET THE COMPOSITION IN MOLES/MOLE OXYGEN OF OXIDANT
C
      PCTRES = RESFRK
      PCTNEW = 1.0 - RESFRK
      IF (RICH) GO TO 10
      X(1) = EPS*PHI*PCTRES
      X(2) = (2.*(1. - EPS) + EPS*Z)*PHI*PCTRES
```

```
      X(3) = 0.
      X(4) = 0.
      X(5) = (1. - PHI)*PCTRES + PCTNEW
      DCDT = 0.
      GO TO 20
   10 K     = 3.5
      ALPHA = 1.0 - K
      BETA  = (2.*(1.- EPS*PHI) + K*(2.*(PHI - 1.) + EPS*PHI))
      GAMMA = 2.*K*EPS*PHI*(PHI - 1.)
      C     = (-BETA + SQRT(BETA*BETA + 4.*ALPHA*GAMMA))/(2.*ALPHA)
      X(1)  = (EPS*PHI - C)*PCTRES
      X(2)  = (2.0*(1. - EPS*PHI) + EPS*PHI*Z +C)*PCTRES
      X(3)  = C*PCTRES
      X(4)  = (2.0*(PHI - 1.) - C)*PCTRES
      X(5)  = PCTNEW
   20 X(6)  = XI + EPS*PHI*W/2.*PCTRES
      X(7)  = PCTNEW * EPS*PHI/CX
C
C        CONVERT COMPOSITION TO MOLE FRACTIONS AND CALCULATE AVERAGE
C        MOLECULAR WEIGHT
C
      IF (LEAN) TMOLES = XI + (1. + EPS*PHI/CX)*PCTNEW
     &          + (1. + (1.-EPS)*PHI + EPS*PHI*(Z + W/2.))*PCTRES
      IF (RICH) TMOLES = XI + (1. + EPS*PHI/CX)*PCTNEW
     &          + ((2. - EPS)*PHI + EPS*PHI*(Z + W/2.))*PCTRES
      DO 30 J = 1,7
         X(J) = X(J)/TMOLES
   30 CONTINUE
      MBAR = EPS*PHI*(12. + 1./DEL + 16.*Z + 14.*W) +32. +28.*XI
      MBAR = MBAR/TMOLES
C
C        CALCULATE H, CP, AND CT AS IN REFERENCE, USING FITTED
C        COEFFICIENTS FROM JANAF TABLES
C
      ENTHLP = 0.
      CSUBP  = 0.
      CSUBT  = 0.
      ST     = T/1000.
      DO 40 J = 1,7
         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)
         CSUBP  = CSUBP + TCP*X(J)
   40 CONTINUE
      ENTHLP = ENTHLP/MBAR
      CSUBP  = CSUBP/MBAR
C
C        NOW CALCULATE RHO AND ITS PARTIAL DERIVATIVES
```

```
C        USING PERFECT GAS LAW
C
      RHO    = 0.012187*MBAR*P/T
      DRHODT = -RHO/T
      DRHODP = RHO/P
C
C        CALCULATE PSI AND CHI FOR BURNED GASES
C
      PSI = (XI + EPS*PHI*W/2.)/(1. + EPS*Z*PHI/2.)
      CHI = PHI*(1. + EPS*Z/2.)/(1. + EPS*Z*PHI/2.)
C
        RETURN
        END
```

```
C_________________ VERSION 3.2 ___ 2/12/82 ____________________________
C
C       SUBROUTINE CLDPRD
C
C       PURPOSE
C        TO CALCULATE THE SPECIFIC ENTHALPY OF THE PRODUCTS OF HC-AIR
C        COMBUSTION AT TEMPERATURES AND PRESSURES WHERE DISSOCIATION
C        OF THE PRODUCT GASES MAY BE IGNORED.  THE DENSITY OF THE
C        PRODUCT GAS IS ALSO CALCULATED, AS ARE THE PARTIAL
C        DERIVATIVES OF BOTH OF THESE QUANTITIES WITH RESPECT TO
C        PRESSURE AND TEMPERATURE.
C
C       USAGE
C          CALL CLDPRD (P, T, ENTHLP, CSUBP, CSUBT, RHO,
C         &             DRHODT, DRHODP, IER)
C
C       DESCRIPTION OF PARAMETERS
C       GIVEN:
C          P      : ABSOLUTE PRESSURE OF PRODUCTS (ATM)
C          T      : TEMPERATURE OF PRODUCTS (DEG K)
C          PHI    : EQUIVALENCE RATIO
C          DEL    : MOLAR C:H RATIO OF PRODUCTS
C          PSI    : MOLAR N:O RATIO OF PRODUCTS
C
C       RETURNS:
C          H      : SPECIFIC ENTHALPY OF PRODUCTS (KCAL/G)
C          CP     : PARTIAL DERIVATIVE OF H WITH RESPECT TO T
C                   (CAL/G-DEG K)
C          CT     : PARTIAL DERIVATIVE OF H WITH RESPECT TO P (CC/G)
C          RHO    : DENSITY OF THE PRODUCTS (G/CC)
C          DRHODT: PARTIAL DERIVATIVE OF RHO WITH RESPECT TO T
C                   (G/CC-DEG K)
C          DRHODP: PARTIAL DERIVATIVE OF RHO WITH RESPECT TO P
C                   (G/CC-ATM)
C          IER    : FLAG, SET TO 1 FOR T < 100 DEG K
C                                2 FOR T > 6000 DEG K
C                                0 OTHERWISE
C
C       RETURNS IN COMMON AREA /FROZEN/:
C         CPFROZ: FROZEN SPECIFIC HEAT (CAL/G-DEG K)
C       RETURNS IN COMMON AREA /MBARB/:
C         MBARB : AVERAGE MOLECULAR WEIGHT OF BURNED GASES
C
C       REMARKS
C          1) ENTHALPY DATUM STATE IS AT T = 0 ABSOLUTE WITH
C             O2,N2,H2 GASEOUS AND C SOLID GRAPHITE
C          2) MULTIPLY ATM-CC BY 0.0242173 TO CONVERT TO CAL
C          3) MODIFIED VERSION OF MIKE MARTIN'S PROGRAM
C          4) COMMON BLOCK MBARB ADDED BY B. BEARD 5/10/79
C          5) EXACTLY THE SAME LOGIC AS VERSION 3.1 (5/10/79),
C             BUT WITH CLEANED UP CODE AND DOCUMENTATION BY
C             S. POULOS. 2/12/82
```

```
C
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, ENTHLP, CSUBP, CSUBT, RHO,
     &                   DRHODT, DRHODP, IER)
C
      LOGICAL RICH, LEAN
      REAL*4 MBAR, K
      REAL MBARB
      DIMENSION A(6,6,2), X(6)
      DIMENSION A1(36), A2(36)
      COMMON/FUEL/ FUELTP, ENW, CX, HY, OZ, DEL, PSI, PHI, QLOWER, FASTO
      COMMON/FROZEN/ CPFROZ
      COMMON/MBARB/ MBARB
      EQUIVALENCE (A1(1), A(1,1,1)), (A2(1), A(1,1,2))
C
C        INITIALIZE PARAMETERS, AND CHECK TO SEE IN WHAT TEMPERATURE
C        RANGE WE ARE SO THAT THE CORRECT FITTED COEFFICIENTS WILL BE
C        USED. FLAG TEMPERATURES TOO HIGH OR TOO LOW.
C
      DATA A1/11.94033,2.088581,-0.47029,.037363,-.589447,-97.1418,
     1  6.139094,4.60783,-.9356009,6.669498E-02,.0335801,-56.62588,
     2  7.099556,1.275957,-.2877457,.022356,-.1598696,-27.73464,
     3  5.555680,1.787191,-.2881342,1.951547E-02,.1611828,.76498,
     4  7.865847,.6883719,-.031944,-2.68708E-03,-.2013873,-.893455,
     5  6.807771,1.453404,-.328985,2.561035E-02,-.1189462,-.331835/
      DATA A2/4.737305,16.65283,-11.23249,2.828001,6.76702E-03,
     1  -93.75793,7.809672,-.2023519,3.418708,-1.179013,1.43629E-03,
     2  -57.08004,6.97393,-.8238319,2.942042,-1.176239,4.132409E-04,
     3  -27.19597,6.991878,.1617044,-.2182071,.2968197,-1.625234E-02,
     4  -.118189,6.295715,2.388387,-.0314788,-.3267433,4.35925E-03,
     5  .103637,7.092199,-1.295825,3.20688,-1.202212,-3.457938E-04,
     6  -.013967/
C
      RICH = PHI .GT. 1.0
      LEAN = .NOT. RICH
      EPS  = 4.*DEL/(1. + 4.*DEL)
      IER  = 0
      IF (T .LT. 100.)  IER = 1
      IF (T .GT. 6000.) IER = 2
      IR = 1
      IF (T .LT. 500.)  IR  = 2
C
C        GET THE COMPOSITION IN MOLES/MOLE OXYGEN
C
```

```
      IF (RICH) GO TO 10
      X(1) = EPS*PHI
      X(2) = 2.*(1.- EPS)*PHI
      X(3) = 0.
      X(4) = 0.
      X(5) = 1.- PHI
      DCDT = 0.
      GO TO 20
   10 K     = 3.5
      ALPHA = 1. - K
      BETA  = (2.*(1.-EPS*PHI) + K*(2.*(PHI - 1.) + EPS*PHI))
      GAMMA = 2.*K*EPS*PHI*(PHI - 1.)
      C     = ( -BETA + SQRT(BETA*BETA + 4.*ALPHA*GAMMA))/(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.
   20 X(6)  = PSI
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*****
C        CALCULATE H, CP, AND CT AS IN WRITEUP, USING FITTED
C        COEFFICIENTS FROM JANAF TABLES
C
      ENTHLP = 0.
      CSUBP  = 0.
      CSUBT  = 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)
         CSUBP  = CSUBP + TCP*X(J)
   40 CONTINUE
      ENTHLP = ENTHLP/MBAR
      CSUBP  = CSUBP/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
      RETURN
      END
```

```
C_____________________ VERSION 3.6 ___ 2/12/82 _____________________
C
C       SUBROUTINE HPROD
C
C       PURPOSE
C          TO CALCULATE THE PROPERTIES OF THE PRODUCTS OF HYDROCARBON-
C          AIR COMBUSTION AS A FUNCTION OF TEMPERATURE AND PRESSURE,
C          USING AN APPROXIMATE CORRECTION FOR DISSOCIATION.
C          H AND RHO ARE CALCULATED AS FUNCTIONS OF R, T, AND PHI.
C          THE PARTIAL DERIVATIVES OF H AND RHO WITH RESPECT TO
C          P AND T ARE ALSO CALCULATED
C
C        USAGE
C           CALL HPROD (P, T, H, CP, CT, RHO, DRHODT, DRHODP)
C
C        DESCRIPTION OF PARAMETERS
C        GIVEN:
C          P      : ABSOLUTE PRESSURE OF PRODUCTS (ATM)
C          T      : TEMPERATURE OF PRODUCTS (DEG K)
C          PHI    : EQUIVALENCE RATIO
C          DEL    : MOLAR C:H RATIO OF PRODUCTS
C          PSI    : MOLAR N:O RATIO OF PRODUCTS
C
C        RETURNS:
C          H      : SPECIFIC ENTHALPY OF PRODUCTS (ATM)
C          CP     : PARTIAL DERIVATIVE OF H WITH RESPECT TO T
C                   (CAL/G-DEG K)
C          CT     : PARTIAL DERIVATIVE OF H WITH RESPECT TO P (CC/G)
C          RHO    : DENSITY OF THE PRODUCTS (G/CC)
C          DRHODT: PARTIAL DERIVATIVE OF RHO WITH RESPECT TO T
C                   (G/CC-DEG K)
C          DRHODP: PARTIAL DERIVATIVE OF RHO WITH RESPECT TO P
C                  (G/CC-ATM)
C
C        RETURNS IN COMMON AREA /FROZEN/:
C          CPFROZ: FROZEN SPECIFIC HEAT (CAL/G-DEG K)
C        RETURNS IN COMMON AREA /MBARB/:
C          MBARB : AVERAGE MOLECULAR WEIGHT OF BURNED GASES
C
C        REMARKS
C           1) ENTHALPY DATUM STATE IS AT T = 0 ABSOLUTE WITH
C              O2, N2, H2 GASEOUS AND C SOLID GRAPHITE
C           2) MULTIPLY ATM-CC BY 0.0242173 TO CONVERT TO CAL
C           3) MODIFIED VERSION OF MIKE MARTIN'S PROGRAM
C           4) COMMON BLOCK MBARB ADDED BY B. BEARD 5/10/79
C           5) EXACTLY THE SAME LOGIC AS VERSION 3.5 (5/10/79),
C              BUT WITH CLEANED UP CODE AND DOCUMENTATION BY
C              S. POULOS. 2/12/82
C
C        SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED
C          CLDPRD
C
```

```
C       METHOD
C         SEE MARTIN AND HEYWOOD 'APPROXIMATE RELATIONSHIPS FOR THE
C         THERMODYNAMIC PROPERTIES OF HYDROCARBON-AIR COMBUSTION
C         PRODUCTS'
C
C
      SUBROUTINE HPROD (P, T, H, CP, CT, RHO, DRHODT, DRHODP)
C
      LOGICAL RICH, LEAN, NOTHOT, NOTWRM, NOTCLD
      REAL MCP, MWT, K1, K2
      REAL MBARB
      COMMON/FUEL/ FUELTP, ENW, CX, HY, OZ, DEL, PSI, PHI, QLOWER, FASTO
      COMMON/FROZEN/ CPFROZ
      COMMON/MBARB/ MBARB
C
C        INITIALIZE PARAMETERS USED IN THE CALCULATION
C
      DATA R,ROVER2 /1.9869,0.99345/, PSCALE /2.42173E-2/
      DATA TCOLD,THOT /1000.,1100./
C
      RICH   = PHI .GE. 1.0
      LEAN   = .NOT. RICH
      NOTHOT = T .LT. THOT
      NOTCLD = T .GT.TCOLD
      NOTWRM = .NOT. (NOTCLD .AND. NOTHOT)
      EPS    = (4.*DEL)/(1. + 4.*DEL)
C
C        USE SIMPLE ROUTINE FOR LOW TEMPERATURE MIXES
C
      IF (NOTCLD) GO TO 5
      CALL CLDPRD (P, T, H, CP, CT, RHO, DRHODT, DRHODP, IER)
      RETURN
C
C        CALCULATE EQUILIBRIUM CONSTANTS FOR DISSOCIATION (EQS. 3.9
C        & 3.10) (NOTE THAT THESE HAVE UNITS ATM**(.5) )
C
    5 K1 = 5.819E-6 * EXP(0.9674*EPS + 35810./T)
      K2 = 2.961E-5 * EXP(2.593*EPS  + 28980./T)
C
C        CALCULATE A, X, Y, & U AS IN EQS. 5.24, 3.6, 5.25, 3.7, 2.18,
C        2.19, & 3.8
C
      C5 = 2.- EPS + PSI
      A  = (C5/(4.*P*K1*K1*EPS))**(.33333333)
C
      C6 = EPS + 2.*C5
      X  = A*EPS*(3.*C5 + C6*A)/(3.*(1.+ 2.*A)*C5 + 2.*C6*A*A)
C
      Z  = ABS((1.-PHI)/X)
      IF (LEAN) Y = X/SQRT(1.+ .666667*Z + 1.3333333*(1.-PHI))
      IF (RICH) Y = X/(1.+.6666667*Z +.3333333*Z*Z -.6666667*(PHI-1.))
      U  = C5*(EPS - 2.*X)/(4.*K1*K2*P*X)
```

```
C
C        CALCULATE THE ENTHALPY OF FORMATION FOR THIS APPROXIMATE
C        COMPOSITION AS IN EQS. 3.21, 3.22, & 5.7. ALSO GET THE
C        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

   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
      H      = 0.001*ROVER2*(C1*T + C2*TVTIL + HF)/MCP
C
C        CALCULATE THE AVERAGE MOLECULAR WEIGHT, AND GET DENSITY
C        BY USING THE PERFECT GAS LAW - EQS. 3.12, 3.13, & 3.14
C
      IF (LEAN) MWT = MCP/(1. + (1.- EPS)*PHI + PSI + Y + U)
      IF (RICH) MWT = MCP/(     (2.- EPS)*PHI + PSI + Y + U)
C*****
      MBARB = MWT
C*****
      RHO = MWT*P*PSCALE/(R*T)
C
C        GET PARTIAL DERIVATIVES IF DESIRED
C
C        THE FOLLOWING USES IN ORDER EQS. 5.8, 5.9, 5.32, 5.31, 5.30,
C        5.29, 5.28, & 5.26
C
      C3 = (121.5 + 29.59*EPS)*1000.
      C4 = 1.175E5
C
```

```
      DUDTPX = 64790.*U/(T*T)
      DUDPTX = -U/P
      DUDXPT = -U*EPS/(X*(EPS - 2.*X))
C
      DADTP  = 23873.*A/(T*T)
      DADPT  = -A/(3.*P)
C
      T5 = 3.*C5
      DXDA = T5*EPS*(T5 + 2.*C6*A)/(T5*(1. + 2.*A) + 2.*C6*A*A)**2
C
C        FOLLOWING USES EQS. 5.23, 5.19-5.22, 5.18-5.14, 5.12, & 5.13
C
      IF (LEAN) DYDX = (Y*Y*Y)/(X*X*X) * (1.+ Z + 1.333333*(1.-PHI))
      IF (RICH) DYDX = (Y*Y)/(X*X)*(1.+ 4.*Z/3. + Z*Z -2.*(PHI-1.)/3.)
C
      DYDTP = DYDX*DXDA*DADTP
      DYDPT = DYDX*DXDA*DADPT
      DUDTP = DUDXPT*DXDA*DADTP + DUDTPX
      DUDPT = DUDXPT*DXDA*DADPT + DUDPTX
C
      DHFDPT = C3*DYDPT + C4*DUDPT
      DC2DPT = -2.*(3.*DYDPT + DUDPT)
      DC1DPT = 5.*DYDPT + 3.*DUDPT
      DHFDTP = C3*DYDTP + C4*DUDTP
      DC2DTP = -2.*(3.*DYDTP + DUDTP)
      DC1DTP = 5.*DYDTP + 3.*DUDTP
C
      DTVDTP = (TVTIL*TVTIL)/(T*T)*EXPTVT
C
C        FOLLOWING USES EQS. 5.10, & 5.11
C
      CPFROZ = ROVER2/MCP*(C1 + C2*DTVDTP)
C
      CP = ROVER2/MCP*(C1 + T*DC1DTP + C2*DTVDTP + TVTIL*DC2DTP
     &     + DHFDTP)
      CT = ROVER2/MCP*(T*DC1DPT + TVTIL*DC2DPT + DHFDPT)*PSCALE
C
C        FOLLOWING USES EQS. 5.46, 5.35-5.37, 5.33, & 5.34
C
      IF (LEAN) D = 1. + (1.- EPS)*PHI + PSI + Y + U
      IF (RICH) D =      (2.- EPS)*PHI + PSI + Y + U
      G     = -MCP/(D*D)
      DMDTP = G*(DYDTP + DUDTP)
      DMDPT = G*(DYDPT + DUDPT)
C
      DRHODT = PSCALE*P*(DMDTP - MWT/T)/(R*T)
      DRHODP = PSCALE*(MWT + P*DMDPT)/(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, TH, TCP, TCT, TRHO, TDRT, TDRP, 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
C
      RETURN
      END
```

```
C_____________________________________________________________________
C
C     SUBROUTINE UTRANS
C
C     PURPOSE
C        CALCULATES DYNAMIC VISCOSITY AND THERMAL CONDUCTIVITY
C        OF UNBURNED MIXTURE
C
C     USAGE
C        CALL UTRANS (TEMP, DYNVIS, THRCON)
C
C     DESCRIPTION OF PARAMETERS
C        PARAMETER  INPUT  OUTPUT   DESCRIPTION
C
C        TEMP       YES    NO       TEMPERATURE (K)
C        DYNVIS     NO     YES      DYNAMIC VISCOSITY (G/SEC CM)
C        THRCON     NO     YES      THERMAL CONDUCTIVITY (ERG/SEC CM K)
C
C     REMARKS
C        UNBURNED MIXTURE IS ASSUMED TO BE THE SAME AS AIR.
C
C     SUBROUTINE AND FUNCTION SUBPROGRAMS REQUIRED
C        NONE
C
C     METHOD
C        SEE S. H. MANSOURI PH.D. THESIS
C
C     WRITTEN BY S. H. MANSOURI
C     EDITED BY S. G. POULOS
C
      SUBROUTINE UTRANS (TEMP, DYNVIS, THRCON)
C
      DYNVIS = 14.58E-6 * (TEMP** 1.5)/(TEMP + 110.4)
      THRCON = 2.6464E+2 * ( TEMP**0.5 )/( 1. + 245.4 *
     &         (10.**(-12./TEMP))/TEMP )
C
      RETURN
      END
```

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

```
C_____________________________________________________________________
C
C     SUBROUTINE FUELDT
C
C     PURPOSE
C        THIS SUBROUTINE IS CALLED TO SET THE VALUES OF THE FUEL
C        RELATED PARAMETERS AT THE START OF PROGRAM EXECUTION. THE
C        ONLY INPUT REQUIRED IS THE FUEL TYPE.  THE PARAMETERS WHICH
C        ARE SET ARE: I) THE ATOM RATIOS WHICH SPECIFY THE PROPERTIES
C        OF THE FUEL AIR MIXTURE, THE SET OF ENTHALPY COEFFICIENTS
C        ASSOCIATED WITH THE FUEL (USED IN THE FROPERTY ROUTINES), AND
C        THE FUEL HEATING VALUE AND STOICHIOMETRIC FUEL/AIR RATIO;
C        II) THE ATOM RATIOS REQUIRED BY SUBROUTINE 'PTCHEM' FOR
C        CALCULATION OF EQUILIBRIUM BURNED GAS COMPOSITION.
C
C     USAGE
C        CALL FUELDT
C
C     DESCRIPTION OF PARAMETERS
C        PARAMETER  INPUT  OUTPUT  DESCRIPTION
C
C        FUELTP     YES    NO      FUEL TYPE
C        PSI        NO     YES     MOLAR N2 TO O2 RATIO FOR AIR
C        XI         NO     YES     MOLAR N2 TO O2 RATIO FOR AIR
C        CX         NO     YES     # OF CARBON ATOMS/FUEL MOLECULE
C        DEL        NO     YES     CARBON/HYDROGEN RATIO OF FUEL
C        HY         NO     YES     HYDROGEN ATOMS PER FUEL MOLECULE
C        ENW        NO     YES     NITROGEN ATOMS PRE FUEL MOLECULE
C        OZ         NO     YES     OXYGEN ATOMS PER FUEL MOLECULE
C        QLOWER     NO     YES     LOWER HEATING VALUE OF THE FUEL
C        FASTO      NO     YES     STOICHIOMETRIC FUEL/AIR RATIO
C        AF(I)      NO     YES     FUEL COEFFICIENT ARRAY
C        D(I)       NO     YES     ATOM RATIO ARRAY (SEE PTCHEM)
C
C     REMARKS
C        ONLY ISSOCTANE AND PROPANE ARE AVAILABLE FOR
C        USE AS FUELS.
C
C     SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED
C
C
C     METHOD
C        SEE PURPOSE, ABOVE
C
C     WRITTEN BY S. G. POULOS
C     EDITED BY S. G. POULOS
C
      SUBROUTINE FUELDT
C
      INTEGER FUELTP
      REAL AF(6)
      REAL*8 D(4)
```

```
C
      COMMON/FUEL/ FUELTP, ENW, CX, HY, OZ, DEL, PSI, PHI, QLOWER, FASTO
      COMMON/FUPRP/ AF
      COMMON/OXDANT/ XI
      COMMON/CHEM/ D
C
      PSI = 3.76
      XI = 3.76
      IF (FUELTP .GT. 1) GO TO 10
C
C        FOLLOWING DATA FOR ISOOCTANE (FUELTP = 1)
C
      CX = 8.0
      DEL = 8.0/18.0
      HY = 18.0
      ENW = 0.0
      OZ = 0.0
      QLOWER = 44.392
      FASTO = 1./15.11
C
C        SET COEFFICIENTS FOR USE BY PROPERTY ROUTINES
C
      AF(1) =   -0.55313
      AF(2) =  181.62
      AF(3) =  -97.787
      AF(4) =   20.402
      AF(5) =   -0.03095
      AF(6) =  -60.518
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
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
C        CALCULATE ATOM RATIOS FOR USE BY 'PTCHEM'
C
   20 D(1) = 1./DEL
      D(2) = 1.0
```

```
      D(4) = 2.*(1. + 0.25/DEL)/PHI
      D(3) = PSI*D(4)
C
      RETURN
      END
```

```
C
C
C     SUBROUTINE LAMFSP
C
C     PURPOSE
C        THIS SUBROUTINE CALCULATES THE LAMINAR FLAME SPEED FOR
C        THE FUEL BEING USED GIVEN TEMPERATURE AND PRESSURE OF THE
C        BURNING GAS MIXTURE. A CORRECTION FOR RESIDUAL GAS CONTENT
C        IS INCLUDED (SEE M. METGALCHI SC.D. THESIS).
C
C     USAGE
C        CALL LAMFSP (TEMP, P, RESFRK, SSUBL)
C
C     DESCRIPTION OF PARAMETERS
C        PARAMETER  INPUT  OUTPUT  DESCRIPTION
C
C        TEMP       YES    NO      TEMPERATURE (K)
C        P          YES    NO      PRESSURE (ATM)
C        RESFRK     YES    NO      RESIDUAL MASS FRACTION (-)
C        SSUBL      NO     YES     LAMINAR FLAME SPEED (CM/SEC)
C
C     REMARKS
C        FUEL TYPE AND PROPERTIES ARE PASSED IN COMMON BLOCKS
C
C     SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED
C        ______     ______     ______     ______
C
C     METHOD
C        SEE PURPOSE, ABOVE
C
C     WRITTEN BY S. G. POULOS
C     EDITED BY S. G. POULOS
C
      SUBROUTINE LAMFSP (TEMP, P, RESFRK, SSUBL)
C
      INTEGER FUELTP
      COMMON/FUEL/ FUELTP, ENW, CX, HY, OZ, DEL, PSI, PHI, QLOWER, FASTO
C
      IF (FUELTP .GT. 1) GO TO 10
C
C        FOLLOWING CORRELATION FOR ISOOCTANE (FUEL TYPE = 1)
C
      SLINF = -89.0009*PHI*PHI + 198.9515*PHI - 82.9507
      ALPHA = -1.625*PHI*PHI + 2.4251*PHI + 1.460
      BETA  = 0.375*PHI*PHI - 0.475*PHI - 0.080
      GO TO 20
C
C        FOLLOWING CORRELATION FOR PROPANE (FUEL TYPE = 2)
C
   10 SLINF = -85.008*PHI*PHI + 196.5013*PHI - 79.6005
      ALPHA = 0.875*PHI*PHI - 2.275*PHI + 3.53
      BETA  = -0.750*PHI*PHI + 1.650*PHI - 1.07
```

```
   20 SSUBL = SLINF*( (TEMP/298.)**ALPHA ) * P**BETA
C
C        CORRECTION FOR RESIDUAL FRACTION
C
      SSUBL = SSUBL * (4.70617*RESFRK*RESFRK - 4.06185*RESFRK + 1)
C
      RETURN
      END
```

```
C_____________________________________________________________________
C
C     SUBROUTINE LAMFSP
C
C     PURPOSE
C        THIS SUBROUTINE CALCULATES THE LAMINAR FLAME SPEED FOR
C        THE FUEL BEING USED GIVEN TEMPERATURE AND PRESSURE OF THE
C        BURNING GAS MIXTURE. A CORRECTION FOR RESIDUAL GAS CONTENT
C        IS INCLUDED (SEE M. METGALCHI SC.D. THESIS).
C
C     USAGE
C        CALL LAMFSP (TEMP, P, RESFRK, SSUBL)
C
C     DESCRIPTION OF PARAMETERS
C        PARAMETER  INPUT  OUTPUT  DESCRIPTION
C
C        TEMP       YES    NO      TEMPERATURE (K)
C        P          YES    NO      PRESSURE (ATM)
C        RESFRK     YES    NO      RESIDUAL MASS FRACTION (-)
C        SSUBL      NO     YES     LAMINAR FLAME SPEED (CM/SEC)
C
C     REMARKS
C        FUEL TYPE AND PROPERTIES ARE PASSED IN COMMON BLOCKS
C
C     SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED
C        ______     ______     ______     _____
C
C     METHOD
C        SEE PURPOSE, ABOVE
C
C     WRITTEN BY S. G. POULOS
C     EDITED BY S. G. POULOS
C
      SUBROUTINE LAMFSP (TEMP, P, RESFRK, SSUBL)
C
      INTEGER FUELTP
      COMMON/FUEL/ FUELTP, ENW, CX, HY, OZ, DEL, PSI, PHI, QLOWER, FASTO
C
      IF (FUELTP .GT. 1) GO TO 10
C
C        FOLLOWING CORRELATION FOR ISOOCTANE (FUEL TYPE = 1)
C
      SLINF = -89.0009*PHI*PHI + 198.9515*PHI - 82.9507
      ALPHA = -1.625*PHI*PHI + 2.4251*PHI + 1.460
      BETA  = 0.375*PHI*PHI - 0.475*PHI - 0.080
      GO TO 20
C
C        FOLLOWING CORRELATION FOR PROPANE (FUEL TYPE = 2)
C
   10 SLINF = -85.008*PHI*PHI + 196.5013*PHI - 79.6005
      ALPHA = 0.875*PHI*PHI - 2.275*PHI + 3.53
      BETA  = -0.750*PHI*PHI + 1.650*PHI - 1.07
```

```
   20 SSUBL = SLINF*( (TEMP/298.)**ALPHA ) * P**BETA
C
C        CORRECTION FOR RESIDUAL FRACTION
C
      SSUBL = SSUBL * (4.70617*RESFRK*RESFRK - 4.06185*RESFRK + 1)
C
      RETURN
      END
```

```
C
      SUBROUTINE PTCHEM (TMP, PRS, D, XMOFR, ISENT)
C
C
C     THE ORIGINAL MIT EQUILIBRIUM PTCHEM SUBROUTINE HAS BEEN REDUCED
C     AND IS DESIGNED TO PROCESS 4 ELEMENTS & 14 SPECIES
C
C     ARRAY D CONTAINS RATIOS OF ELEMENTS H, C, N, O RESPECTIVELY;
C
C     E.G., DATA D / 1.43, 1.0, 13.0, 3.46 /
C
C
C     ARRAY XMOFR CONTAINS MOLE FRACTIONS OF EACH SPECIES;
C     SYMBOLS OF EACH SPECIES 1 TO 14 (HEX'E') ARE AS FOLLOWS:
C
C    0          'HCO ', 'CO  ', 'CO2 ', 'H   ', 'OH  ', 'H2  ',
C    1          'H2O2', 'N   ', 'NO  ', 'NO2 ', 'N2  ', 'N2O ',
C    2          'O   ', 'O2  ' /
C
C
C     INPUT:     ( DOUBLE PREC. )
C
C        TMP   = TEMPERATURE ( DEGREES K )
C        PRS   = PRESSURE  ( ATMOSPHERES )
C        D     = ARRAY(4)  ( RATIO, 4 ELEMENTS )
C
C     OUTPUT:    ( DOUBLE PREC. )
C
C        XMOFR = ARRAY(14) ( MOLE FRACTIONS, 14 SPECIES )
C        ISENT = ERROR CODE:
C            0 = NO ERROR
C            1 = TEMP TOO HIGH
C            2 = TEMP TOO LOW
C            3 = ( UNUSED )
C            4 = TOO MANY ITERATIONS, RESULTS DOUBTFUL, LOOK UP NU
C            5 = TOO MANY ITERATIONS
C            6 = THERE ARE NO GASES PRESENT
C            7 = CHECK IF THERE ARE ENOUGH SPECIES
C            8 = TOO MANY TRIES FOR T
C
C     AUTHOR:  DAN DANTZER     LATEST REVISION 12/14/72
C
C
      IMPLICIT REAL*8(A-H,O-Z)
C
      EQUIVALENCE ( ITOTSP, M      )
      EQUIVALENCE ( ITOTSP, M1     )
      EQUIVALENCE ( NELEM , N      )
      EQUIVALENCE ( G(1,1), CMN(1) )
C
      DIMENSION D(1), XMOFR(1)
      DIMENSION A(4,14), ZL(14,8)
```

```
      DIMENSION ZL1(56), ZL2(56)
C
C        FOLLOWING ARRAYS ARE 'NELEM' IN SIZE
C
      DIMENSION DD(4), XMU(4), XNU(4), E(4), F(4,4)
C
C        FOLLOWING ARRAYS ARE 'NELEM' + 2  = 'INXNSL'IN SIZE
C
      DIMENSION R(6), G(6,6)
C
C        FOLLOWING ARRAYS ARE 'ITOTSP' IN SIZE
C
      DIMENSION CMN(14), CP(14), CPT(14), X(14), XMAX(14)
      DIMENSION HORT(14), SR(14), C(14)
C
C
C        NSAME  = INITIALIZATION FLAG
C        NELEM  = NUMBER OF ELEMENTS INVOLVED
C        ITOTSP = TOTAL NUMBER OF SPECIES INVOLVED
C
      DATA NSAME  /  0 /
      DATA NELEM  /  4 /
      DATA INXNSL /  6 /
      DATA ITOTSP / 14 /
C
      DATA  DD, XMU, XNU, E, F  /  32 * 0. /
      DATA  R, G  /  42 * 0. /
      DATA  A, CMN, CP, CPT, X, XMAX  /  126 * 0. /
C
C         ARRAY ZL(K,J) CONTAINS THE HI-TEMP DATA FOR EACH OF 14 SPECIES
C
C           K = SPECIES NUMBER ( 1 - 14 )
C           J = DATA ( 1 - 8 EACH SPECIES )
C
C         DATA WAS TAKEN FROM ORIGINAL DATA SET ( CARDS), ARRANGED IN
C         ROW,COL (14,8),  BUT DATA STATEMENT INTERNALLY STORES
C         BY COL,ROW;  THEREFORE,  DATA MUST BE REVERSED FOR PROG EXEC.
C         ORIGINAL DATA ARRANGEMENT MAINTAINED FOR CONVENIENCE IN MAKING
C         CHANGES TO SPECIES DATA.
C
C         NUMBER OF CONTINUATION CARDS LIMITED TO 19
C         CONTINUATION COL #6 CONTAINS THE HEXIDECIMAL SPECIES NUMBER
C
      DATA  ZL1  /
     1  9.3434439D 00, 2.9512196D 00,-6.7088366D-01, 5.0901942D-02,
     1 -4.1140777D-01,-6.9903498D 00, 6.2395554D 01, 2.3009987D 00,
     2  7.0995646D 00, 1.2759562D 00,-2.8774744D-01, 2.2356123D-02,
     2 -1.5986955D-01,-2.9023636D 01, 5.4823700D 01, 1.2890015D 00,
     3  1.1940331D 01, 2.0885811D 00,-4.7029203D-01, 3.7363116D-02,
     3 -5.8944768D-01,-9.9468796D 01, 6.2207169D 01, 2.3269949D 00,
     4  4.9679995D 00,-5.9678716D-13, 1.9345219D-13,-1.8732195D-14,
     4 -7.4194936D-14, 5.0619217D 01, 3.3404419D 01, 1.0119925D 00,
```

```
     5  5.6197815D 00, 1.9668446D 00,-3.8645178D-01, 2.7364515D-02,
     5  1.3418680D-01, 8.0923529D 00, 5.0777405D 01, 2.0489998D 00,
     6  5.5556803D 00, 1.7871914D 00,-2.8813416D-01, 1.9515470D-02,
     6  1.6118270D-01,-1.2590199D 00, 3.8126053D 01, 2.0239983D 00,
     7  6.1390944D 00, 4.6078291D 00,-9.3560094D-01, 6.6694975D-02,
     7  3.3580098D-02,-5.9687866D 01, 5.1456772D 01, 3.0619965D 00 /
      DATA  ZL2  /
     8  5.1632023D 00,-1.8977487D-01, 3.6921006D-02, 3.6241105D-03,
     8 -3.2718156D-02, 1.1134157D 02, 4.2783066D 01, 1.0359793D 00,
     9  7.5180626D 00, 1.0245209D 00,-2.3053735D-01, 1.7926671D-02,
     9 -1.9369543D-01, 1.8756821D 01, 5.8378296D 01, 2.0729971D 00,
     A  1.2123282D 01, 1.2564993D 00,-3.0112296D-01, 2.3658749D-02,
     A -6.2256289D-01, 2.3839598D 00, 6.8810959D 01, 3.1109982D 00,
     B  6.8077698D 00, 1.4534035D 00,-3.2898575D-01, 2.5610346D-02,
     B -1.1894619D-01,-2.4038353D 00, 5.3165161D 01, 2.0719986D 00,
     C  1.2365961D 01, 1.7261782D 00,-4.0528846D-01, 3.1418435D-02,
     C -5.8120877D-01, 1.4105570D 01, 6.4331467D 01, 3.1099997D 00,
     D  5.1006308D 00,-1.5177220D-01, 4.8953138D-02,-2.8814352D-03,
     D  8.9299418D-03, 5.8080948D 01, 4.4752548D 01, 1.0379944D 00,
     E  7.8658457D 00, 6.8837190D-01,-3.1944100D-02,-2.6870817D-03,
     E -2.0138729D-01,-2.9684544D 00, 5.7424637D 01, 2.0749989D 00 /
C
      IF (NSAME) 2000, 2000, 2004
 2000 NSAME = 1
      AR = 1.98726D0
      ITMAX = 500
      ITW  = 400
      DIF = 15.0D0
      DIF1 = DIF
      T = 1.0D0
      TLUB = 6000.
      XN = N
      TOL1 = .01D0
      TOL3 = .00001D0
      TOL5 = 1.0D-5
      TOL6 = .1D0
      TOL7 = 10.0D0
C
C         ARRAY A(I,K) CONTAINS NUMBER OF ATOMS PER ELEMENT
C
C           I = ELEMENTS H, C, N, O RESPECTIVELY
C           K = SPECIES NUMBER
C
      A(1,1) = 1.
      A(1,4) = 1.
      A(1,5) = 1.
      A(1,6) = 2.
      A(1,7) = 2.
      A(2,1) = 1.
      A(2,2) = 1.
      A(2,3) = 1.
      A(3,8) = 1.
```

```
      A(3,9) = 1.
      A(3,10)= 1.
      A(3,11)= 2.
      A(3,12)= 2.
      A(4,1) = 1.
      A(4,2) = 1.
      A(4,3) = 2.
      A(4,5) = 1.
      A(4,7) = 1.
      A(4,9) = 1.
      A(4,10)= 2.
      A(4,12)= 1.
      A(4,13)= 1.
      A(4,14)= 2.
C
C     LOAD DATA INTO SPECIES ARRAY ZL
C
      II = 0
      DO 1060 K = 1, 7
         I = K + 7
         DO 1050 J = 1, 8
            II = II + 1
            ZL(K,J) = ZL1(II)
            ZL(I,J) = ZL2(II)
 1050    CONTINUE
 1060 CONTINUE
C
C         END OF ONE-TIME INITIALIZATION
C
 2004 IF ( TMP - 700.0 )  2112, 2112, 2355
 2355 IF ( TMP - TLUB ) 2012, 2012, 2009
 2009 ISENT = 1
      GO TO 5000
 2112 ISENT = 2
      GO TO 5000
 2012 TK  = TMP / 1.0D+3
      XLP = DLOG( PRS )
C
C         START OF ORIGINAL 'HS' SUBROUTINE
C
      DO 5004 K10 = 1, M
         IF ( ZL(K10,1) )  5003, 5002, 5003
 5002    HORT(K10) = 0.11111111D0
         SR (K10) = -1.0D6
         GO TO 5004
 5003    HORT(K10) = (((( ZL(K10,4) * TK / 4.D0 + ZL(K10,3) / 3.0D0 ) *
     1                TK + ZL(K10,2) / 2.D0 ) * TK  + ZL(K10,1) ) * TK -
     2                ZL(K10,5) / TK + ZL(K10,6) ) / ( AR * TK )
         SR(K10) = ( ZL(K10,1) * DLOG(TK) + TK * ( ZL(K10,2) +
     1              ZL(K10,3) * 0.5D0 * TK + ZL(K10,4) * TK **2/3.D0 ) -
     2              ZL(K10,5) * 0.5D0 / TK ** 2 + ZL(K10,7) ) / AR
 5004 C(K10) = HORT(K10) - SR(K10) + XLP
```

```
C
C         END OF ORIGINAL 'HS' SUBROUTINE
C
      ISENT = 0
      ITER = 0
      ITTRDG = 0
      TOL4 = 0.1D0
      YMAX = 0.
      DO 412 J = 1, M1
         XMAX(J) = 1.0D10
         DO 412 I = 1, N
         IF (A(I,J)) 412, 412, 413
  413    IF (D(I)/A(I,J) - XMAX(J)) 414, 412, 412
  414    XMAX(J) = D(I)/A(I,J)
  412 CONTINUE
      X0 = 0.0D0
      DO 90 I = 1, N
         X0 = X0 + D(I)
   90 CONTINUE
      AVD = X0/XN
      Y0 = 0.0D0
      DO 93 J = 1, M
         Y0 = Y0 + XMAX(J)
   93 CONTINUE
      X0 = DMIN1(X0,Y0)
      X0 = X0 * 1.05D0
      DO 825 J = 1, M1
         XMAX(J) = XMAX(J)*1.05D0
  825 CONTINUE
C
C         CAUTION !!! ASSUMPTION: THAT EACH ELEMENT MOLE RATIO DIVIDED
C         BY THE SUM OF THE RATIOS WILL BE GREATER THAN 0.01;
C         IF = OR < 0.01, THEN MUST USE FOLLOWING ROUTINE;
C         I.E., REMOVE THE 'C' COMMENT FROM COL 1 FROM HERE TO LABEL
C         530 & FROM LABEL 503 TO 475
C         NOTE:  ARRAY K2 IS DIMENSIONED (2)
C
C     L1 = 0
C     NGO5 = 1
C     RATIO = .01D0
C     DO 526 I = 1, N
C        IF ( D(I)/SUM - RATIO ) 527, 527, 526
C 527    L1 = L1 + 1
C        K2(L1) = I
C 526 CONTINUE
C     NL = L1
C     IF (NL) 528, 528, 529
C 528 NGO5 = 1
C     GO TO 530
C 529 NGO5 = 2
C 530 CONTINUE
C
```

```
      ITER4 = 0
      NGO6 = 1
      RH2 = 1.0D0
C
C         END OF ENTRY INITIALIZATION & CHECKING OF TEMPERATURE
C
C         BEGINNING OF MAIN PROGRAM LOOP
C
   99 NGO = 1
      ITER2 = 0
      IF (ITER - 1) 473, 473, 474
  474 RH2 = DSQRT(H2)
      RH2 = DMIN1(RH2,1.0D0)
  473 NGO1 = 1
      DO 101 J = 1, M1
         SUM = C(J)
         DO 1002 I = 1, N
            SUM = SUM + XMU(I)*A(I,J)
 1002    CONTINUE
         CP(J) = SUM
  101 CONTINUE
      DO 1012 J = 1, M1
 1012    CPT(J) = CP(J)
      DO 1001 I = 1, N
 1001    DD(I)= D(I)
      L1 = 0
      SUMEX = 0.0D0
      DO 102 J = 1, M
         J1 = J
         IF (CPT(J) + 30.0D0) 420, 420, 421
  421    XJ = DEXP(-CPT(J))
         SUMEX = SUMEX + XJ
         X(J) = XJ
  102 CONTINUE
      IF (SUMEX - 1.0D0 - TOL1*RH2) 103, 103, 107
  103 IF (SUMEX - 1.0D0 + TOL1*RH2) 112, 104, 104
  104 L1 = 1
      DO 106 I = 1, N
         SUM = 0.0
         DO 105 J = 1, M
  105    SUM = SUM + A(I,J)*X(J)
         F(I,1) = SUM
  106 CONTINUE
      YMAX = X0
      GO TO 123
  420 CPT1 = CPT(J1)
      DO 423 J = 1, M
         J1 = J
         CPT2 = CPT(J) - CPT1
         IF (CPT2 + 30.0D0) 420, 420, 422
  422    X(J) = DEXP(-CPT2)
  423 CONTINUE
```

```
  107 SUM = 0.0D0
      DO 416 J = 1, M
  416    SUM = SUM + X(J)
      SUM= X0/SUM
      DO 108 J = 1, M
  108    X(J) = X(J)*SUM
      DO 109 I = 1, N
         SUM = DD(I)
         DO 110 J = 1, M
  110       SUM = SUM - A(I,J)*X(J)
  109 DD(I) = SUM
      GO TO 123
  112 DO 113 J = 1, M
  113    X(J) = 0.0D0
  123 L = L1
C
C         L = 0 OR 1 ONLY
C
      IF (L) 131, 131, 200
  131 DO 132 I = 1, N
  132    XNU(I) = -DD(I)
      GO TO 23
  430 DO 431 J = 1, M1
         CMN(J) = 0.0D0
         DO 431 I = 1, N
  431       CMN(J) = CMN(J) + XNU(I)*A(I,J)
      COMP = TOL5*TOL5/H2
      XNUD = 0.0D0
      DO 432 I = 1, N
  432    XNUD = XNUD + XNU(I)*D(I)
  446 H = -XNUD
      ITTRDG = ITTRDG + 1
      IF (ITTRDG - 5000) 2358, 2358, 2356
 2356 ISENT = 8
      GO TO 5000
 2358 CONTINUE
      DO 433 J = 1, M1
  433    CPT(J) = CP(J) + T*CMN(J)
      EXMIN = 1.0D10
      DO 510 J = 1, M
         IF (CPT(J) - EXMIN) 511, 510, 510
  511    CONTINUE
         EXMIN = CPT(J)
  510 CONTINUE
      SUMEX = 0.0D0
      DO 513 J = 1, M
         IF (CPT(J) - EXMIN - DIF1) 517, 517, 516
  516    X(J) = 0.0D0
         GO TO 513
  517    X(J) = DEXP(EXMIN - CPT(J))
         SUMEX = SUMEX + X(J)
  513 CONTINUE
```

```
      IF (EXMIN) 521, 521, 519
  519 IF (SUMEX*DEXP(-EXMIN) - 1.0D0) 443, 521, 521
  521 PROD = X0/SUMEX
      DO 522 J = 1, M
  522    H = H + PROD*X(J)*CMN(J)
  443 CONTINUE
      IF (H) 458, 458, 457
  457 T0 = T
      H0 = H
      GO TO (448,459) , NG0
  448 T = T + T
      IF (T - 1.0D15) 446, 446, 908
  908 ISENT = 7
      GO TO 5000
  458 T1 = T
      NG0 = 2
  459 IF (DABS(H/H2) - TOL3) 453, 453, 460
  460 IF ((T1 - T0)**2 - COMP) 453, 453, 452
  452 T = 0.5D0*(T0 + T1)
      GO TO 446
  453 DO 454 I = 1, N
  454    XMU(I) = XMU(I) + T*XNU(I)
      GO TO  99
C
C         L = 1 AT THIS POINT
C
  200 SDUM = 0.0D0
      SUM = 0.0D0
      DO 2 I = 1, N
         SDUM = SDUM + F(I,1)*F(I,1)
    2 SUM = SUM + F(I,1)*DD(I)
      E(1) = SUM/SDUM
      G(1,1) = 0.0D0
      Y1     = 0.0D0
      Z1     = 0.0D0
   71 SUM = E(1) + G(1,1)*Z1
      IF (SUM) 10, 10, 11
   10 Z1 = 0.0D0
      GO TO 8
   11 IF (SUM - YMAX) 471, 471, 472
  472 Z1 = YMAX
      GO TO 8
  471 Z1 = SUM
    8 IF ( DABS(Z1 - Y1) - TOL3 ) 15, 15, 13
   13 Y1 = Z1
      GO TO 71
   15 DO 16 I = 1, N
   16 XNU(I) = -DD(I) + F(I,1)*Z1
      DO 19 J = 1, M
   19 X(J) = X(J)*Z1
C
C         L = 0 OR 1 BELOW THIS POINT
```

```
C
   23 DO 24 I = 1, N
         IF (DABS(XNU(I)) - TOL4*AVD) 24, 24, 25
   24 CONTINUE
      NGO1 = 2
      GO TO 330
   25 GO TO (550,551), NGO6
  551 ITER4 = ITER4 + 1
      IF (L) 550, 550, 814
  814 IF (ITER4 - 20) 550, 552, 552
  552 ITER4 = 0
      NGO1 = 2
      GO TO 330
  550 HO = 0.0D0
      DO 26 I = 1, N
   26    HO = HO + XNU(I)**2
      H2 = HO
      TO = 0.0D0
      T = 1.0D0
      GO TO 330
C
C         SEE COMMENTS ABOVE ( LABEL 527 )
C
  503 CONTINUE
C
C     GO TO (475,476), NGO5
C 476 K = ITER - ( ITER/N )*N
C     IF (K) 531, 532, 531
C 532 K = N
C 531 DO 540 L1 = 1, NL
C        IF(K2(L1) - K) 540, 541, 540
C 540 CONTINUE
C     GO TO 475
C 541 IF (DABS(XNU(K)) - TOL5*D(K)) 475, 475, 542
C 542 IF (DABS(XNU(K)) - 1.D-15) 475, 475, 8000
C8000 SUM = XNU(K)
C     DO 543 I = 1, N
C 543    XNU(I)=0.0D0
C     XNU(K) = SUM
C     HO = SUM*SUM
C     DIF1 = 100.0D0
C     H2 = HO
C     TO = 0.0D0
C     T = 1.0D0
C     GO TO 430
C 475 DIF1 = DIF
C
      GO TO 430
  330 ITER = ITER + 1
      IF (ITER - ITW) 333, 670, 670
  670 ISENT = 4
      GO TO 5079
```

```
C
  333 GO TO (503,500), NGO1
C
  500 NTOT = N + L
      DO 820 I = 1, N
  820    DD(I) = XMU(I)
      DO 821 J = 1, M1
  821    CPT(J) = X(J)
      IF (L) 727, 727, 502
  502 XBAR = Z1
      ITER2 = 1
  750 IF (XBAR) 727, 727, 701
  701 G(N+1,N+1) = 0.0D0
      DO 704 K = 1, M
         SUM = -C(K)
         DO 705 I = 1, N
  705       SUM = SUM - XMU(I)*A(I,K)
         IF (SUM - 30.0D0) 425, 727, 727
  425    X(K) = XBAR*DEXP(SUM)
  704 CONTINUE
      DO 706 I = 1, N
         SUM = 0.0D0
         DO 707 K = 1, M
  707       SUM = SUM + A(I,K)*X(K)
         SUM = SUM/XBAR
         G(I,N + 1) = SUM
         G(N + 1,I) = SUM
         R(I) = D(I) - SUM*XBAR
         DO 706 J = 1, N
             SUM = 0.0D0
             DO 709 K = 1, M
  709           SUM = SUM - A(I,K)*A(J,K)*X(K)
         G(I,J)=SUM
  706 CONTINUE
      SUM = -XBAR
      DO 710 K = 1, M
  710    SUM = SUM + X(K)
      R(N + 1) = SUM/XBAR
      DO 728 I = 1, N
         IF (DABS(R(I)) - TOL6*AVD) 728, 728, 727
  728 CONTINUE
      GO TO 730
  727 DO 903 I = 1, N
         IF (DABS(XNU(I)) - TOL5*D(I)) 903, 903, 801
  903 CONTINUE
      DO 822 I = 1, N
  822    XMU(I) = DD(I)
      DO 823 J = 1, M1
  823    X(J) = CPT(J)
      GO TO 5079
  801 TOL4 = 0.1D0*TOL4
      NGO6 = 2
```

```
      H2 = 1.0D0
      GO TO 99
  730 IPP = NXNSOL(INXNSL,NTOT,G,R)
      IF (IPP - 2) 8001, 727, 8001
 8001 ITER2 = ITER2 + 1
      DO 465 I = 1, N
      IF (DABS(R(I)) - TOL7) 465, 465, 727
  465 CONTINUE
      DO 731 I = 1, NTOT
         IF (DABS(R(I)) - TOL5) 731, 731, 739
  731 CONTINUE
      GO TO 737
  733 DO 734 I = 1, N
  734    XMU(I) = XMU(I) + R(I)
      XBAR = XBAR + R(N + 1)
      GO TO 750
  739 CONTINUE
      IF (ITER2 - ITMAX) 733, 740, 740
  740 ISENT = 5
      GO TO 5000
C
C         TEST IF X(J) NEGATIVE
C
  737 DO 470 J = 1, M1
         IF (X(J)) 801, 470, 470
  470 CONTINUE
C
C    END OF MAIN PROGRAM LOOP
C
 5079 SUMNI = 0.0D0
      DO 5010 I = 1, M
         SUMNI = SUMNI + X(I)
 5010 CONTINUE
      IF (SUMNI) 751, 752, 751
  752 ISENT = 6
      GO TO 5000
  751 CONTINUE
      DO 5011 I = 1, M
 5011    XMOFR(I) = X(I)/SUMNI
C
C         NOTE: ROUTINE TO CHECK FOR A SINGULAR DERIVATIVE MATRIX
C         IN RTP & RPP ARRAYS HAS BEEN REMOVED.
C
      RETURN
C
C         ERROR: SET MOLE FRACTIONS TO 0.
C
 5000 DO 5100 I = 1, ITOTSP
         XMOFR(I) = 0.
 5100 CONTINUE
C
```

```
RETURN
END
```

```
C_____________________________________________________________________
      FUNCTION NXNSOL(IM,IN,A,B)
C
C        THIS FUNCTION IS CALLED BY SUBROUTINE 'PTCHEM'
C
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION A(2),B(2)
      INTEGER XROW
      XROW(K000FX,K001FX) = K001FX*M - M + K000FX
      M = IM
      N = IN
      N1 = N - 1
      DO 44  J = 1, N1
      K = J
      J1 = J + 1
      JJ = XROW(J,J)
      WS1 = DABS(A(JJ))
C
C        LOOP TO FIND LARGEST
C
      DO 11 L = J1, N
         LJ = XROW(L,J)
         WWS1 = DABS(A(LJ))
         IF (WS1-WWS1) 12, 11, 11
   12    WS1 = WWS1
         K = L
   11 CONTINUE
      IF (J-K) 13, 31, 31
C
C        $ IF DIAG NOT LARGEST INTERCHANGE ROWS
C
   13 DO 26   L = J, N
         JL = XROW(J,L)
         KL = XROW(K,L)
         WS1 = A(JL)
         A(JL) = A(KL)
   26 A(KL) = WS1
      WS1 = B(J)
      B(J) = B(K)
      B(K) = WS1
   31 DO 33 L = J1, N
         JL = XROW(J,L)
         IF (A(JJ)) 33, 54, 33
  33   A(JL) = A(JL)/A(JJ)
       B(J) = B(J)/A(JJ)
       DO 43 L = 1, N
          IF (L -J) 37, 43, 37
  37      LJ = XROW(L,J)
  38      DO 41 L2 = J1, N
             LL2 = XROW(L,L2)
             JL2 = XROW(J,L2)
  41      A(LL2) = A(LL2) - A(LJ)*A(JL2)
```

```
         B(L) = B(L) - A(LJ)*B(J)
 43   CONTINUE
 44   CONTINUE
C
C       LAST COLUMN HAS NOT BEEN DONE YET
C
      NN = XROW(N,N)
      IF (A(NN)) 46, 54, 46
   46 B(N) = B(N)/A(NN)
      DO 50 L = 1, N1
         LN = XROW(L,N)
   50 B(L) = B(L) - A(LN)*B(N)
      NXNSOL = 1
      RETURN
   54 NXNSOL = 2
C
      RETURN
      END
```

```
C_____________________________________________________________________
C
C     SUBROUTINE WRITE
C
C     PURPOSE
C        WRITES THE CONTENTS OF DUMMY FILES INTO THE
C        OUTPUT FILE
C
C     USAGE
C        CALL WRITE
C
C     DESCRIPTION OF PARAMETERS
C        NONE
C
C     REMARKS
C        FILE NUMBER    6   IS THE OUTPUT FILE
C        FILE NUMBER   11   IS A DUMMY FILE
C        FILE NUMBER   12   IS A DUMMY FILE
C        FILE NUMBER   13   IS A DUMMY FILE
C        FILE NUMBER   14   IS A DUMMY FILE
C        FILE NUMBER   15   IS A DUMMY FILE
C        FILE NUMBER   16   IS A DUMMY FILE
C     ------------------------------------------------------------
C     FILEDEF 6  DISK OUTPUT DATA A1 (RECFM FB LRECL 132 BLOCK 264
C     FILEDEF 11 DISK DUMMY2 DATA A1 (RECFM FB LRECL 132 BLOCK 264
C     FILEDEF 12 DISK DUMMY3 DATA A1 (RECFM FB LRECL 132 BLOCK 264
C     FILEDEF 13 DISK DUMMY4 DATA A1 (RECFM FB LRECL 132 BLOCK 264
C     FILEDEF 14 DISK DUMMY5 DATA A1 (RECFM FB LRECL 132 BLOCK 264
C     FILEDEF 15 DISK DUMMY6 DATA A1 (RECFM FB LRECL 132 BLOCK 264
C     FILEDEF 16 DISK DUMMY7 DATA A1 (RECFM FB LRECL 132 BLOCK 264
C     ------------------------------------------------------------
C
C     SUBROUTINE AND FUNCTION SUBPROGRAMS REQUIRED
C        NONE
C
C     WRITTEN BY S. H. MANSOURI
C     EDITED BY S. H. MANSOURI AND S. G. POULOS
C
      SUBROUTINE WRITE
C
      INTEGER*2 I
      DIMENSION I(66), IR(6)
      COMMON/HTRC/ CONHT, EXPHT
      DATA IR /14, 15, 16, 11, 12, 13/
C
      N = 9
      WRITE (11,10) N
      WRITE (12,10) N
      WRITE (13,10) N
      WRITE (14,10) N
      WRITE (15,10) N
      WRITE (16,10) N
```

```
      REWIND 11
      REWIND 12
      REWIND 13
      REWIND 14
      REWIND 15
      REWIND 16
   10 FORMAT (1I1)
      DO 50 K = 1, 6
           IF ((CONHT .LE. 0.0) .AND. (K .EQ. 6)) GO TO 50
           IREAD = IR(K)
   20      READ (IREAD,30) L, (I(J), J = 1, 65)
   30      FORMAT (1I1,65A2)
   40      FORMAT (1H ,65A2)
           IF (L .NE. 1) WRITE (6,40) (I(J), J = 1, 65)
           IF (L .EQ. 1) WRITE (6,30) L, (I(J), J = 1, 65)
           IF (L .EQ. 9) GO TO 50
           GO TO 20
   50 CONTINUE
C
      RETURN
      END
```

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

```
C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
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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
```

```
C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
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C   *                                                                     *
C   * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C
C   WRITTEN BY L. F. SHAMPINE AND M. K. GORDON
C
C   ABSTRACT
C
C
C   THE METHODS IN SUBROUTINE  STEP1  APPROXIMATE THE SOLUTION NEAR  X
C   BY A POLYNOMIAL.  SUBROUTINE  INTRP  APPROXIMATES THE SOLUTION AT
C   XOUT  BY EVALUATING THE POLYNOMIAL THERE.  INFORMATION DEFINING THIS
C   POLYNOMIAL IS PASSED FROM  STEP1  SO  INTRP  CANNOT BE USED ALONE.
C
C   THIS CODE IS COMPLETELY EXPLAINED AND DOCUMENTED IN THE TEXT,
C   COMPUTER SOLUTION OF ORDINARY DIFFERENTIAL EQUATIONS, THE INITIAL
C   VALUE PROBLEM  BY L. F. SHAMPINE AND M. K. GORDON.
C   FURTHER DETAILS ON USE OF THIS CODE ARE AVAILABLE IN *SOLVING
C   ORDINARY DIFFERENTIAL EQUATIONS WITH ODE, STEP, AND INTRP*,
C   BY L. F. SHAMPINE AND M. K. GORDON, SLA-73-1060.
C
C   INPUT TO INTRP --
C
```

```
C   THE USER PROVIDES STORAGE IN THE CALLING PROGRAM FOR THE ARRAYS IN
C   THE CALL LIST
C      DIMENSION Y(NEQN),YOUT(NEQN),YPOUT(NEQN),PHI(NEQN,16),PSI(12)
C   AND DEFINES
C      XOUT -- POINT AT WHICH SOLUTION IS DESIRED.
C   THE REMAINING PARAMETERS ARE DEFINED IN  STEP1  AND PASSED TO
C   INTRP  FROM THAT SUBROUTINE
C
C   OUTPUT FROM  INTRP --
C
C      YOUT(*) -- SOLUTION AT  XOUT
C      YPOUT(*) -- DERIVATIVE OF SOLUTION AT  XOUT
C   THE REMAINING PARAMETERS ARE RETURNED UNALTERED FROM THEIR INPUT
C   VALUES.  INTEGRATION WITH  STEP1  MAY BE CONTINUED.
C
      SUBROUTINE INTRP(X,Y,XOUT,YOUT,YPOUT,NEQN,KOLD,PHI,PSI)
      IMPLICIT REAL *8 (A-H,O-Z)
C
C
      GENERIC
      DIMENSION Y(20),YOUT(20),YPOUT(20),PHI(20,16),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 * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
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C  *                                                                     *
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C  *                                                                     *
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),...,Y(NEQN))
C             Y(I) GIVEN AT T.
C   THE SUBROUTINE INTEGRATES FROM  T  IN THE DIRECTION OF  TOUT  UNTIL
C   IT LOCATES THE FIRST ROOT OF THE NONLINEAR EQUATION
C         G(T,Y(1),...,Y(NEQN),YP(1),...,YP(NEQN)) = 0.
C   UPON FINDING THE ROOT, THE CODE RETURNS WITH ALL PARAMETERS IN THE
C   CALL LIST SET FOR CONTINUING THE INTEGRATION TO THE NEXT ROOT OR
C   THE FIRST ROOT OF A NEW FUNCTION  G  .  IF NO ROOT IS FOUND, THE
C   INTEGRATION PROCEEDS TO  TOUT .  AGAIN ALL PARAMETERS ARE SET TO
C   CONTINUE.
C
```

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

```
C      REROOT, AEROOT -- RELATIVE AND ABSOLUTE ERROR TOLERANCES FOR
C           ACCEPTING THE ROOT.  THE INTERVAL CONTAINING THE ROOT IS
C           REDUCED UNTIL IT SATISFIES
C            0.5*ABS(LENGTH OF INTERVAL) .LE. REROOT*ABS(ROOT)+AEROOT
C           WHERE ROOT IS THAT ENDPOINT YIELDING THE SMALLER VALUE OF
C           G  IN MAGNITUDE.  PURE RELATIVE ERROR IS NOT RECOMMENDED
C           IF THE ROOT MIGHT BE ZERO.
C*********************************************************************
C   FIRST CALL TO  ODERT --
C*********************************************************************
C   THE USER MUST PROVIDE STORAGE IN HIS CALLING PROGRAM FOR THE
C   ARRAYS IN THE CALL LIST,
C              Y(NEQN), WORK(100+21*NEQN), IWORK(5)
C   AND DECLARE  F , G  IN AN EXTERNAL STATEMENT.  HE MUST SUPPLY THE
C   SUBROUTINE  F(T,Y,YP)  TO EVALUATE
C           DY(I)/DT = YP(I) = F(T,Y(1),...,Y(NEQN))
C   AND THE FUNCTION  G(T,Y,YP)  TO EVALUATE
C           G = G(T,Y(1),...,Y(NEQN),YP(1),...,YP(NEQN)).
C   NOTE THAT THE ARRAY YP IS AN INPUT ARGUMENT AND SHOULD NOT BE
C   COMPUTED IN THE FUNCTION SUBPROGRAM.  FINALLY THE USER MUST
C   INITIALIZE THE PARAMETERS
C      NEQN -- NUMBER OF EQUATIONS TO BE INTEGRATED
C      Y(*) -- VECTOR OF INITIAL CONDITIONS
C      T -- STARTING POINT OF INTEGRATION
C      TOUT -- ARBITRARY POINT BEYOND THE ROOT DESIRED
C      RELERR,ABSERR -- RELATIVE AND ABSOLUTE LOCAL ERROR TOLERANCES
C                       FOR INTEGRATING THE EQUATIONS
C      IFLAG -- +1,-1.  INDICATOR TO INITIALIZE THE CODE.  NORMAL INPUT
C           IS +1.  THE USER SHOULD SET IFLAG=-1 ONLY IF IT IS
C           IMPOSSIBLE TO CONTINUE THE INTEGRATION BEYOND  TOUT .
C      REROOT,AEROOT -- RELATIVE AND ABSOLUTE ERROR TOLERANCES FOR
C                       COMPUTING THE ROOT OF  G
C
C   ALL PARAMETERS EXCEPT F, G, NEQN, TOUT, REROOT AND AEROOT MAY BE
C   ALTERED BY THE CODE ON OUTPUT SO MUST BE VARIABLES IN THE CALLING
C   PROGRAM.
C*********************************************************************
C   OUTPUT FROM  ODERT --
C*********************************************************************
C      NEQN -- UNCHANGED
C      Y(*) -- SOLUTION AT  T
C      T -- LAST POINT REACHED IN INTEGRATION.  NORMAL RETURN HAS
C           T = TOUT OR T = ROOT
C      TOUT -- UNCHANGED
C      RELERR,ABSERR -- NORMAL RETURN HAS TOLERANCES UNCHANGED.  IFLAG=3
C           SIGNALS TOLERANCES INCREASED
C      IFLAG = 2 -- NORMAL RETURN.  INTEGRATION REACHED  TOUT
C            = 3 -- INTEGRATION DID NOT REACH  TOUT  BECAUSE ERROR
C                   TOLERANCES TOO SMALL.  RELERR ,  ABSERR  INCREASED
C                   APPROPRIATELY FOR CONTINUING
C            = 4 -- INTEGRATION DID NOT REACH  TOUT  BECAUSE MORE THAN
C                   500 STEPS NEEDED
```

```
C            = 5 -- INTEGRATION DID NOT REACH  TOUT  BECAUSE EQUATIONS
C                   APPEAR TO BE STIFF
C            = 6 -- INTEGRATION DID NOT REACH  TOUT  BECAUSE SOLUTION
C                   VANISHED MAKING PURE RELATIVE ERROR IMPOSSIBLE.
C                   MUST USE NON-ZERO  ABSERR  TO CONTINUE
C            = 7 -- INVALID INPUT PARAMETERS (FATAL ERROR)
C            = 8 -- NORMAL RETURN.  A ROOT WAS FOUND WHICH SATISFIED
C                   THE ERROR CRITERION OR HAD A ZERO RESIDUAL
C            = 9 -- ABNORMAL RETURN.  AN ODD ORDER POLE OF  G  WAS
C                   FOUND.
C            =10 -- ABNORMAL RETURN.  TOO MANY EVALUATIONS OF  G  WERE
C                   REQUIRED (AS PROGRAMMED 500 ARE ALLOWED.)
C           THE VALUE OF  IFLAG  IS RETURNED NEGATIVE WHEN THE INPUT
C           VALUE IS NEGATIVE AND THE INTEGRATION DOES NOT REACH
C           TOUT , I.E., -3,...,-6,-8,-9,-10.
C      WORK(*),IWORK(*) -- INFORMATION GENERALLY OF NO INTEREST TO THE
C                          USER BUT NECESSARY FOR SUBSEQUENT CALLS
C      REROOT,AEROOT -- UNCHANGED
C*********************************************************************
C   SUBSEQUENT CALLS TO  ODERT --
C*********************************************************************
C   SUBROUTINE  ODERT  RETURNS WITH ALL INFORMATION NEEDED TO CONTINUE
C   THE INTEGRATION.  IF THE INTEGRATION DID NOT REACH  TOUT  AND THE
C   USER WANTS TO CONTINUE, HE JUST CALLS AGAIN.  IF THE INTEGRATION
C   REACHED  TOUT , THE USER NEED ONLY DEFINE A NEW  TOUT  AND CALL
C   AGAIN.  THE OUTPUT VALUE OF  IFLAG  IS THE APPROPRIATE INPUT VALUE
C   FOR SUBSEQUENT CALLS.  THE ONLY SITUATION IN WHICH IT SHOULD BE
C   ALTERED IS TO STOP THE INTEGRATION INTERNALLY AT THE NEW  TOUT ,
C   I.E., CHANGE OUTPUT  IFLAG=2  TO INPUT  IFLAG=-2 .  ONLY THE ERROR
C   TOLERANCES AND THE FUNCTION  G  MAY BE CHANGED BY THE USER BEFORE
C   CONTINUING.  ALL OTHER PARAMETERS MUST REMAIN UNCHANGED.  A NEW
C   FUNCTION  G  IS DETECTED AUTOMATICALLY.
C
      SUBROUTINE ODERT(F,NEQN,Y,T,TOUT,RELERR,ABSERR,IFLAG,WORK,IWORK,
     1  G,REROOT,AEROOT)
      IMPLICIT REAL*8 (A-H,O-Z)
C
C
      GENERIC
      LOGICAL START,PHASE1,NORND
      DIMENSION Y(20),WORK(520),IWORK(5)
      EXTERNAL F,G
      DATA IALPHA,IBETA,ISIG,IV,IW,IGG,IPHASE,IPSI,IX,IH,IHOLD,ISTART,
     1  ITOLD,IDELSN,IGX,ITROOT/1,13,25,38,50,62,75,76,88,89,90,91,
     2  92,93,94,95/
      IYY = 100
      IWT = IYY + NEQN
      IP = IWT + NEQN
      IYP = IP + NEQN
      IYPOUT = IYP + NEQN
      IPHI = IYPOUT + NEQN
      IF(IABS(IFLAG) .EQ. 1) GO TO 1
```

```
      START = WORK(ISTART) .GT. 0.0
      PHASE1 = WORK(IPHASE) .GT. 0.0
      NORND = IWORK(2) .NE. -1
1     CALL DERT1(F,NEQN,Y,T,TOUT,RELERR,ABSERR,IFLAG,G,REROOT,AEROOT,
     1  WORK(IYY),WORK(IWT),WORK(IP),WORK(IYP),WORK(IYPOUT),WORK(IPHI),
     2  WORK(IALPHA),WORK(IBETA),WORK(ISIG),WORK(IV),WORK(IW),WORK(IGG),
     3  PHASE1,WORK(IPSI),WORK(IX),WORK(IH),WORK(IHOLD),START,
     4  WORK(ITOLD),WORK(IDELSN),WORK(IGX),WORK(ITROOT),IWORK(1),
     5  NORND,IWORK(3),IWORK(4),IWORK(5))
      WORK(ISTART) = -1.0
      IF(START) WORK(ISTART) = 1.0
      WORK(IPHASE) = -1.0
      IF(PHASE1) WORK(IPHASE) = 1.0
      IWORK(2) = -1
      IF(NORND) IWORK(2) = 1
      RETURN
      END
```

```
C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C
      SUBROUTINE DERT1(F,NEQN,Y,T,TOUT,RELERR,ABSERR,IFLAG,G,REROOT,
     1  AEROOT,YY,WT,P,YP,YPOUT,PHI,ALPHA,BETA,SIG,V,W,GG,PHASE1,PSI,
     2  X,H,HOLD,START,TOLD,DELSGN,GX,TROOT,NS,NORND,K,KOLD,ISNOLD)
C ***NAME CHANGED FROM DERT TO DERT1 TO AVOID A NAMING CONFLICT.
C
C   ODERT  MERELY ALLOCATES STORAGE FOR  DERT  TO RELIEVE THE USER OF
C   THE INCONVENIENCE OF A LONG CALL LIST.  CONSEQUENTLY  DERT  IS USED
C   AS DESCRIBED IN THE COMMENTS FOR  ODERT .
C
C   THE CODES STEP, INTRP AND ROOT AND THAT PORTION OF DERT DIRECTING
C   THE INTEGRATION ARE COMPLETELY EXPLAINED AND DOCUMENTED IN THE TEXT,
C   COMPUTER SOLUTION OF ORDINARY DIFFERENTIAL EQUATIONS, THE INITIAL
C   VALUE PROBLEM BY L. F. SHAMPINE AND M. K. GORDON.
C
      IMPLICIT REAL*8 (A-H,O-Z)
C
      GENERIC
      LOGICAL STIFF,CRASH,START,PHASE1,NORND
      DIMENSION Y(20),YY(20),WT(20),PHI(20,16),P(20),YP(20),
     1  YPOUT(20),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
C            ***            ***            ***
C
C   TEST FOR IMPROPER PARAMETERS
C
      IF(IABS(IFLAG) .EQ. 7) CALL ERRCHK(-31,
     1  31HIN ODERT, ENTERED WITH IFLAG=7.)
      IF(NEQN .LT. 1) CALL ERRCHK(32,
     1  32HIN ODERT, NEQN MUST BE POSITIVE.)
      IF(NEQN .LT. 1) GO TO 10
      IF(T .EQ. TOUT) CALL ERRCHK(61,
     1 61HIN ODERT, ENDPOINTS OF INTEGRATION INTERVAL MUST BE DISTINCT.)
```

```
      IF(T .EQ. TOUT) GO TO 10
      IF(RELERR .LT. 0.0  .OR.  ABSERR .LT. 0.0)  CALL ERRCHK(49,
     1  49HIN ODERT, RELERR AND ABSERR MUST BE NON-NEGATIVE.)
      IF(RELERR .LT. 0.0  .OR.  ABSERR .LT. 0.0) GO TO 10
      EPS = MAX(RELERR,ABSERR)
      IF(EPS .LE. 0.0) CALL ERRCHK(51,
     1  51HIN ODERT, EITHER RELERR OR ABSERR MUST BE POSITIVE.)
      IF(EPS .LE. 0.0) GO TO 10
      IF(REROOT .LT. 0.0  .OR.  AEROOT .LT. 0.0) CALL ERRCHK(49,
     1  49HIN ODERT, REROOT AND AEROOT MUST BE NON-NEGATIVE.)
      IF(REROOT .LT. 0.0  .OR.  AEROOT .LT. 0.0) GO TO 10
      IF(REROOT+AEROOT .LE. 0.0) CALL ERRCHK(51,
     1  51HIN ODERT, EITHER REROOT OR AEROOT MUST BE POSITIVE.)
      IF(REROOT+AEROOT .LE. 0.0) GO TO 10
      IF(IFLAG .EQ. 0) CALL ERRCHK(34,
     1  34HIN ODERT, INVALID INPUT FOR IFLAG.)
      IF(IFLAG .EQ. 0) GO TO 10
      ISN = ISIGN(1,IFLAG)
      IFLAG = IABS(IFLAG)
      IF(IFLAG .EQ. 1) GO TO 20
      IF(T .NE. TOLD) CALL ERRCHK(68,
     1  68HIN ODERT, INPUT VALUE OF T MUST BE OUTPUT VALUE FROM PRECEDIN
     2G CALL.)
      IF(T .NE. TOLD) GO TO 10
      IF(IFLAG .GE. 2  .AND.  IFLAG .LE. 6) GO TO 15
      IF(IFLAG .GE. 8  .AND.  IFLAG .LE. 10) GO TO 15
      CALL ERRCHK(-34,34HIN ODERT, INVALID INPUT FOR IFLAG.)
   10 IFLAG = 7
      RETURN
C
15    CONTINUE
      IF (ISNOLD.LT.0 .OR. DELSGN*(TOUT-T).LT.0.) GO TO 20
C--      EVALUATE  G  AT EITHER TOUT (OUTPUT POINT THIS CALL)  OR AT
C--         X (POINT TO WHICH INTERNAL INTEGRATION HAS ALREADY
C--         PROCEEDED), WHICHEVER OCCURS FIRST.
      T2=X
      IF((X-T.GT.0..AND.X-TOUT.GT.0.).OR.(X-T.LT.0..AND.X-TOUT.LT.0.))
     1            T2=TOUT
      CALL INTRP(X,YY,T2,Y,YPOUT,NEQN,KOLD,PHI,PSI)
      GOFT2=G(T2,Y,YPOUT)
C--   NOW EVALUATE AT T1=T
      T1=T
      CALL INTRP(X,YY,T1,Y,YPOUT,NEQN,KOLD,PHI,PSI)
      GOFT1=G(T1,Y,YPOUT)
C--      NOW SEE IF A ROOT OF  G  OCCURS IN CLOSED INTERVAL (T1,T2).
      IF( GOFT1.EQ.0. .OR. GOFT2.EQ.0.)              GO TO 134
      IF( SIGN(1.D0,GOFT1)  * SIGN(1.D0,GOFT2) .LT. 0.D0 ) GO TO 134
                GO TO 21
C
C   ON EACH CALL SET INTERVAL OF INTEGRATION AND COUNTER FOR NUMBER OF
C   STEPS.  ADJUST INPUT ERROR TOLERANCES TO DEFINE WEIGHT VECTOR FOR
C   SUBROUTINE  STEP
```

```
C
20    T2=T
      CALL F(T2,Y,YPOUT)
      GOFT2 = G(T2,Y,YPOUT)
   21 CONTINUE
      DEL = TOUT - T
      ABSDEL = ABS(DEL)
      TEND = T + 10.0*DEL
      IF(ISN .LT. 0) TEND = TOUT
      NOSTEP = 0
      KLE4 = 0
      STIFF = .FALSE.
      RELEPS = RELERR/EPS
      ABSEPS = ABSERR/EPS
      IF(IFLAG .EQ. 1) GO TO 30
      IF(ISNOLD .LT. 0) GO TO 30
      IF(DELSGN*DEL .GT. 0.0) GO TO 50
C
C   ON START AND RESTART ALSO SET WORK VARIABLES X AND YY(*), STORE THE
C   DIRECTION OF INTEGRATION, AND INITIALIZE THE STEP SIZE.
C
   30 START = .TRUE.
      X = T
      TROOT = T
      DO 40 L = 1,NEQN
   40   YY(L) = Y(L)
      DELSGN = SIGN(1.0D0,DEL)
      H = SIGN(MAX(ABS(TOUT-X),FOURU*ABS(X)),TOUT-X)
C
C   IF ALREADY PAST OUTPUT POINT, INTERPOLATE AND RETURN
C
50    CONTINUE
      IF(ABS(X-T) .LT. ABSDEL) GO TO 60
      CALL INTRP(X,YY,TOUT,Y,YPOUT,NEQN,KOLD,PHI,PSI)
      IFLAG = 2
      T = TOUT
      TOLD = T
      ISNOLD = ISN
      RETURN
C
C   IF CANNOT GO PAST OUTPUT POINT AND SUFFICIENTLY CLOSE,
C   EXTRAPOLATE AND RETURN
C
   60 IF(ISN .GT. 0  .OR.  ABS(TOUT-X) .GE. FOURU*ABS(X)) GO TO 80
      H = TOUT - X
      CALL F(X,YY,YP)
      DO 70 L = 1,NEQN
   70   Y(L) = YY(L) + H*YP(L)
C *** NEXT STMT ADDED BY LIENESCH TO ENSURE YPOUT VALUES WILL ALWAYS BE
C *** AVAILABLE UNDER ANY CIRCUMSTANCES
      CALL F(X,Y,YPOUT)
      IFLAG = 2
```

```
      T = TOUT
      TOLD = T
      ISNOLD = ISN
      RETURN
C
C   TEST FOR TOO MUCH WORK
C
   80 IF(NOSTEP .LT. MAXNUM) GO TO 100
      IFLAG = ISN*4
      IF(STIFF) IFLAG = ISN*5
      DO 90 L = 1,NEQN
   90   Y(L) = YY(L)
      T = X
      TOLD = T
      ISNOLD = 1
      RETURN
C
C   LIMIT STEP SIZE, SET WEIGHT VECTOR AND TAKE A STEP
C
  100 H = SIGN(MIN(ABS(H),ABS(TEND-X)),H)
      DO 110 L = 1,NEQN
        WT(L) = RELEPS*ABS(YY(L)) + ABSEPS
        IF(WT(L) .LE. 0.0) GO TO 160
  110 CONTINUE
      CALL STEP1(F,NEQN,YY,X,H,EPS,WT,START,
     1  HOLD,K,KOLD,CRASH,PHI,P,YP,PSI,
     2  ALPHA,BETA,SIG,V,W,GG,PHASE1,NS,NORND)
C
C   TEST FOR TOLERANCES TOO SMALL.  IF SO, SET THE DERIVATIVE AT X
C   BEFORE RETURNING
C
      IF(.NOT.CRASH) GO TO 130
      IFLAG = ISN*3
      RELERR = EPS*RELEPS
      ABSERR = EPS*ABSEPS
      DO 120 L = 1,NEQN
        YP(L) = PHI(L,1)
  120   Y(L) = YY(L)
      T = X
      TOLD = T
      ISNOLD = 1
      RETURN
C
C   AUGMENT COUNTER ON WORK AND TEST FOR STIFFNESS.  ALSO TEST FOR A
C   ROOT IN THE STEP JUST COMPLETED
C
  130 NOSTEP = NOSTEP + 1
      KLE4 = KLE4 + 1
      IF(KOLD .GT. 4) KLE4 = 0
      IF(KLE4 .GE. 50) STIFF = .TRUE.
      T1=T2
      GOFT1=GOFT2
```

```
      T2=TOUT
C--     EVALUATE G AT INTERNAL INTEGRATION POINT X UNLESS X IS PAST TOUT
C--     IF X IS PAST TOUT EVALUATE G AT TOUT.
      IF( ABS(X-T).LT.ABSDEL) T2=X
      CALL INTRP(X,YY,T2,Y,YPOUT,NEQN,KOLD,PHI,PSI)
      GOFT2=G(T2,Y,YPOUT)
      IF(GOFT1.EQ.0. .OR. GOFT2.EQ.0.) GO TO 134
      IF( SIGN(1.D0,GOFT1)*SIGN(1.0D0,GOFT2) .LT.0.D0)GO TO 134
      GO TO 50
C
C   LOCATE ROOT OF G.  INTERPOLATE WITH  INTRP  FOR SOLUTION AND
C   DERIVATIVE VALUES
C
134   JFLAG=1
C--     HERE ROOT IS BETWEEN  T1 AND T2
      B=T1
      IF(GOFT1.EQ.0.)GO TO 150
      B=T2
      IF(GOFT2.EQ.0.)GO TO 150
      C=T1
  140 CALL ROOT(T,GT,B,C,REROOT,AEROOT,JFLAG)
      IF(JFLAG .GT. 0) GO TO 150
        IF( T.EQ.T1)GT=GOFT1
        IF( T.EQ.T2)GT=GOFT2
        IF( T.EQ.T1 .OR.T.EQ.T2)GO TO 140
      CALL INTRP(X,YY,T,Y,YPOUT,NEQN,KOLD,PHI,PSI)
      GT = G(T,Y,YPOUT)
      GO TO 140
  150 CONTINUE
      IFLAG = JFLAG+7
      IF(JFLAG .EQ. 2  .OR.  JFLAG .EQ. 4) IFLAG = 8
      IF(JFLAG .EQ. 3) IFLAG = 9
      IF(JFLAG .EQ. 5) IFLAG = 10
      IFLAG = IFLAG*ISN
      CALL INTRP(X,YY,B,Y,YPOUT,NEQN,KOLD,PHI,PSI)
      T = B
      IF(ABS(T-TROOT) .LE. REROOT*ABS(T) + AEROOT) GO TO 50
      TROOT = T
      TOLD = T
      ISNOLD = 1
      RETURN
  160 CALL ERRCHK(72,72HIN ODERT, PURE ABSOLUTE ERROR IMPOSSIBLE.  USE N
     1ON-ZERO VALUE OF ABSERR.)
      IFLAG = 6
      RETURN
      END
```

```
C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C
C  ROOT COMPUTES A ROOT OF THE NONLINEAR EQUATION F(X)=0
C  WHERE F(X) IS A CONTINUOUS REAL FUNCTION OF A SINGLE REAL
C  VARIABLE X.  THE METHOD USED IS A COMBINATION OF BISECTION
C  AND THE SECANT RULE.
C
C  NORMAL INPUT CONSISTS OF A CONTINUOUS FUNCTION F AND AN
C  INTERVAL (B,C) SUCH THAT F(B)*F(C).LE.0.0.  EACH ITERATION
C  FINDS NEW VALUES OF B AND C SUCH THAT THE INTERVAL (B,C) IS
C  SHRUNK AND F(B)*F(C).LE.0.0.  THE STOPPING CRITERION IS
C
C          ABS(B-C).LE.2.0*(RELERR*ABS(B)+ABSERR)
C
C  WHERE RELERR=RELATIVE ERROR AND ABSERR=ABSOLUTE ERROR ARE
C  INPUT QUANTITIES.  SET THE FLAG, IFLAG, POSITIVE TO INITIALIZE
C  THE COMPUTATION.  AS B,C AND IFLAG ARE USED FOR BOTH INPUT AND
C  OUTPUT, THEY MUST BE VARIABLES IN THE CALLING PROGRAM.
C
C  IF 0 IS A POSSIBLE ROOT, ONE SHOULD NOT CHOOSE ABSERR=0.0.
C
C  THE OUTPUT VALUE OF B IS THE BETTER APPROXIMATION TO A ROOT
C  AS B AND C ARE ALWAYS REDEFINED SO THAT ABS(F(B)).LE.ABS(F(C)).
C
C  TO SOLVE THE EQUATION, ROOT MUST EVALUATE F(X) REPEATEDLY. THIS
C  IS DONE IN THE CALLING PROGRAM.  WHEN AN EVALUATION OF F IS
C  NEEDED AT T, ROOT RETURNS WITH IFLAG NEGATIVE.  EVALUATE FT=F(T)
C  AND CALL ROOT AGAIN.  DO NOT ALTER IFLAG.
C
C  WHEN THE COMPUTATION IS COMPLETE, ROOT RETURNS TO THE CALLING
C  PROGRAM WITH IFLAG POSITIVE.
C
C     IFLAG=1  IF F(B)*F(C).LT.0 AND THE STOPPING CRITERION IS MET.
C
C          =2  IF A VALUE B IS FOUND SUCH THAT THE COMPUTED VALUE
C              F(B) IS EXACTLY ZERO.  THE INTERVAL (B,C) MAY NOT
C              SATISFY THE STOPPING CRITERION.
C
C          =3  IF ABS(F(B)) EXCEEDS THE INPUT VALUES ABS(F(B)),
C              ABS(F(C)).   IN THIS CASE IT IS LIKELY THAT B IS CLOSE
C              TO A POLE OF F.
C
C          =4  IF NO ODD ORDER ROOT WAS FOUND IN THE INTERVAL.  A
C              LOCAL MINIMUM MAY HAVE BEEN OBTAINED.
C
C          =5  IF TOO MANY FUNCTION EVALUATIONS WERE MADE.
C              (AS PROGRAMMED, 500 ARE ALLOWED.)
C
C  THIS CODE IS A MODIFICATION OF THE CODE  ZEROIN  WHICH IS COMPLETELY
C  EXPLAINED AND DOCUMENTED IN THE TEXT, NUMERICAL COMPUTING, AN
C  INTRODUCTION  BY L. F. SHAMPINE AND R. C. ALLEN.
C
```

```
      SUBROUTINE ROOT(T,FT,B,C,RELERR,ABSERR,IFLAG)
C
      IMPLICIT REAL*8 (A-H,O-Z)
      GENERIC
      COMMON/MLDRT/A,ACBS,AE,FA,FB,FC,FX,IC,KOUNT,RE
C*****************************************************************************
C*  THE ONLY MACHINE DEPENDENT CONSTANT IS BASED ON THE MACHINE UNIT         *
C*  ROUNDOFF ERROR  U  WHICH IS THE SMALLEST POSITIVE NUMBER SUCH THAT       *
C*  1.0+U .GT. 1.0 .  U  MUST BE CALCULATED AND INSERTED IN THE              *
C*  FOLLOWING DATA STATEMENT BEFORE USING  ROOT .  THE ROUTINE  MACHIN       *
C*  CALCULATES  U .                                                          *
C*****************************************************************************
      DATA U /2.2E-16/
C*****************************************************************************
C
      IF(IFLAG.LT.0.0) GO TO 100
      RE=MAX(RELERR,U)
      AE=MAX(ABSERR,0.0D0)
      IC=0
      ACBS=ABS(B-C)
      A=C
      T=A
      IFLAG=-1
      RETURN
  100 IFLAG=IABS(IFLAG)
      GO TO (200,300,400),IFLAG
  200 FA=FT
      T=B
      IFLAG=-2
      RETURN
  300 FB=FT
      FC=FA
      KOUNT=2
      FX=MAX(ABS(FB),ABS(FC))
      GO TO 1
  400 FB=FT
      IF(FB.EQ.0.0) GO TO 9
      KOUNT=KOUNT+1
      IF(SIGN(1.0D0,FB).NE.SIGN(1.0D0,FC))GO TO 1
      C=A
      FC=FA
    1 IF(ABS(FC).GE.ABS(FB))GO TO 2
C
C  INTERCHANGE B AND C SO THAT ABS(F(B)).LE.ABS(F(C)).
C
      A=B
      FA=FB
      B=C
      FB=FC
      C=A
      FC=FA
    2 CMB=0.5*(C-B)
```

```
      ACMB=ABS(CMB)
      TOL=RE*ABS(B)+AE
C
C  TEST STOPPING CRITERION AND FUNCTION COUNT.
C
      IF(ACMB.LE.TOL)GO TO 8
      IF(KOUNT.GE.500)GO TO 12
C
C  CALCULATE NEW ITERATE IMPLICITLY AS B+P/Q
C  WHERE WE ARRANGE P.GE.0.  THE IMPLICIT
C  FORM IS USED TO PREVENT OVERFLOW.
C
      P=(B-A)*FB
      Q=FA-FB
      IF(P.GE.0.0)GO TO 3
      P=-P
      Q=-Q
C
C  UPDATE A, CHECK IF REDUCTION IN THE SIZE OF BRACKETING
C  INTERVAL IS SATISFACTORY.  IF NOT, BISECT UNTIL IT IS.
C
    3 A=B
      FA=FB
      IC=IC+1
      IF(IC.LT.4)GO TO 4
      IF(8.0*ACMB.GE.ACBS)GO TO 6
      IC=0
      ACBS=ACMB
C
C  TEST FOR TOO SMALL A CHANGE.
C
    4 IF(P.GT.ABS(Q)*TOL)GO TO 5
C
C  INCREMENT BY TOLERANCE.
C
      B=B+SIGN(TOL,CMB)
      GO TO 7
C
C  ROOT OUGHT TO BE BETWEEN B AND (C+B)/2.
C
    5 IF(P.GE.CMB*Q)GO TO 6
C
C  USE SECANT RULE.
C
      B=B+P/Q
      GO TO 7
C
C  USE BISECTION.
C
    6 B=0.5*(C+B)
C
C  HAVE COMPLETED COMPUTATION FOR NEW ITERATE B.
```

```
C
    7 T=B
      IFLAG=-3
      RETURN
C
C  FINISHED.  SET IFLAG.
C
    8 IF(SIGN(1.0D0,FB).EQ.SIGN(1.0D0,FC))GO TO 11
      IF(ABS(FB).GT.FX)GO TO 10
      IFLAG=1
      RETURN
    9 IFLAG=2
      RETURN
   10 IFLAG=3
      RETURN
   11 IFLAG=4
      RETURN
   12 IFLAG=5
      RETURN
      END
```

```
C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C
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
C   * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C   *                                                                     *
C   *                 ISSUED BY SANDIA LABORATORIES,                      *
C   *                   A PRIME CONTRACTOR TO THE                         *
C   *   UNITED STATES ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION      *
C   *                                                                     *
C   * * * * * * * * * * * * * * *  NOTICE  * * * * * * * * * * * * * * * *
C   *
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C   *
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   SUBROUTINE  STEP1  IS NORMALLY USED INDIRECTLY THROUGH SUBROUTINE
C   ODE .  BECAUSE  ODE  SUFFICES FOR MOST PROBLEMS AND IS MUCH EASIER
C   TO USE, USING IT SHOULD BE CONSIDERED BEFORE USING  STEP1  ALONE.
C
C   SUBROUTINE STEP1 INTEGRATES A SYSTEM OF  NEQN  FIRST ORDER ORDINARY
C   DIFFERENTIAL EQUATIONS ONE STEP, NORMALLY FROM X TO X+H, USING A
C   MODIFIED DIVIDED DIFFERENCE FORM OF THE ADAMS PECE FORMULAS.  LOCAL
C   EXTRAPOLATION IS USED TO IMPROVE ABSOLUTE STABILITY AND ACCURACY.
C   THE CODE ADJUSTS ITS ORDER AND STEP SIZE TO CONTROL THE LOCAL ERROR
C   PER UNIT STEP IN A GENERALIZED SENSE.  SPECIAL DEVICES ARE INCLUDED
C   TO CONTROL ROUNDOFF ERROR AND TO DETECT WHEN THE USER IS REQUESTING
C   TOO MUCH ACCURACY.
C
C   THIS CODE IS COMPLETELY EXPLAINED AND DOCUMENTED IN THE TEXT,
C   COMPUTER SOLUTION OF ORDINARY DIFFERENTIAL EQUATIONS, THE INITIAL
```

```
C   VALUE PROBLEM  BY L. F. SHAMPINE AND M. K. GORDON.
C   FURTHER DETAILS ON USE OF THIS CODE ARE AVAILABLE IN *SOLVING
C   ORDINARY DIFFERENTIAL EQUATIONS WITH ODE, STEP, AND INTRP*,
C   BY L. F. SHAMPINE AND M. K. GORDON, SLA-73-1060.
C
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(NEQN),WT(NEQN),PHI(NEQN,16),P(NEQN),YP(NEQN),PSI(12),
C    1  ALPHA(12),BETA(12),SIG(13),V(12),W(12),G(13)
C                                --                --    **NOTE**
C
C   THE USER MUST ALSO DECLARE  START ,  CRASH ,  PHASE1  AND  NORND
C   LOGICAL VARIABLES AND  F  AN EXTERNAL SUBROUTINE, SUPPLY THE
C   SUBROUTINE  F(X,Y,YP)  TO EVALUATE
C      DY(I)/DX = YP(I) = F(X,Y(1),Y(2),...,Y(NEQN))
C   AND INITIALIZE ONLY THE FOLLOWING PARAMETERS.
C      NEQN -- NUMBER OF EQUATIONS TO BE INTEGRATED
C      Y(*) -- VECTOR OF INITIAL VALUES OF DEPENDENT VARIABLES
C      X -- INITIAL VALUE OF THE INDEPENDENT VARIABLE
C      H -- NOMINAL STEP SIZE INDICATING DIRECTION OF INTEGRATION
C           AND MAXIMUM SIZE OF STEP.  MUST BE VARIABLE
C      EPS -- LOCAL ERROR TOLERANCE PER STEP.  MUST BE VARIABLE
C      WT(*) -- VECTOR OF NON-ZERO WEIGHTS FOR ERROR CRITERION
```

```
C      START -- .TRUE.
C
C   STEP1  REQUIRES THAT THE L2 NORM OF THE VECTOR WITH COMPONENTS
C   LOCAL ERROR(L)/WT(L)  BE LESS THAN  EPS  FOR A SUCCESSFUL STEP.  THE
C   ARRAY  WT  ALLOWS THE USER TO SPECIFY AN ERROR TEST APPROPRIATE
C   FOR HIS PROBLEM.  FOR EXAMPLE,
C      WT(L) = 1.0  SPECIFIES ABSOLUTE ERROR,
C            = ABS(Y(L))  ERROR RELATIVE TO THE MOST RECENT VALUE OF THE
C                 L-TH COMPONENT OF THE SOLUTION,
C            = ABS(YP(L))  ERROR RELATIVE TO THE MOST RECENT VALUE OF
C                 THE L-TH COMPONENT OF THE DERIVATIVE,
C            = AMAX1(WT(L),ABS(Y(L)))  ERROR RELATIVE TO THE LARGEST
C                 MAGNITUDE OF L-TH COMPONENT OBTAINED SO FAR,
C            = ABS(Y(L))*RELERR/EPS + ABSERR/EPS  SPECIFIES A MIXED
C                 RELATIVE-ABSOLUTE TEST WHERE  RELERR  IS RELATIVE
C                 ERROR,  ABSERR  IS ABSOLUTE ERROR AND  EPS =
C                 AMAX1(RELERR,ABSERR) .
C
C      SUBSEQUENT CALLS --
C
C   SUBROUTINE  STEP1  IS DESIGNED SO THAT ALL INFORMATION NEEDED TO
C   CONTINUE THE INTEGRATION, INCLUDING THE STEP SIZE  H  AND THE ORDER
C   K , IS RETURNED WITH EACH STEP.  WITH THE EXCEPTION OF THE STEP
C   SIZE, THE ERROR TOLERANCE, AND THE WEIGHTS, NONE OF THE PARAMETERS
C   SHOULD BE ALTERED.  THE ARRAY  WT  MUST BE UPDATED AFTER EACH STEP
C   TO MAINTAIN RELATIVE ERROR TESTS LIKE THOSE ABOVE.  NORMALLY THE
C   INTEGRATION IS CONTINUED JUST BEYOND THE DESIRED ENDPOINT AND THE
C   SOLUTION INTERPOLATED THERE WITH SUBROUTINE  INTRP .  IF IT IS
C   IMPOSSIBLE TO INTEGRATE BEYOND THE ENDPOINT, THE STEP SIZE MAY BE
C   REDUCED TO HIT THE ENDPOINT SINCE THE CODE WILL NOT TAKE A STEP
C   LARGER THAN THE  H  INPUT.  CHANGING THE DIRECTION OF INTEGRATION,
C   I.E., THE SIGN OF  H , REQUIRES THE USER SET  START = .TRUE. BEFORE
C   CALLING  STEP1  AGAIN.  THIS IS THE ONLY SITUATION IN WHICH  START
C   SHOULD BE ALTERED.
C
C   OUTPUT FROM STEP1
C
C      SUCCESSFUL STEP --
C
C   THE SUBROUTINE RETURNS AFTER EACH SUCCESSFUL STEP WITH  START  AND
C   CRASH  SET .FALSE. .  X  REPRESENTS THE INDEPENDENT VARIABLE
C   ADVANCED ONE STEP OF LENGTH  HOLD  FROM ITS VALUE ON INPUT AND  Y
C   THE SOLUTION VECTOR AT THE NEW VALUE OF  X .  ALL OTHER PARAMETERS
C   REPRESENT INFORMATION CORRESPONDING TO THE NEW  X  NEEDED TO
C   CONTINUE THE INTEGRATION.
C
C      UNSUCCESSFUL STEP --
C
C   WHEN THE ERROR TOLERANCE IS TOO SMALL FOR THE MACHINE PRECISION,
C   THE SUBROUTINE RETURNS WITHOUT TAKING A STEP AND  CRASH = .TRUE. .
C   AN APPROPRIATE STEP SIZE AND ERROR TOLERANCE FOR CONTINUING ARE
C   ESTIMATED AND ALL OTHER INFORMATION IS RESTORED AS UPON INPUT
```

```
C   BEFORE RETURNING.  TO CONTINUE WITH THE LARGER TOLERANCE, THE USER
C   JUST CALLS THE CODE AGAIN.  A RESTART IS NEITHER REQUIRED NOR
C   DESIRABLE.
C
      SUBROUTINE STEP1(F,NEQN,Y,X,H,EPS,WT,START,
     1 HOLD,K,KOLD,CRASH,PHI,P,YP,PSI,
     2 ALPHA,BETA,SIG,V,W,G,PHASE1,NS,NORND)
C
      IMPLICIT REAL*8 (A-H,O-Z)
      GENERIC
      LOGICAL START,CRASH,PHASE1,NORND
      DIMENSION Y(20),WT(20),PHI(20,16),P(20),YP(20),PSI(12),
     1  ALPHA(12),BETA(12),SIG(13),V(12),W(12),G(13)
      DIMENSION TWO(13),GSTR(13)
      EXTERNAL F
C*****************************************************************************
C*  THE ONLY MACHINE DEPENDENT CONSTANTS ARE BASED ON THE MACHINE UNIT *
C*  ROUNDOFF ERROR  U  WHICH IS THE SMALLEST POSITIVE NUMBER SUCH THAT *
C*  1.0+U .GT. 1.0  .  THE USER MUST CALCULATE  U  AND INSERT          *
C*  TWOU=2.0*U  AND  FOURU=4.0*U  IN THE DATA STATEMENT BEFORE CALLING *
C*  THE CODE.  THE ROUTINE  MACHIN  CALCULATES  U .                    *
      DATA TWOU,FOURU/4.4E-16,8.8E-16/
C*****************************************************************************
C
      DATA TWO/2.0,4.0,8.0,16.0,32.0,64.0,128.0,256.0,512.0,1024.0,
     1  2048.0,4096.0,8192.0/
      DATA GSTR/0.500,0.0833,0.0417,0.0264,0.0188,0.0143,0.0114,0.00936,
     1  0.00789,0.00679,0.00592,0.00524,0.00468/
C
C
C       ***     BEGIN BLOCK 0     ***
C   CHECK IF STEP SIZE OR ERROR TOLERANCE IS TOO SMALL FOR MACHINE
C   PRECISION.  IF FIRST STEP, INITIALIZE PHI ARRAY AND ESTIMATE A
C   STARTING STEP SIZE.
C                    ***
C
C   IF STEP SIZE IS TOO SMALL, DETERMINE AN ACCEPTABLE ONE
C
      CRASH = .TRUE.
      IF(ABS(H) .GE. FOURU*ABS(X)) GO TO 5
      H = SIGN(FOURU*ABS(X),H)
      RETURN
 5    P5EPS = 0.5*EPS
C
C   IF ERROR TOLERANCE IS TOO SMALL, INCREASE IT TO AN ACCEPTABLE VALUE
C
      ROUND = 0.0
      DO 10 L = 1,NEQN
 10     ROUND = ROUND + (Y(L)/WT(L))**2
      ROUND = TWOU*SQRT(ROUND)
      IF(P5EPS .GE. ROUND) GO TO 15
      EPS = 2.0*ROUND*(1.0 + FOURU)
```

```
      RETURN
 15   CRASH = .FALSE.
      G(1) = 1.0
      G(2) = 0.5
      SIG(1) = 1.0
      IF(.NOT.START) GO TO 99
C
C   INITIALIZE.  COMPUTE APPROPRIATE STEP SIZE FOR FIRST STEP
C
      CALL F(X,Y,YP)
      SUM = 0.0
      DO 20 L = 1,NEQN
        PHI(L,1) = YP(L)
        PHI(L,2) = 0.0
 20     SUM = SUM + (YP(L)/WT(L))**2
      SUM = SQRT(SUM)
      ABSH = ABS(H)
      IF(EPS .LT. 16.0*SUM*H*H) ABSH = 0.25*SQRT(EPS/SUM)
      H = SIGN(MAX(ABSH,FOURU*ABS(X)),H)
      HOLD = 0.0
      K = 1
      KOLD = 0
      START = .FALSE.
      PHASE1 = .TRUE.
      NORND = .TRUE.
      IF(P5EPS .GT. 100.0*ROUND) GO TO 99
      NORND = .FALSE.
      DO 25 L = 1,NEQN
 25     PHI(L,15) = 0.0
 99   IFAIL = 0
C       ***     END BLOCK 0     ***
C
C       ***     BEGIN BLOCK 1     ***
C   COMPUTE COEFFICIENTS OF FORMULAS FOR THIS STEP.  AVOID COMPUTING
C   THOSE QUANTITIES NOT CHANGED WHEN STEP SIZE IS NOT CHANGED.
C                    ***
C
 100  KP1 = K+1
      KP2 = K+2
      KM1 = K-1
      KM2 = K-2
C
C   NS IS THE NUMBER OF STEPS TAKEN WITH SIZE H, INCLUDING THE CURRENT
C   ONE.  WHEN K.LT.NS, NO COEFFICIENTS CHANGE
C
      IF(H .NE. HOLD) NS = 0
      IF (NS.LE.KOLD) NS = NS+1
      NSP1 = NS+1
      IF (K .LT. NS) GO TO 199
C
C   COMPUTE THOSE COMPONENTS OF ALPHA(*),BETA(*),PSI(*),SIG(*) WHICH
C   ARE CHANGED
```

```
C
      BETA(NS) = 1.0
      REALNS = NS
      ALPHA(NS) = 1.0/REALNS
      TEMP1 = H*REALNS
      SIG(NSP1) = 1.0
      IF(K .LT. NSP1) GO TO 110
      DO 105 I = NSP1,K
        IM1 = I-1
        TEMP2 = PSI(IM1)
        PSI(IM1) = TEMP1
        BETA(I) = BETA(IM1)*PSI(IM1)/TEMP2
        TEMP1 = TEMP2 + H
        ALPHA(I) = H/TEMP1
        REALI = I
 105    SIG(I+1) = REALI*ALPHA(I)*SIG(I)
 110  PSI(K) = TEMP1
C
C   COMPUTE COEFFICIENTS G(*)
C
C   INITIALIZE V(*) AND SET W(*).
C
      IF(NS .GT. 1) GO TO 120
      DO 115 IQ = 1,K
        TEMP3 = IQ*(IQ+1)
        V(IQ) = 1.0/TEMP3
 115    W(IQ) = V(IQ)
      GO TO 140
C
C   IF ORDER WAS RAISED, UPDATE DIAGONAL PART OF V(*)
C
 120  IF(K .LE. KOLD) GO TO 130
      TEMP4 = K*KP1
      V(K) = 1.0/TEMP4
      NSM2 = NS-2
      IF(NSM2 .LT. 1) GO TO 130
      DO 125 J = 1,NSM2
        I = K-J
 125    V(I) = V(I) - ALPHA(J+1)*V(I+1)
C
C   UPDATE V(*) AND SET W(*)
C
 130  LIMIT1 = KP1 - NS
      TEMP5 = ALPHA(NS)
      DO 135 IQ = 1,LIMIT1
        V(IQ) = V(IQ) - TEMP5*V(IQ+1)
 135    W(IQ) = V(IQ)
      G(NSP1) = W(1)
C
C   COMPUTE THE G(*) IN THE WORK VECTOR W(*)
C
 140  NSP2 = NS + 2
```

```
      IF(KP1 .LT. NSP2) GO TO 199
      DO 150 I = NSP2,KP1
        LIMIT2 = KP2 - I
        TEMP6 = ALPHA(I-1)
        DO 145 IQ = 1,LIMIT2
 145      W(IQ) = W(IQ) - TEMP6*W(IQ+1)
 150    G(I) = W(1)
 199    CONTINUE
C       ***     END BLOCK 1     ***
C
C       ***     BEGIN BLOCK 2     ***
C   PREDICT A SOLUTION P(*), EVALUATE DERIVATIVES USING PREDICTED
C   SOLUTION, ESTIMATE LOCAL ERROR AT ORDER K AND ERRORS AT ORDERS K,
C   K-1, K-2 AS IF CONSTANT STEP SIZE WERE USED.
C                    ***
C
C   CHANGE PHI TO PHI STAR
C
      IF(K .LT. NSP1) GO TO 215
      DO 210 I = NSP1,K
        TEMP1 = BETA(I)
        DO 205 L = 1,NEQN
 205      PHI(L,I) = TEMP1*PHI(L,I)
 210    CONTINUE
C
C   PREDICT SOLUTION AND DIFFERENCES
C
 215  DO 220 L = 1,NEQN
        PHI(L,KP2) = PHI(L,KP1)
        PHI(L,KP1) = 0.0
 220    P(L) = 0.0
      DO 230 J = 1,K
        I = KP1 - J
        IP1 = I+1
        TEMP2 = G(I)
        DO 225 L = 1,NEQN
          P(L) = P(L) + TEMP2*PHI(L,I)
 225      PHI(L,I) = PHI(L,I) + PHI(L,IP1)
 230    CONTINUE
      IF(NORND) GO TO 240
      DO 235 L = 1,NEQN
        TAU = H*P(L) - PHI(L,15)
        P(L) = Y(L) + TAU
 235    PHI(L,16) = (P(L) - Y(L)) - TAU
      GO TO 250
 240  DO 245 L = 1,NEQN
 245    P(L) = Y(L) + H*P(L)
 250  XOLD = X
      X = X + H
      ABSH = ABS(H)
      CALL F(X,P,YP)
C
```

```
C   ESTIMATE ERRORS AT ORDERS K,K-1,K-2
C
      ERKM2 = 0.0
      ERKM1 = 0.0
      ERK = 0.0
      DO 265 L = 1,NEQN
        TEMP3 = 1.0/WT(L)
        TEMP4 = YP(L) - PHI(L,1)
        IF(KM2)265,260,255
 255    ERKM2 = ERKM2 + ((PHI(L,KM1)+TEMP4)*TEMP3)**2
 260    ERKM1 = ERKM1 + ((PHI(L,K)+TEMP4)*TEMP3)**2
 265    ERK = ERK + (TEMP4*TEMP3)**2
      IF(KM2)280,275,270
 270  ERKM2 = ABSH*SIG(KM1)*GSTR(KM2)*SQRT(ERKM2)
 275  ERKM1 = ABSH*SIG(K)*GSTR(KM1)*SQRT(ERKM1)
 280  TEMP5 = ABSH*SQRT(ERK)
      ERR = TEMP5*(G(K)-G(KP1))
      ERK = TEMP5*SIG(KP1)*GSTR(K)
      KNEW = K
C
C   TEST IF ORDER SHOULD BE LOWERED
C
      IF(KM2)299,290,285
 285  IF(MAX(ERKM1,ERKM2) .LE. ERK) KNEW = KM1
      GO TO 299
 290  IF(ERKM1 .LE. 0.5*ERK) KNEW = KM1
C
C   TEST IF STEP SUCCESSFUL
C
 299  IF(ERR .LE. EPS) GO TO 400
C       ***      END BLOCK 2      ***
C
C       ***      BEGIN BLOCK 3      ***
C   THE STEP IS UNSUCCESSFUL.  RESTORE  X, PHI(*,*), PSI(*) .
C   IF THIRD CONSECUTIVE FAILURE, SET ORDER TO ONE.  IF STEP FAILS MORE
C   THAN THREE TIMES, CONSIDER AN OPTIMAL STEP SIZE.  DOUBLE ERROR
C   TOLERANCE AND RETURN IF ESTIMATED STEP SIZE IS TOO SMALL FOR MACHINE
C   PRECISION.
C                    ***
C
C   RESTORE X, PHI(*,*) AND PSI(*)
C
      PHASE1 = .FALSE.
      X = XOLD
      DO 310 I = 1,K
        TEMP1 = 1.0/BETA(I)
        IP1 = I+1
        DO 305 L = 1,NEQN
 305      PHI(L,I) = TEMP1*(PHI(L,I) - PHI(L,IP1))
 310    CONTINUE
      IF(K .LT. 2) GO TO 320
      DO 315 I = 2,K
```

```
 315    PSI(I-1) = PSI(I) - H
C
C   ON THIRD FAILURE, SET ORDER TO ONE.  THEREAFTER, USE OPTIMAL STEP
C   SIZE
C
 320  IFAIL = IFAIL + 1
      TEMP2 = 0.5
      IF(IFAIL - 3) 335,330,325
 325  IF(P5EPS .LT. 0.25*ERK) TEMP2 = SQRT(P5EPS/ERK)
 330  KNEW = 1
 335  H = TEMP2*H
      K = KNEW
      IF(ABS(H) .GE. FOURU*ABS(X)) GO TO 340
      CRASH = .TRUE.
      H = SIGN(FOURU*ABS(X),H)
      EPS = EPS + EPS
      RETURN
 340  GO TO 100
C       ***     END BLOCK 3     ***
C
C       ***     BEGIN BLOCK 4     ***
C   THE STEP IS SUCCESSFUL.  CORRECT THE PREDICTED SOLUTION, EVALUATE
C   THE DERIVATIVES USING THE CORRECTED SOLUTION AND UPDATE THE
C   DIFFERENCES.  DETERMINE BEST ORDER AND STEP SIZE FOR NEXT STEP.
C                    ***
 400  KOLD = K
      HOLD = H
C
C   CORRECT AND EVALUATE
C
      TEMP1 = H*G(KP1)
      IF(NORND) GO TO 410
      DO 405 L = 1,NEQN
        RHO = TEMP1*(YP(L) - PHI(L,1)) - PHI(L,16)
        Y(L) = P(L) + RHO
 405    PHI(L,15) = (Y(L) - P(L)) - RHO
      GO TO 420
 410  DO 415 L = 1,NEQN
 415    Y(L) = P(L) + TEMP1*(YP(L) - PHI(L,1))
 420  CALL F(X,Y,YP)
C
C   UPDATE DIFFERENCES FOR NEXT STEP
C
      DO 425 L = 1,NEQN
        PHI(L,KP1) = YP(L) - PHI(L,1)
 425    PHI(L,KP2) = PHI(L,KP1) - PHI(L,KP2)
      DO 435 I = 1,K
        DO 430 L = 1,NEQN
 430      PHI(L,I) = PHI(L,I) + PHI(L,KP1)
 435    CONTINUE
C
C   ESTIMATE ERROR AT ORDER K+1 UNLESS:
```

```
C     IN FIRST PHASE WHEN ALWAYS RAISE ORDER,
C     ALREADY DECIDED TO LOWER ORDER,
C     STEP SIZE NOT CONSTANT SO ESTIMATE UNRELIABLE
C
      ERKP1 = 0.0
      IF(KNEW .EQ. KM1  .OR.  K .EQ. 12) PHASE1 = .FALSE.
      IF(PHASE1) GO TO 450
      IF(KNEW .EQ. KM1) GO TO 455
      IF(KP1 .GT. NS) GO TO 460
      DO 440 L = 1,NEQN
 440    ERKP1 = ERKP1 + (PHI(L,KP2)/WT(L))**2
      ERKP1 = ABSH*GSTR(KP1)*SQRT(ERKP1)
C
C   USING ESTIMATED ERROR AT ORDER K+1, DETERMINE APPROPRIATE ORDER
C   FOR NEXT STEP
C
      IF(K .GT. 1) GO TO 445
      IF(ERKP1 .GE. 0.5*ERK) GO TO 460
      GO TO 450
 445  IF(ERKM1 .LE. MIN(ERK,ERKP1)) GO TO 455
      IF(ERKP1 .GE. ERK  .OR.  K .EQ. 12) GO TO 460
C
C   HERE ERKP1 .LT. ERK .LT. AMAX1(ERKM1,ERKM2) ELSE ORDER WOULD HAVE
C   BEEN LOWERED IN BLOCK 2.  THUS ORDER IS TO BE RAISED
C
C   RAISE ORDER
C
 450  K = KP1
      ERK = ERKP1
      GO TO 460
C
C   LOWER ORDER
C
 455  K = KM1
      ERK = ERKM1
C
C   WITH NEW ORDER DETERMINE APPROPRIATE STEP SIZE FOR NEXT STEP
C
 460  HNEW = H + H
      IF(PHASE1) GO TO 465
      IF(P5EPS .GE. ERK*TWO(K+1)) GO TO 465
      HNEW = H
      IF(P5EPS .GE. ERK) GO TO 465
      TEMP2 = K+1
      R = (P5EPS/ERK)**(1.0/TEMP2)
      HNEW = ABSH*MAX(0.5D0,MIN(0.9D0,R))
      HNEW = SIGN(MAX(HNEW,FOURU*ABS(X)),H)
 465  H = HNEW
      RETURN
C       ***     END BLOCK 4     ***
      END
```

APPENDIX B

SAMPLE INPUT TO SI ENGINE CYCLE SIMULATION

```
$INPUT
FUELTP = 1
FIRE = .TRUE.
SPBURN = .FALSE.
CBETA = 1.5
CMULT = 1.70
CONSPB = 5.
EXSPB = 1.
DTBRN = 29.
TSPARK = 344.
CONHT = 0.07
BORE = 8.000
XBZERO = 0.0001
PIM = 0.5
PEM = 1.00
TPSTON = 400.
THEAD = 400.
TCW = 400.
PHI = 1.000
REL = .1E-4
AREROT = .1E-5
CIINTG = .1E-4
CCINTG = .1E-4
CBINTG = .1E-5
CEINTG = .1E-4
MAXERR = .1E-4
MAXTRY = 100
MAXITS = 3
TFRESH = 350.
TEGR = 450.
EGR = 0.0
TPRINX = 1.0
TPRINT = 2.0
PATM = 1.000
TATM = 298.
RPM = 1500.
$END
```

APPENDIX C

SAMPLE OUTPUT FROM SI ENGINE CYCLE SIMULATION

M.I.T. QUASI-DIMENSIONAL SI ENGINE CYCLE SIMULATION

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

>>>>> OPERATING MODE

FIRING CYCLE

PREDICTED BURN RATE

>>>>> OPERATING CONDITIONS

FUEL USED IS ISOOCTANE

F/A EQUIVALENCE RATIO = 1.000

SPARK TIMING = 344.00 DEG CA

ENGINE SPEED = 1500.0 RPM

>>>>> MANIFOLD CONDITIONS

INTAKE MANIFOLD PRESSURE = 0.5000 ATM

EXHAUST MANIFOLD PRESSURE = 1.0000 ATM

FRESH CHARGE TEMPERATURE	=	350.00	K
EXHAUST GAS RECIRCULATION	=	0.0	%
EGR TEMPERATURE	=	450.00	K
INTAKE CHARGE TEMPERATURE	=	350.00	K
ATMOSPHERIC PRESSURE	=	1.0000	ATM
ATMOSPHERIC TEMPERATURE	=	298.00	K

>>>>> HEAT TRANSFER AND TURBULENCE PARAMETERS

HEAT TRANSFER CONSTANT	=	0.0700	
HEAT TRANSFER EXPONENT	=	0.8000	
PISTON TEMPERATURE	=	400.00	K
CYLINDER HEAD TEMPERATURE	=	400.00	K
CYLINDER WALL TEMPERATURE	=	400.00	K
TURBULENT DISSIPATION CONSTANT	=	1.5000	
UPRIME MULTIPLYER	=	1.7000	

>>>>> ENGINE DESIGN PARAMETERS

CYLINDER BORE	=	8.000	CM
CRANKSHAFT STROKE	=	7.958	CM
CONNECTING ROD LENGTH	=	14.000	CM
COMPRESSION RATIO	=	8.500	
DISPLACED VOLUME	=	400.000	CC
CLEARANCE VOLUME	=	53.333	CC
INTAKE VALVE OPENS	=	-16.0	DEG CA
INTAKE VALVE CLOSES	=	218.0	DEG CA
EXHAUST VALVE OPENS	=	476.0	DEG CA
EXHAUST VALVE CLOSES	=	737.0	DEG CA

>>>>> COMPUTATIONAL PARAMETERS

MAXIMUN # OF ITERATIONS	=	3
OUTPUT AT ITERATION #	=	2
TPRINT	=	2.00
TPRINX	=	1.00
XBZERO	=	0.00010
XESTOP	=	0.99500
XBSTOP	=	0.99500
CIINTG	=	0.000010
CCINTG	=	0.000010
CBINTG	=	0.000001
CEINTG	=	0.000010
AREROT	=	0.000001
REL	=	0.000010
MAXERR	=	0.000010
MAXTRY	=	100

1

>>>>> START OF INTAKE PROCESS

CA (DEG)	P (ATM)	TEMP (K)	MIN (G)	MEX (G)	VIV (M/SEC)	VEV (M/SEC)	X1 (-)	Q DOT (J/DEG)	WORK (KJ)	IMF	IFG
-16.0	1.0084	929.76	0.0	0.0	0.0		0.0		0.0		
-14.0	1.0078	927.87	-0.00004	0.00080	-342.2	66.9	0.0	0.02621	-0.000235	0	2
-12.0	1.0059	925.67	-0.00015	0.00143	-341.8	58.4	0.0	0.02548	-0.000440	0	2
-10.0	1.0032	923.28	-0.00036	0.00187	-341.3	42.8	0.0	0.02477	-0.000614	0	2
-8.0	1.0002	920.84	-0.00069	0.00208	-340.8	9.6	0.0	0.02411	-0.000756	0	2
-6.0	0.9981	918.57	-0.00117	0.00201	-340.3	-33.3	0.0	0.02600	-0.000866	0	2
-4.0	0.9876	913.40	-0.00184	0.00174	-339.2	-85.6	0.0	0.05608	-0.000945	0	2
-2.0	0.9606	901.10	-0.00272	0.00131	-336.5	-153.1	0.0	0.11150	-0.000991	0	2
0.0	0.9103	878.45	-0.00386	0.00079	-331.4	-232.9	0.0	0.17313	-0.001006	0	2
2.0	0.8342	844.07	-0.00523	0.00025	-321.4	-320.9	0.0	0.22108	-0.000992	0	2
4.0	0.7370	799.24	-0.00678	-0.00021	-299.9	-411.9	0.0	0.23829	-0.000955	0	2
6.0	0.6322	748.47	-0.00835	-0.00056	-254.4	-498.6	0.0	0.22070	-0.000901	0	2
8.0	0.5397	699.49	-0.00967	-0.00078	-158.8	-570.3	0.0	0.18192	-0.000837	0	2
9.3	0.4999	674.24	-0.01011	-0.00086	10.0	-603.9	0.0	0.15658	-0.000791	0	8
11.3	0.4896	654.73	-0.00960	-0.00089	85.7	0.0	0.0	0.12899	-0.000711	0	2
13.3	0.4888	641.69	-0.00881	-0.00089	88.0	0.0	0.0	0.10781	-0.000617	0	2
15.3	0.4900	631.75	-0.00792	-0.00089	81.9	0.0	0.0	0.09334	-0.000508	0	2
17.3	0.4913	623.51	-0.00697	-0.00089	75.8	0.0	0.0	0.08291	-0.000384	0	2
19.3	0.4922	616.44	-0.00596	-0.00089	71.1	0.0	0.0	0.07522	-0.000245	0	2

21.3	0.4928	610.26	-0.00488	-0.00089	67.6	0.0	0.0	0.06948	-0.000091	0	2
23.3	0.4932	604.77	-0.00373	-0.00089	64.7	0.0	0.0	0.06518	0.000076	0	2
25.3	0.4936	599.85	-0.00250	-0.00089	62.4	0.0	0.0	0.06192	0.000257	0	2
27.3	0.4939	595.39	-0.00120	-0.00089	60.5	0.0	0.0	0.05942	0.000452	0	2
29.0	0.4940	591.82	-0.00000	-0.00089	59.0	0.0	0.0	0.05772	0.000631	0	8
31.0	0.4870	553.86	0.00280	-0.00089	63.6	0.0	0.09194	0.04993	0.000846	1	2
33.0	0.4897	533.36	0.00564	-0.00089	56.3	0.0	0.17680	0.04501	0.001074	1	2
35.0	0.4905	516.19	0.00845	-0.00089	53.7	0.0	0.24637	0.04009	0.001315	1	2
37.0	0.4909	501.46	0.01133	-0.00089	52.1	0.0	0.30640	0.03563	0.001567	1	2
39.0	0.4913	488.83	0.01428	-0.00089	50.7	0.0	0.35887	0.03168	0.001829	1	2
41.0	0.4915	477.86	0.01731	-0.00089	49.4	0.0	0.40506	0.02815	0.002103	1	2
43.0	0.4917	468.25	0.02043	-0.00089	48.3	0.0	0.44601	0.02499	0.002386	1	2
45.0	0.4919	459.79	0.02362	-0.00089	47.4	0.0	0.48251	0.02216	0.002678	1	2
47.0	0.4921	452.31	0.02688	-0.00089	46.4	0.0	0.51519	0.01961	0.002979	1	2
49.0	0.4922	445.65	0.03021	-0.00089	45.6	0.0	0.54455	0.01731	0.003288	1	2
51.0	0.4923	439.71	0.03361	-0.00089	44.9	0.0	0.57104	0.01522	0.003605	1	2
53.0	0.4924	434.39	0.03707	-0.00089	44.1	0.0	0.59504	0.01332	0.003929	1	2
55.0	0.4925	429.60	0.04059	-0.00089	43.4	0.0	0.61682	0.01159	0.004259	1	2
57.0	0.4926	425.28	0.04415	-0.00089	42.6	0.0	0.63666	0.01000	0.004595	1	2
59.0	0.4927	421.38	0.04777	-0.00089	41.9	0.0	0.65477	0.00854	0.004937	1	2
61.0	0.4928	417.84	0.05143	-0.00089	41.2	0.0	0.67134	0.00719	0.005283	1	2
63.0	0.4929	414.62	0.05512	-0.00089	40.5	0.0	0.68653	0.00595	0.005633	1	2
65.0	0.4931	411.68	0.05885	-0.00089	39.8	0.0	0.70049	0.00480	0.005987	1	2
67.0	0.4931	409.00	0.06260	-0.00089	39.1	0.0	0.71334	0.00373	0.006344	1	2
69.0	0.4933	406.55	0.06637	-0.00089	38.5	0.0	0.72519	0.00275	0.006703	1	2
71.0	0.4934	404.30	0.07015	-0.00089	37.9	0.0	0.73615	0.00183	0.007064	1	2
73.0	0.4935	402.23	0.07394	-0.00089	37.2	0.0	0.74628	0.00096	0.007427	1	2
75.0	0.4936	400.33	0.07774	-0.00089	36.6	0.0	0.75568	0.00015	0.007789	1	2
77.0	0.4937	398.58	0.08153	-0.00089	36.0	0.0	0.76440	-0.00063	0.008152	1	2
79.0	0.4938	396.97	0.08532	-0.00089	35.4	0.0	0.77250	-0.00136	0.008515	1	2
81.0	0.4939	395.48	0.08909	-0.00089	34.9	0.0	0.78004	-0.00204	0.008877	1	2
83.0	0.4940	394.10	0.09285	-0.00089	34.3	0.0	0.78707	-0.00269	0.009237	1	2
85.0	0.4942	392.83	0.09659	-0.00089	33.7	0.0	0.79362	-0.00330	0.009595	1	2
87.0	0.4943	391.65	0.10030	-0.00089	33.2	0.0	0.79974	-0.00388	0.009951	1	2
89.0	0.4944	390.56	0.10398	-0.00089	32.7	0.0	0.80546	-0.00442	0.010304	1	2
91.0	0.4946	389.55	0.10762	-0.00089	32.1	0.0	0.81081	-0.00493	0.010654	1	2
93.0	0.4947	388.61	0.11122	-0.00089	31.6	0.0	0.81582	-0.00540	0.011000	1	2
95.0	0.4949	387.73	0.11478	-0.00089	31.1	0.0	0.82052	-0.00585	0.011342	1	2
97.0	0.4950	386.92	0.11829	-0.00089	30.6	0.0	0.82492	-0.00627	0.011679	1	2
99.0	0.4952	386.17	0.12175	-0.00089	30.1	0.0	0.82906	-0.00666	0.012011	1	2
101.0	0.4953	385.47	0.12515	-0.00089	29.7	0.0	0.83294	-0.00702	0.012339	1	2
103.0	0.4955	384.82	0.12850	-0.00089	29.2	0.0	0.83658	-0.00736	0.012660	1	2
105.0	0.4957	384.22	0.13178	-0.00089	28.7	0.0	0.84001	-0.00767	0.012976	1	2
107.0	0.4958	383.65	0.13500	-0.00089	28.3	0.0	0.84323	-0.00797	0.013285	1	2
109.0	0.4960	383.13	0.13815	-0.00089	27.8	0.0	0.84626	-0.00824	0.013588	1	2
111.0	0.4962	382.65	0.14123	-0.00089	27.3	0.0	0.84912	-0.00848	0.013885	1	2
113.0	0.4963	382.19	0.14424	-0.00089	26.8	0.0	0.85180	-0.00871	0.014174	1	2
115.0	0.4965	381.78	0.14717	-0.00089	26.4	0.0	0.85433	-0.00892	0.014456	1	2
117.0	0.4966	381.39	0.15003	-0.00089	25.9	0.0	0.85671	-0.00911	0.014731	1	2
119.0	0.4968	381.03	0.15280	-0.00089	25.5	0.0	0.85895	-0.00928	0.014998	1	2
121.0	0.4969	380.69	0.15550	-0.00089	25.0	0.0	0.86105	-0.00943	0.015258	1	2
123.0	0.4971	380.38	0.15811	-0.00089	24.5	0.0	0.86304	-0.00957	0.015510	1	2
125.0	0.4972	380.09	0.16064	-0.00089	24.1	0.0	0.86490	-0.00969	0.015753	1	2
127.0	0.4974	379.83	0.16308	-0.00089	23.7	0.0	0.86666	-0.00980	0.015989	1	2
129.0	0.4975	379.59	0.16543	-0.00089	23.2	0.0	0.86831	-0.00989	0.016216	1	2
131.0	0.4977	379.36	0.16770	-0.00089	22.8	0.0	0.86986	-0.00997	0.016435	1	2
133.0	0.4978	379.15	0.16987	-0.00089	22.3	0.0	0.87132	-0.01003	0.016646	1	2
135.0	0.4979	378.97	0.17196	-0.00089	21.9	0.0	0.87268	-0.01008	0.016848	1	2

137.0	0.4981	378.80	0.17396	-0.00089	21.4	0.0	0.87396	-0.01012	0.017041	1	2
139.0	0.4982	378.64	0.17587	-0.00089	21.0	0.0	0.87516	-0.01015	0.017226	1	2
141.0	0.4983	378.50	0.17768	-0.00089	20.5	0.0	0.87628	-0.01016	0.017402	1	2
143.0	0.4984	378.37	0.17940	-0.00089	20.1	0.0	0.87732	-0.01017	0.017570	1	2
145.0	0.4985	378.26	0.18104	-0.00089	19.6	0.0	0.87829	-0.01016	0.017728	1	2
147.0	0.4986	378.17	0.18258	-0.00089	19.0	0.0	0.87920	-0.01014	0.017878	1	2
149.0	0.4987	378.08	0.18403	-0.00089	18.5	0.0	0.88004	-0.01012	0.018019	1	2
151.0	0.4988	378.01	0.18538	-0.00089	18.0	0.0	0.88081	-0.01008	0.018152	1	2
153.0	0.4989	377.95	0.18665	-0.00089	17.3	0.0	0.88153	-0.01004	0.018275	1	2
155.0	0.4990	377.90	0.18782	-0.00089	16.7	0.0	0.88218	-0.00999	0.018390	1	2
157.0	0.4991	377.87	0.18890	-0.00089	15.9	0.0	0.88277	-0.00993	0.018496	1	2
159.0	0.4992	377.84	0.18989	-0.00089	15.4	0.0	0.88331	-0.00986	0.018593	1	2
161.0	0.4993	377.83	0.19079	-0.00089	14.5	0.0	0.88380	-0.00978	0.018681	1	2
163.0	0.4994	377.82	0.19159	-0.00089	13.7	0.0	0.88423	-0.00970	0.018760	1	2
165.0	0.4995	377.83	0.19230	-0.00089	12.7	0.0	0.88461	-0.00961	0.018831	1	2
167.0	0.4996	377.85	0.19292	-0.00089	11.7	0.0	0.88494	-0.00952	0.018892	1	2
169.0	0.4997	377.88	0.19345	-0.00089	10.5	0.0	0.88522	-0.00942	0.018945	1	2
171.0	0.4997	377.92	0.19389	-0.00089	9.3	0.0	0.88545	-0.00931	0.018989	1	2
173.0	0.4998	377.97	0.19422	-0.00089	8.6	0.0	0.88562	-0.00920	0.019024	1	2
175.0	0.4999	378.03	0.19448	-0.00089	6.5	0.0	0.88576	-0.00909	0.019051	1	2
177.0	0.5000	378.10	0.19465	-0.00089	2.2	0.0	0.88585	-0.00897	0.019068	1	2
178.1	0.5001	378.13	0.19472	-0.00089	-4.6	0.0	0.88588	-0.00891	0.019074	1	8
180.0	0.5000	378.23	0.19469	-0.00089	-1.7	0.0	0.88587	-0.00879	0.019078	0	2
182.0	0.5001	378.31	0.19462	-0.00089	-4.4	0.0	0.88587	-0.00866	0.019073	0	2
184.0	0.5002	378.40	0.19448	-0.00089	-7.8	0.0	0.88587	-0.00854	0.019060	0	2
186.0	0.5004	378.51	0.19430	-0.00089	-11.7	0.0	0.88587	-0.00841	0.019038	0	2
188.0	0.5007	378.64	0.19406	-0.00089	-16.0	0.0	0.88587	-0.00827	0.019007	0	2
190.0	0.5011	378.80	0.19379	-0.00089	-20.8	0.0	0.88587	-0.00812	0.018967	0	2
192.0	0.5018	378.99	0.19350	-0.00089	-26.1	0.0	0.88587	-0.00796	0.018918	0	2
194.0	0.5027	379.23	0.19319	-0.00089	-31.8	0.0	0.88587	-0.00779	0.018861	0	2
196.0	0.5038	379.51	0.19288	-0.00089	-37.9	0.0	0.88587	-0.00761	0.018794	0	2
198.0	0.5052	379.84	0.19258	-0.00089	-44.4	0.0	0.88587	-0.00741	0.018718	0	2
200.0	0.5070	380.24	0.19229	-0.00089	-51.2	0.0	0.88587	-0.00719	0.018633	0	2
202.0	0.5091	380.71	0.19204	-0.00089	-58.3	0.0	0.88587	-0.00696	0.018538	0	2
204.0	0.5116	381.24	0.19182	-0.00089	-65.6	0.0	0.88587	-0.00670	0.018434	0	2
206.0	0.5145	381.85	0.19162	-0.00089	-73.0	0.0	0.88587	-0.00643	0.018321	0	2
208.0	0.5178	382.54	0.19147	-0.00089	-80.5	0.0	0.88587	-0.00613	0.018197	0	2
210.0	0.5216	383.29	0.19135	-0.00089	-88.0	0.0	0.88587	-0.00582	0.018064	0	2
212.0	0.5258	384.12	0.19126	-0.00089	-95.5	0.0	0.88587	-0.00549	0.017920	0	2
214.0	0.5304	385.03	0.19120	-0.00089	-102.9	0.0	0.88587	-0.00513	0.017766	0	2
216.0	0.5355	386.01	0.19116	-0.00089	-110.2	0.0	0.88587	-0.00476	0.017601	0	2
218.0	0.5411	387.06	0.19114	-0.00089	0.0	0.0	0.88587	-0.00438	0.017424	0	2

>>>>> START OF COMPRESSION PROCESS

1

CA (DEG)	P (ATM)	TEMP (K)	QREL (-)	Q DOT (J/DEG)	WORK (KJ)	IFG
218.0	0.5411	387.06	0.0	-0.00438	0.017424	2
220.0	0.5471	388.18	0.000016	-0.00397	0.017236	2
222.0	0.5535	389.36	0.000030	-0.00355	0.017037	2

224.0	0.5603	390.60	0.000043	-0.00312	0.016825	2
226.0	0.5676	391.31	0.000054	-0.00267	0.016601	2
228.0	0.5754	393.29	0.000063	-0.00220	0.016364	2
230.0	0.5837	394.74	0.000070	-0.00172	0.016113	2
232.0	0.5925	396.25	0.000076	-0.00121	0.015849	2
234.0	0.6019	397.84	0.000080	-0.00070	0.015571	2
236.0	0.6119	399.51	0.000081	-0.00016	0.015279	2
238.0	0.6225	401.25	0.000081	0.00040	0.014971	2
240.0	0.6338	403.08	0.000078	0.00098	0.014647	2
242.0	0.6458	404.99	0.000073	0.00158	0.014308	2
244.0	0.6586	406.98	0.000066	0.00220	0.013952	2
246.0	0.6722	409.06	0.000057	0.00285	0.013578	2
248.0	0.6867	411.24	0.000045	0.00352	0.013187	2
250.0	0.7020	413.51	0.000030	0.00422	0.012777	2
252.0	0.7184	415.87	0.000012	0.00495	0.012347	2
254.0	0.7358	418.34	-0.000008	0.00570	0.011898	2
256.0	0.7544	420.92	-0.000031	0.00649	0.011428	2
258.0	0.7741	423.60	-0.000057	0.00731	0.010936	2
260.0	0.7951	426.40	-0.000087	0.00817	0.010422	2
262.0	0.8176	429.31	-0.000119	0.00906	0.009885	2
264.0	0.8415	432.34	-0.000155	0.00999	0.009324	2
266.0	0.8670	435.50	-0.000195	0.01096	0.008738	2
268.0	0.8943	438.78	-0.000239	0.01197	0.008125	2
270.0	0.9234	442.20	-0.000286	0.01303	0.007486	2
272.0	0.9546	445.76	-0.000338	0.01414	0.006818	2
274.0	0.9879	449.47	-0.000394	0.01530	0.006122	2
276.0	1.0236	453.32	-0.000454	0.01652	0.005395	2
278.0	1.0618	457.32	-0.000519	0.01779	0.004637	2
280.0	1.1028	461.48	-0.000589	0.01912	0.003846	2
282.0	1.1468	465.81	-0.000664	0.02052	0.003021	2
284.0	1.1941	470.30	-0.000745	0.02199	0.002160	2
286.0	1.2448	474.97	-0.000831	0.02353	0.001264	2
288.0	1.2994	479.82	-0.000924	0.02516	0.000329	2
290.0	1.3582	484.86	-0.001023	0.02686	-0.000645	2
292.0	1.4215	490.08	-0.001128	0.02866	-0.001659	2
294.0	1.4897	495.50	-0.001241	0.03071	-0.002715	2
296.0	1.5633	501.12	-0.001361	0.03295	-0.003815	2
298.0	1.6431	507.04	-0.001491	0.03536	-0.004960	2
300.0	1.7292	513.15	-0.001630	0.03792	-0.006151	2
302.0	1.8221	519.47	-0.001779	0.04064	-0.007390	2
304.0	1.9226	525.99	-0.001939	0.04353	-0.008677	2
306.0	2.0313	532.71	-0.002110	0.04660	-0.010014	2
308.0	2.1488	539.64	-0.002293	0.04986	-0.011401	2
310.0	2.2759	546.77	-0.002489	0.05332	-0.012840	2
312.0	2.4133	554.11	-0.002698	0.05700	-0.014329	2
314.0	2.5619	561.64	-0.002922	0.06090	-0.015870	2
316.0	2.7224	569.36	-0.003161	0.06504	-0.017462	2
318.0	2.8956	577.26	-0.003416	0.06942	-0.019103	2
320.0	3.0823	585.32	-0.003689	0.07404	-0.020792	2
322.0	3.2833	593.53	-0.003979	0.07891	-0.022526	2
324.0	3.4991	601.86	-0.004288	0.08403	-0.024301	2
326.0	3.7301	610.28	-0.004617	0.08938	-0.026113	2
328.0	3.9765	618.77	-0.004967	0.09495	-0.027954	2
330.0	4.2381	627.28	-0.005339	0.10071	-0.029818	2
332.0	4.5144	635.75	-0.005732	0.10662	-0.031694	2
334.0	4.8041	644.13	-0.006148	0.11262	-0.033571	2
336.0	5.1053	652.35	-0.006588	0.11866	-0.035436	2
338.0	5.4155	660.33	-0.007049	0.12463	-0.037271	2

340.0	5.7309	668.00	-0.007534	0.13044	-0.039060	2
342.0	6.0470	675.24	-0.008040	0.13596	-0.040781	2
344.0	6.3581	681.97	-0.008566	0.14105	-0.042413	2

1

>>>>> START OF COMBUSTION AND EXPANSION PROCESSES

CA (DEG)	P (ATM)	TB (K)	TU (K)	XENTRA (-)	XBURND (-)	QREL (-)	Q DOT (J/DEG)	WORK (KJ)	IFG
344.0	6.3581	2352.67	681.77	0.00010	0.00010	-0.008566	0.14105	-0.042413	2
345.0	6.5080	2354.45	684.69	0.00029	0.00011	-0.008807	0.18899	-0.043188	2
346.0	6.6547	2356.13	687.45	0.00063	0.00017	-0.009116	0.19274	-0.043932	2
347.0	6.7981	2357.82	690.06	0.00124	0.00029	-0.009365	0.19732	-0.044641	2
348.0	6.9387	2359.50	692.52	0.00242	0.00054	-0.009496	0.20205	-0.045313	2
349.0	7.0782	2361.19	694.89	0.00469	0.00103	-0.009392	0.20729	-0.045945	2
350.0	7.2204	2362.96	697.25	0.00828	0.00195	-0.008872	0.21355	-0.046534	2
351.0	7.3693	2365.04	699.69	0.01360	0.00349	-0.007745	0.22104	-0.047079	2
352.0	7.5317	2367.59	702.34	0.02160	0.00594	-0.005718	0.23086	-0.047578	2
353.0	7.7172	2370.77	705.39	0.03270	0.00973	-0.002385	0.24420	-0.048029	2
354.0	7.9353	2374.80	708.99	0.04728	0.01523	0.002643	0.26170	-0.048431	2
355.0	8.1992	2380.00	713.37	0.06651	0.02301	0.009896	0.28518	-0.048781	2
356.0	8.5241	2386.60	718.74	0.09070	0.03369	0.020007	0.31633	-0.049079	2
357.0	8.9276	2394.97	725.30	0.12107	0.04803	0.033711	0.35505	-0.049320	2
358.0	9.4295	2405.27	733.24	0.15682	0.06690	0.051865	0.40604	-0.049501	2
359.0	10.0362	2416.92	742.46	0.19620	0.09071	0.074832	0.49605	-0.049617	2
360.0	10.7480	2428.96	752.75	0.23843	0.11971	0.102773	0.62479	-0.049657	2
361.0	11.5516	2441.13	763.70	0.28159	0.15362	0.135356	0.77165	-0.049613	2
362.0	12.4304	2453.00	774.89	0.32636	0.19201	0.172117	0.95050	-0.049470	2
363.0	13.3707	2464.28	786.06	0.37350	0.23461	0.212729	1.15747	-0.049213	2
364.0	14.3605	2474.67	797.01	0.42314	0.28123	0.256919	1.40619	-0.048829	2
365.0	15.3861	2484.03	807.57	0.47499	0.33158	0.304346	1.67137	-0.048298	2
366.0	16.4324	2492.32	817.57	0.52898	0.38527	0.354600	1.94730	-0.047606	2
367.0	17.4814	2499.47	826.85	0.58384	0.44176	0.407125	2.23394	-0.046734	2
368.0	18.5071	2505.26	835.20	0.63878	0.50012	0.460967	2.52616	-0.045668	2
369.0	19.4858	2509.54	842.48	0.69326	0.55943	0.515206	2.81811	-0.044395	2
370.0	20.3929	2512.19	848.54	0.74614	0.61866	0.568805	3.10026	-0.042903	2
371.0	21.2067	2513.09	853.30	0.79688	0.67678	0.620763	3.38603	-0.041186	2
372.0	21.8944	2511.97	856.58	0.84085	0.73215	0.669466	3.63484	-0.039241	2
373.0	22.4091	2508.34	858.14	0.87675	0.78229	0.712484	3.87129	-0.037072	2
374.0	22.7243	2501.90	857.99	0.90374	0.82548	0.748158	4.04112	-0.034691	2
375.0	22.8387	2492.82	856.10	0.92550	0.86105	0.775983	4.11998	-0.032115	2
376.0	22.8006	2481.85	852.77	0.94566	0.89080	0.797884	4.14449	-0.029365	2
377.0	22.6422	2469.40	848.25	0.96177	0.91585	0.815074	4.13240	-0.026457	2
378.0	22.3714	2455.47	842.54	0.97314	0.93614	0.827574	4.08465	-0.023411	2
379.0	22.0013	2440.12	835.88	0.98066	0.95194	0.835678	4.02798	-0.020247	2
380.0	21.5456	2423.17	830.93	0.98480	0.96361	0.839683	4.00339	-0.016983	2
381.0	21.0324	2405.27	826.56	0.98858	0.97221	0.840838	3.83791	-0.013641	2
382.0	20.4885	2386.93	821.82	0.99219	0.97887	0.840370	3.67152	-0.010234	2
383.0	19.9295	2368.36	816.85	0.99546	0.98428	0.838961	3.50817	-0.006777	2
384.0	19.3611	2349.60	811.68	0.99763	0.98859	0.836769	3.34885	-0.003279	2

385.0	18.7882	2330.67	806.34	0.99907	0.99197	0.833938	3.19442	0.000247	2
386.0	18.2144	2311.60	800.85	0.99991	0.99450	0.830546	3.04532	0.003791	2
387.0	17.6427	2292.39	795.23	0.99991	0.99627	0.826670	2.90187	0.007346	2
388.0	17.0770	2273.09	789.53	0.99991	0.99743	0.822454	2.76463	0.010901	2
389.0	16.5217	2253.81	783.77	0.99991	0.99821	0.818102	2.63429	0.014451	2
390.0	15.9794	2234.61	778.00	0.99991	0.99873	0.813737	2.51110	0.017988	2
391.0	15.4518	2215.53	772.22	0.99991	0.99908	0.809433	2.39502	0.021506	2
392.0	14.9399	2196.61	766.46	0.99991	0.99932	0.805231	2.28585	0.025002	2
393.0	14.4443	2177.86	760.72	0.99991	0.99949	0.801157	2.18331	0.028471	2
394.0	13.9651	2159.30	755.02	0.99991	0.99960	0.797221	2.08709	0.031908	2
395.0	13.5025	2140.96	749.36	0.99991	0.99969	0.793428	1.99682	0.035312	2
396.0	13.0562	2122.82	743.75	0.99991	0.99974	0.789777	1.91216	0.038679	2
397.0	12.6262	2104.92	738.18	0.99991	0.99979	0.786266	1.83273	0.042006	2
398.0	12.2120	2087.24	732.67	0.99991	0.99982	0.782888	1.75821	0.045291	2
399.0	11.8134	2069.80	727.23	0.99991	0.99984	0.779640	1.68828	0.048533	2
400.0	11.4299	2052.60	721.84	0.99991	0.99986	0.776514	1.62261	0.051730	2
401.0	11.0612	2035.64	716.52	0.99991	0.99987	0.773505	1.56091	0.054881	2
402.0	10.7068	2018.93	711.26	0.99991	0.99988	0.770607	1.50291	0.057984	2
403.0	10.3662	2002.47	706.07	0.99991	0.99989	0.767813	1.44836	0.061039	2
404.0	10.0391	1986.26	700.96	0.99991	0.99989	0.765118	1.39700	0.064045	2
405.0	9.7248	1970.30	695.91	0.99991	0.99990	0.762516	1.34861	0.067001	2
406.0	9.4231	1954.60	690.94	0.99991	0.99990	0.760002	1.30300	0.069907	2
407.0	9.1333	1939.14	686.04	0.99991	0.99990	0.757572	1.25996	0.072763	2
408.0	8.8552	1923.94	681.21	0.99991	0.99990	0.755221	1.21932	0.075568	2
409.0	8.5881	1909.00	676.45	0.99991	0.99991	0.752945	1.18091	0.078323	2
410.0	8.3317	1894.30	671.77	0.99991	0.99991	0.750739	1.14457	0.081028	2
411.0	8.0856	1879.85	667.17	0.99991	0.99991	0.748599	1.11016	0.083683	2
412.0	7.8493	1865.66	662.63	0.99991	0.99991	0.746524	1.07755	0.086289	2
413.0	7.6225	1851.71	658.18	0.99991	0.99991	0.744508	1.04662	0.088844	2
414.0	7.4047	1838.00	653.79	0.99991	0.99991	0.742550	1.01726	0.091351	2
415.0	7.1955	1824.54	649.48	0.99991	0.99991	0.740645	0.98936	0.093809	2
416.0	6.9947	1811.32	645.24	0.99991	0.99991	0.738793	0.96282	0.096220	2
417.0	6.8018	1798.34	641.08	0.99991	0.99991	0.736989	0.93757	0.098582	2
418.0	6.6166	1785.59	636.98	0.99991	0.99991	0.735232	0.91350	0.100898	2
419.0	6.4386	1773.07	632.96	0.99991	0.99991	0.733520	0.89056	0.103168	2
420.0	6.2676	1760.79	629.00	0.99991	0.99991	0.731851	0.86866	0.105392	2
421.0	6.1033	1748.73	625.12	0.99991	0.99991	0.730222	0.84774	0.107571	2
422.0	5.9454	1736.89	621.31	0.99991	0.99991	0.728631	0.82775	0.109705	2
423.0	5.7935	1725.27	617.56	0.99991	0.99991	0.727078	0.80862	0.111796	2
424.0	5.6476	1713.87	613.88	0.99991	0.99991	0.725560	0.79031	0.113844	2
425.0	5.5072	1702.68	610.27	0.99991	0.99991	0.724077	0.77276	0.115850	2
426.0	5.3722	1691.70	606.72	0.99991	0.99991	0.722626	0.75593	0.117814	2
427.0	5.2423	1680.92	603.24	0.99991	0.99991	0.721206	0.73979	0.119737	2
428.0	5.1173	1670.35	599.82	0.99991	0.99991	0.719816	0.72428	121620	2
429.0	4.9971	1659.98	596.47	0.99991	0.99991	0.718456	0.70937	0.123464	2
430.0	4.8813	1649.80	593.17	0.99991	0.99991	0.717122	0.69504	0.125269	2
431.0	4.7698	1639.82	589.94	0.99991	0.99991	0.715816	0.68125	0.127036	2
432.0	4.6624	1630.02	586.77	0.99991	0.99991	0.714535	0.66797	0.128766	2
433.0	4.5590	1620.41	583.65	0.99991	0.99991	0.713279	0.65517	0.130459	2
434.0	4.4594	1610.98	580.60	0.99991	0.99991	0.712047	0.64283	0.132117	2
435.0	4.3633	1601.72	577.60	0.99991	0.99991	0.710838	0.63092	0.133739	2
436.0	4.2708	1592.65	574.66	0.99991	0.99991	0.709651	0.61943	0.135326	2
437.0	4.1815	1583.74	571.77	0.99991	0.99991	0.708486	0.60833	0.136880	2
438.0	4.0955	1575.00	568.94	0.99991	0.99991	0.707341	0.59760	0.138400	2
439.0	4.0125	1566.43	566.16	0.99991	0.99991	0.706217	0.58722	0.139888	2
440.0	3.9324	1558.02	563.43	0.99991	0.99991	0.705111	0.57719	0.141344	2
441.0	3.8552	1549.76	560.76	0.99991	0.99991	0.704025	0.56747	0.142769	2
442.0	3.7806	1541.67	558.14	0.99991	0.99991	0.702956	0.55807	0.144163	2

443.0	3.7086	1533.72	555.57	0.99991	0.99991	0.701906	0.54895	0.145526	2
444.0	3.6391	1525.93	553.04	0.99991	0.99991	0.700872	0.54012	0.146861	2
445.0	3.5720	1518.28	550.57	0.99991	0.99991	0.699854	0.53155	0.148166	2
446.0	3.5071	1510.78	548.14	0.99991	0.99991	0.698853	0.52324	0.149443	2
447.0	3.4445	1503.41	545.76	0.99991	0.99991	0.697868	0.51517	0.150692	2
448.0	3.3839	1496.19	543.42	0.99991	0.99991	0.696897	0.50734	0.151914	2
449.0	3.3254	1489.10	541.14	0.99991	0.99991	0.695941	0.49973	0.153109	2
450.0	3.2689	1482.14	538.89	0.99991	0.99991	0.694999	0.49234	0.154279	2
451.0	3.2142	1475.32	536.69	0.99991	0.99991	0.694071	0.48516	0.155422	2
452.0	3.1613	1468.62	534.53	0.99991	0.99991	0.693157	0.47818	0.156540	2
453.0	3.1101	1462.05	532.41	0.99991	0.99991	0.692255	0.47139	0.157634	2
454.0	3.0606	1455.60	530.34	0.99991	0.99991	0.691367	0.46478	0.158703	2
455.0	3.0127	1449.27	528.31	0.99991	0.99991	0.690490	0.45835	0.159749	2
456.0	2.9664	1443.06	526.31	0.99991	0.99991	0.689626	0.45209	0.160772	2
457.0	2.9215	1436.96	524.36	0.99991	0.99991	0.688774	0.44600	0.161772	2
458.0	2.8781	1430.98	522.44	0.99991	0.99991	0.687933	0.44007	0.162749	2
459.0	2.8361	1425.11	520.56	0.99991	0.99991	0.687103	0.43429	0.163705	2
460.0	2.7953	1419.35	518.72	0.99991	0.99991	0.686283	0.42866	0.164639	2
461.0	2.7559	1413.69	516.92	0.99991	0.99991	0.685475	0.42317	0.165552	2
462.0	2.7177	1408.14	515.15	0.99991	0.99991	0.684676	0.41782	0.166445	2
463.0	2.6807	1402.70	513.42	0.99991	0.99991	0.683888	0.41261	0.167317	2
464.0	2.6448	1397.35	511.72	0.99991	0.99991	0.683110	0.40753	0.168170	2
465.0	2.6101	1392.11	510.06	0.99991	0.99991	0.682341	0.40257	0.169003	2
466.0	2.5764	1386.96	508.43	0.99991	0.99991	0.681581	0.39774	0.169817	2
467.0	2.5437	1381.91	506.83	0.99991	0.99991	0.680830	0.39302	0.170612	2
468.0	2.5121	1376.95	505.27	0.99991	0.99991	0.680089	0.38842	0.171389	2
469.0	2.4814	1372.08	503.73	0.99991	0.99991	0.679355	0.38393	0.172148	2
470.0	2.4516	1367.31	502.23	0.99991	0.99991	0.678631	0.37955	0.172889	2
471.0	2.4228	1362.62	500.76	0.99991	0.99991	0.677914	0.37528	0.173613	2
472.0	2.3948	1358.02	499.32	0.99991	0.99991	0.677206	0.37111	0.174320	2
473.0	2.3676	1353.50	497.92	0.99991	0.99991	0.676505	0.36704	0.175011	2
474.0	2.3413	1349.07	496.56	0.99991	0.99991	0.675812	0.36306	0.175685	2
475.0	2.3157	1344.72	495.23	0.99991	0.99991	0.675126	0.35918	0.176343	2
476.0	2.2910	1340.45	493.92	0.99991	0.99991	0.674448	0.35539	0.176985	2

1

>>>>> START OF EXHAUST PROCESS

CA (DEG)	P (ATM)	TEMP (K)	MEX (G)	VEV (M/SEC)	Q DOT (J/DEG)	WORK (KJ)	IFG
476.0	2.2910	1340.45	-0.00089	0.0	0.35539	0.176985	2
478.0	2.2439	1332.59	-0.00085	417.7	0.28875	0.178223	2
480.0	2.1983	1324.87	-0.00071	416.6	0.28232	0.179402	2
482.0	2.1540	1317.25	-0.00046	415.6	0.27625	0.180522	2
484.0	2.1103	1309.67	-0.00007	414.5	0.27071	0.181586	2
486.0	2.0669	1302.05	0.00051	413.4	0.26603	0.182593	2
488.0	2.0230	1294.31	0.00132	412.3	0.26269	0.183546	2
490.0	1.9781	1286.32	0.00240	411.2	0.26136	0.184444	2
492.0	1.9314	1277.96	0.00383	410.0	0.26269	0.185288	2
494.0	1.8824	1269.11	0.00564	408.7	0.26730	0.186079	2
496.0	1.8306	1259.63	0.00790	407.9	0.27547	0.186818	2

498.0	1.7753	1249.37	0.01065	406.7	0.28691	0.187503	2
500.0	1.7165	1238.23	0.01393	404.7	0.30070	0.188137	2
502.0	1.6540	1226.11	0.01774	401.4	0.31564	0.188719	2
504.0	1.5880	1212.94	0.02210	396.3	0.32992	0.189250	2
506.0	1.5190	1198.75	0.02695	388.8	0.34204	0.189732	2
508.0	1.4477	1183.59	0.03225	378.1	0.35006	0.190166	2
510.0	1.3754	1167.60	0.03789	363.1	0.35238	0.190553	2
512.0	1.3036	1151.06	0.04374	342.7	0.34749	0.190898	2
514.0	1.2341	1134.36	0.04960	315.6	0.33296	0.191201	2
516.0	1.1688	1117.99	0.05526	280.4	0.31180	0.191467	2
518.0	1.1100	1102.55	0.06048	235.7	0.27992	0.191699	2
520.0	1.0601	1088.90	0.06495	180.2	0.23578	0.191901	2
522.0	1.0225	1078.11	0.06829	112.6	0.17869	0.192076	2
524.0	1.0010	1071.55	0.07000	24.4	0.11340	0.192228	2
526.0	0.9992	1069.98	0.06963	-20.8	0.10905	0.192360	2
528.0	0.9994	1068.86	0.06908	-18.1	0.11083	0.192475	2
530.0	0.9996	1067.74	0.06859	-15.0	0.11161	0.192572	2
532.0	0.9997	1066.61	0.06816	-12.3	0.11170	0.192652	2
534.0	0.9998	1065.48	0.06779	-9.9	0.11136	0.192714	2
536.0	0.9999	1064.34	0.06748	-7.7	0.11077	0.192758	2
538.0	0.9999	1063.21	0.06723	-5.8	0.11004	0.192784	2
540.0	1.0000	1062.09	0.06704	-4.0	0.10924	0.192793	2
542.0	1.0000	1060.97	0.06691	-2.6	0.10842	0.192784	2
544.0	1.0000	1059.85	0.06684	-2.7	0.10761	0.192758	2
546.0	1.0000	1058.75	0.06683	-1.0	0.10681	0.192714	2
548.0	1.0000	1057.65	0.06687	1.7	0.10612	0.192652	2
550.0	1.0000	1056.56	0.06697	2.4	0.10544	0.192572	2
552.0	1.0000	1055.47	0.06713	3.9	0.10502	0.192475	2
554.0	1.0001	1054.40	0.06735	4.8	0.10462	0.192360	2
556.0	1.0001	1053.32	0.06763	5.6	0.10426	0.192227	2
558.0	1.0002	1052.25	0.06796	7.0	0.10428	0.192077	2
560.0	1.0002	1051.17	0.06835	7.5	0.10401	0.191909	2
562.0	1.0003	1050.10	0.06879	8.4	0.10401	0.191723	2
564.0	1.0004	1049.02	0.06929	9.2	0.10414	0.191519	2
566.0	1.0004	1047.94	0.06986	9.9	0.10418	0.191298	2
568.0	1.0006	1046.86	0.07047	10.7	0.10447	0.191058	2
570.0	1.0007	1045.77	0.07115	11.4	0.10472	0.190801	2
572.0	1.0008	1044.67	0.07188	12.1	0.10503	0.190526	2
574.0	1.0009	1043.57	0.07267	12.8	0.10546	0.190234	2
576.0	1.0011	1042.46	0.07352	13.5	0.10583	0.189924	2
578.0	1.0012	1041.34	0.07442	14.2	0.10633	0.189596	2
580.0	1.0014	1040.22	0.07538	14.9	0.10689	0.189250	2
582.0	1.0016	1039.08	0.07639	15.5	0.10738	0.188887	2
584.0	1.0018	1037.93	0.07747	16.2	0.10785	0.188506	2
586.0	1.0021	1036.77	0.07859	16.9	0.10853	0.188107	2
588.0	1.0023	1035.59	0.07978	17.5	0.10901	0.187692	2
590.0	1.0026	1034.40	0.08102	18.2	0.10945	0.187259	2
592.0	1.0029	1033.20	0.08232	18.8	0.10993	0.186808	2
594.0	1.0032	1031.98	0.08367	19.5	0.11052	0.186341	2
596.0	1.0035	1030.74	0.08508	20.2	0.11094	0.185857	2
598.0	1.0038	1029.48	0.08655	20.8	0.11123	0.185357	2
600.0	1.0041	1028.21	0.08807	21.5	0.11150	0.184840	2
602.0	1.0044	1026.91	0.08965	22.1	0.11180	0.184307	2
604.0	1.0047	1025.60	0.09128	22.9	0.11211	0.183758	2
606.0	1.0050	1024.25	0.09296	23.8	0.11246	0.183194	2
608.0	1.0052	1022.87	0.09471	24.4	0.11237	0.182615	2
610.0	1.0055	1021.48	0.09650	25.1	0.11228	0.182021	2
612.0	1.0058	1020.06	0.09834	25.8	0.11215	0.181413	2

614.0	1.0060	1018.62	0.10024	26.5	0.11196	0.180792	2
616.0	1.0063	1017.16	0.10218	27.3	0.11177	0.180157	2
618.0	1.0065	1015.66	0.10417	28.1	0.11132	0.179509	2
620.0	1.0067	1014.13	0.10621	28.8	0.11076	0.178850	2
622.0	1.0068	1012.58	0.10830	29.5	0.11009	0.178179	2
624.0	1.0069	1011.00	0.11042	30.2	0.10936	0.177498	2
626.0	1.0071	1009.39	0.11258	31.1	0.10859	0.176807	2
628.0	1.0072	1007.75	0.11479	31.8	0.10754	0.176106	2
630.0	1.0072	1006.09	0.11703	32.5	0.10637	0.175398	2
632.0	1.0072	1004.40	0.11930	33.2	0.10516	0.174682	2
634.0	1.0072	1002.68	0.12160	34.0	0.10374	0.173959	2
636.0	1.0072	1000.94	0.12393	34.7	0.10230	0.173231	2
638.0	1.0072	999.18	0.12628	35.5	0.10079	0.172498	2
640.0	1.0072	997.40	0.12865	36.3	0.09912	0.171762	2
642.0	1.0072	995.59	0.13103	37.0	0.09736	0.171023	2
644.0	1.0072	993.77	0.13343	37.9	0.09566	0.170283	2
646.0	1.0070	991.91	0.13584	38.5	0.09355	0.169542	2
648.0	1.0070	990.05	0.13826	39.3	0.09154	0.168802	2
650.0	1.0069	988.16	0.14067	40.0	0.08938	0.168064	2
652.0	1.0068	986.26	0.14309	40.8	0.08723	0.167329	2
654.0	1.0067	984.34	0.14549	41.5	0.08537	0.166598	2
656.0	1.0066	982.39	0.14789	42.3	0.08366	0.165872	2
658.0	1.0065	980.40	0.15027	43.0	0.08182	0.165153	2
660.0	1.0065	978.40	0.15263	43.8	0.08004	0.164442	2
662.0	1.0064	976.36	0.15496	44.5	0.07809	0.163740	2
664.0	1.0063	974.29	0.15727	45.3	0.07607	0.163048	2
666.0	1.0063	972.22	0.15955	46.3	0.07425	0.162367	2
668.0	1.0062	970.09	0.16179	47.0	0.07218	0.161699	2
670.0	1.0062	967.95	0.16398	47.8	0.07008	0.161044	2
672.0	1.0062	965.78	0.16614	48.8	0.06803	0.160404	2
674.0	1.0061	963.58	0.16824	49.7	0.06592	0.159781	2
676.0	1.0061	961.35	0.17029	50.4	0.06363	0.159174	2
678.0	1.0062	959.12	0.17229	51.6	0.06165	0.158586	2
680.0	1.0062	956.85	0.17422	52.7	0.05950	0.158017	2
682.0	1.0063	954.56	0.17608	53.8	0.05734	0.157469	2
684.0	1.0063	952.25	0.17788	54.9	0.05516	0.156942	2
686.0	1.0064	949.92	0.17961	56.0	0.05294	0.156437	2
688.0	1.0061	947.50	0.18126	54.9	0.05113	0.155956	2
690.0	1.0066	945.23	0.18282	58.3	0.04855	0.155499	2
692.0	1.0070	942.93	0.18430	60.5	0.04669	0.155067	2
694.0	1.0072	940.59	0.18569	62.1	0.04461	0.154661	2
696.0	1.0075	938.25	0.18699	63.8	0.04255	0.154282	2
698.0	1.0077	935.92	0.18820	65.3	0.04047	0.153930	2
700.0	1.0079	933.59	0.18932	66.5	0.03854	0.153607	2
702.0	1.0082	931.29	0.19033	67.7	0.03659	0.153312	2
704.0	1.0084	929.02	0.19124	68.8	0.03470	0.153046	2

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>--------------+--------------<
>                             <
>     CALCULATION RESULTS     <
>                             <
>--------------+--------------<
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--> VOLUMETRIC EFFICIENCY; (%) BASED ON: INTAKE / ATM	---->	79.8	34.0
--> PUMPING MEAN EFFECTIVE PRESSURE; (KPA) : PEMP	---->	-51.7	
--> GROSS INDICATED MEAN EFFECTIVE PRESSURE; (KPA) : IMEP	---->	434.3	
--> GROSS INDICATED SPECIFIC FUEL CONSUMPTION; (G/IKW-HR) : ISFC	---->	245.9	
--> GROSS INDICATED THERMAL EFFICIENCY; (%)	---->	33.0	
--> NET INDICATED THERMAL EFFICIENCY; (%)	---->	29.1	
--> (HEAT TRANSFER PER CYCLE)/ (MASS OF FUEL TIMES LHV); (%)	---->	39.1	
--> IGNITION DELAY (0 - 10%) (CRANK ANGLE) / (MS)	---->	15.32	1.70
--> BURN DURATION (10 - 90%) (CRANK ANGLE) / (MS)	---->	17.05	1.89
--> NOX EMISSIONS; (PPM) : NOX	---->	1475.	
--> GROSS INDICATED SPECIFIC NOX; (G/IKW-HR) : ISNO	---->	6.6	
--> MEAN EXHAUST TEMPERATURE; (K)	---->	1065.6	

MASS IN CYLINDER AT TIVO = 0.02390 G

MASS IN CYLINDER AT TIVC = 0.21593 G

MASS OF AIR INDUCTED = 0.17928 G

MASS OF FUEL INDUCTED = 0.01186 G

RESIDUAL FRACTION = 0.11413

HEATI = 0.004425 KJ (TIVO - 180)
WORKI = 0.019078 KJ

HEATC = 0.004244 KJ (180 - TSPARK)
WORKC = -0.061491 KJ

HEATCE = 0.186698 KJ (180 - 540)
WORKCE = 0.173715 KJ

HEATE = 0.015075 KJ (540 - TIVO)
WORKE = -0.039747 KJ

INITIAL ENTHALPY / CYCLE = -0.04406 KJ

TOTAL ENTHALPY IN / CYCLE = 0.04105 KJ

TOTAL ENTHALPY OUT / CYCLE = -0.31938 KJ

TOTAL HEAT LOSS / CYCLE = 0.20620 KJ

TOTAL WORK OUTPUT / CYCLE = 0.15305 KJ

RESIDUAL ENTHALPY / CYCLE = -0.04412 KJ

NET ENERGY GAIN / CYCLE = -0.00125 KJ

(ENERGY GAIN)/(H @ IVC) = 41.51837 %

(ENERGY GAIN)/(MFUEL*LHV) = -0.23695 %

1

FLAME PROPAGATION DATA

CA	VENONV	VBRONV	DFLONB	AFLONB	AHUONB	AHBONB	APUONB	APBONB	ACUONB	ACBONB
344.0	0.00037	0.00037	0.00001	0.00164	0.98262	0.00040	0.78539	0.0	0.08463	0.0
345.0	0.00059	0.00042	0.00161	0.00260	0.98257	0.00045	0.78539	0.0	0.07222	0.0
346.0	0.00107	0.00061	0.00406	0.00459	0.98238	0.00065	0.78539	0.0	0.05981	0.0

347.0	0.00200	0.00105	0.00831	0.00847	0.98193	0.00109	0.78539	0.0	0.05554	0.0
348.0	0.00382	0.00194	0.01609	0.01590	0.98103	0.00199	0.78539	0.0	0.05126	0.0
349.0	0.00736	0.00370	0.02576	0.02865	0.97927	0.00375	0.78539	0.0	0.04699	0.0
350.0	0.01329	0.00698	0.01233	0.04101	0.97610	0.00692	0.78539	0.0	0.04272	0.0
351.0	0.02245	0.01242	0.01938	0.05988	0.97153	0.01149	0.78539	0.0	0.03845	0.0
352.0	0.03640	0.02098	0.02889	0.08785	0.96441	0.01861	0.78539	0.0	0.03418	0.0
353.0	0.05633	0.03391	0.02152	0.11147	0.95378	0.02924	0.78539	0.0	0.02990	0.0
354.0	0.08307	0.05223	0.02609	0.14291	0.93971	0.04331	0.78539	0.0	0.02563	0.0
355.0	0.11820	0.07711	0.02937	0.17829	0.92099	0.06203	0.78539	0.0	0.02136	0.0
356.0	0.16216	0.10963	0.02623	0.21358	0.89723	0.08579	0.78539	0.0	0.01709	0.0
357.0	0.21572	0.15053	0.03235	0.25641	0.87107	0.11195	0.78539	0.0	0.01282	0.0
358.0	0.27723	0.20015	0.03176	0.26623	0.83943	0.14359	0.78539	0.0	0.00854	0.0
359.0	0.34305	0.25684	0.03365	0.27454	0.80353	0.17949	0.75647	0.02892	0.00427	0.0
360.0	0.41030	0.31838	0.03662	0.26238	0.76441	0.21861	0.70625	0.07915	0.0	0.0
361.0	0.47528	0.38181	0.03709	0.25090	0.72076	0.26227	0.66445	0.12094	0.00427	0.0
362.0	0.53708	0.44475	0.03818	0.24269	0.67148	0.31154	0.61845	0.16694	0.00854	0.0
363.0	0.59546	0.50578	0.03885	0.23667	0.62241	0.36062	0.56831	0.21709	0.01272	0.00009
364.0	0.65014	0.56407	0.03808	0.23001	0.56477	0.41825	0.51407	0.27132	0.01598	0.00111
365.0	0.70082	0.61910	0.03795	0.22268	0.51091	0.47211	0.46325	0.32214	0.01883	0.00253
366.0	0.74756	0.67054	0.03623	0.21484	0.46082	0.52220	0.41756	0.36783	0.02106	0.00457
367.0	0.78991	0.71819	0.03686	0.20116	0.41364	0.56938	0.37457	0.41082	0.02285	0.00705
368.0	0.82783	0.76175	0.03582	0.18860	0.36872	0.61430	0.33388	0.45152	0.02440	0.00978
369.0	0.86157	0.80118	0.03524	0.17515	0.32573	0.65729	0.29518	0.49022	0.02574	0.01271
370.0	0.89117	0.83651	0.03603	0.16105	0.28532	0.69770	0.25887	0.52652	0.02682	0.01590
371.0	0.91697	0.86788	0.03524	0.14150	0.24132	0.74170	0.22017	0.56522	0.02742	0.01957
372.0	0.93770	0.89515	0.03857	0.11330	0.20240	0.78062	0.18595	0.59945	0.02790	0.02337
373.0	0.95354	0.91793	0.03478	0.08784	0.15770	0.82532	0.14753	0.63787	0.02747	0.02807
374.0	0.96483	0.93624	0.04530	0.06023	0.11873	0.86430	0.11413	0.67126	0.02695	0.03285
375.0	0.97346	0.95051	0.03736	0.05570	0.09414	0.88888	0.09399	0.69140	0.03007	0.04215
376.0	0.98105	0.96192	0.02993	0.05221	0.07459	0.90843	0.07775	0.70765	0.03244	0.05219
377.0	0.98691	0.97118	0.03686	0.03691	0.05709	0.92593	0.06308	0.72231	0.03431	0.06273
378.0	0.99094	0.97846	0.04191	0.02344	0.04178	0.94124	0.05020	0.73519	0.03583	0.07362
379.0	0.99356	0.98399	0.02985	0.01697	0.02616	0.95686	0.03439	0.75101	0.03079	0.09107
380.0	0.99497	0.98796	0.0	0.01089	0.0	0.98302	0.0	0.78539	0.0	0.12026
381.0	0.99624	0.99084	0.0	0.01066	0.0	0.98302	0.0	0.78539	0.0	0.13237
382.0	0.99743	0.99305	0.0	0.01044	0.0	0.98302	0.0	0.78539	0.0	0.14502
383.0	0.99851	0.99484	0.0	0.01022	0.0	0.98302	0.0	0.78539	0.0	0.15821
384.0	0.99922	0.99626	0.0	0.01000	0.0	0.98302	0.0	0.78539	0.0	0.17194
385.0	0.99970	0.99737	0.0	0.00978	0.0	0.98302	0.0	0.78539	0.0	0.18619
386.0	0.99997	0.99820	0.0	0.00957	0.0	0.98302	0.0	0.78539	0.0	0.20097
387.0	0.99997	0.99878	0.0	0.00936	0.0	0.98302	0.0	0.78539	0.0	0.21626
388.0	0.99997	0.99916	0.0	0.00915	0.0	0.98302	0.0	0.78539	0.0	0.23205
389.0	0.99997	0.99941	0.0	0.00894	0.0	0.98302	0.0	0.78539	0.0	0.24834
390.0	0.99997	0.99958	0.0	0.00874	0.0	0.98302	0.0	0.78539	0.0	0.26513
391.0	0.99997	0.99970	0.0	0.00854	0.0	0.98302	0.0	0.78539	0.0	0.28239
392.0	0.99997	0.99978	0.0	0.00834	0.0	0.98302	0.0	0.78539	0.0	0.30013
393.0	0.99997	0.99983	0.0	0.00814	0.0	0.98302	0.0	0.78539	0.0	0.31834
394.0	0.99997	0.99987	0.0	0.00794	0.0	0.98302	0.0	0.78539	0.0	0.33700
395.0	0.99997	0.99990	0.0	0.00775	0.0	0.98302	0.0	0.78539	0.0	0.35611
396.0	0.99997	0.99992	0.0	0.00756	0.0	0.98302	0.0	0.78539	0.0	0.37566
397.0	0.99997	0.99993	0.0	0.00737	0.0	0.98302	0.0	0.78539	0.0	0.39564
398.0	0.99997	0.99994	0.0	0.00719	0.0	0.98302	0.0	0.78539	0.0	0.41605
399.0	0.99997	0.99995	0.0	0.00701	0.0	0.98302	0.0	0.78539	0.0	0.43686
400.0	0.99997	0.99995	0.0	0.00682	0.0	0.98302	0.0	0.78539	0.0	0.45807
401.0	0.99997	0.99996	0.0	0.00665	0.0	0.98302	0.0	0.78539	0.0	0.47968
402.0	0.99997	0.99996	0.0	0.00647	0.0	0.98302	0.0	0.78539	0.0	0.50166
403.0	0.99997	0.99996	0.0	0.00630	0.0	0.98302	0.0	0.78539	0.0	0.52402
404.0	0.99997	0.99996	0.0	0.00613	0.0	0.98302	0.0	0.78539	0.0	0.54674

405.0	0.99997	0.99997	0.0	0.00596	0.0	0.98302	0.0	0.78539	0.0	0.56981
406.0	0.99997	0.99997	0.0	0.00579	0.0	0.98302	0.0	0.78539	0.0	0.59321
407.0	0.99997	0.99997	0.0	0.00563	0.0	0.98302	0.0	0.78539	0.0	0.61695
408.0	0.99997	0.99997	0.0	0.00546	0.0	0.98302	0.0	0.78539	0.0	0.64101
409.0	0.99997	0.99997	0.0	0.00530	0.0	0.98302	0.0	0.78539	0.0	0.66537
410.0	0.99997	0.99997	0.0	0.00515	0.0	0.98302	0.0	0.78539	0.0	0.69002
411.0	0.99997	0.99997	0.0	0.00499	0.0	0.98302	0.0	0.78539	0.0	0.71496
412.0	0.99997	0.99997	0.0	0.00484	0.0	0.98302	0.0	0.78539	0.0	0.74018
413.0	0.99997	0.99997	0.0	0.00469	0.0	0.98302	0.0	0.78539	0.0	0.76566
414.0	0.99997	0.99997	0.0	0.00454	0.0	0.98302	0.0	0.78539	0.0	0.79138
415.0	0.99997	0.99997	0.0	0.00440	0.0	0.98302	0.0	0.78539	0.0	0.81735
416.0	0.99997	0.99997	0.0	0.00425	0.0	0.98302	0.0	0.78539	0.0	0.84355
417.0	0.99997	0.99997	0.0	0.00411	0.0	0.98302	0.0	0.78539	0.0	0.86996
418.0	0.99997	0.99997	0.0	0.00397	0.0	0.98302	0.0	0.78539	0.0	0.89658
419.0	0.99997	0.99997	0.0	0.00384	0.0	0.98302	0.0	0.78539	0.0	0.92339
420.0	0.99997	0.99997	0.0	0.00371	0.0	0.98302	0.0	0.78539	0.0	0.95038
421.0	0.99997	0.99997	0.0	0.00357	0.0	0.98302	0.0	0.78539	0.0	0.97754
422.0	0.99997	0.99997	0.0	0.00345	0.0	0.98302	0.0	0.78539	0.0	1.00486
423.0	0.99997	0.99997	0.0	0.00332	0.0	0.98302	0.0	0.78539	0.0	1.03233
424.0	0.99997	0.99997	0.0	0.00319	0.0	0.98302	0.0	0.78539	0.0	1.05994
425.0	0.99997	0.99997	0.0	0.00307	0.0	0.98302	0.0	0.78539	0.0	1.08767
426.0	0.99997	0.99997	0.0	0.00295	0.0	0.98302	0.0	0.78539	0.0	1.11551
427.0	0.99997	0.99997	0.0	0.00284	0.0	0.98302	0.0	0.78539	0.0	1.14345
428.0	0.99997	0.99997	0.0	0.00272	0.0	0.98302	0.0	0.78539	0.0	1.17149
429.0	0.99997	0.99997	0.0	0.00261	0.0	0.98302	0.0	0.78539	0.0	1.19960
430.0	0.99997	0.99997	0.0	0.00250	0.0	0.98302	0.0	0.78539	0.0	1.22778
431.0	0.99997	0.99997	0.0	0.00239	0.0	0.98302	0.0	0.78539	0.0	1.25602
432.0	0.99997	0.99997	0.0	0.00229	0.0	0.98302	0.0	0.78539	0.0	1.28430
433.0	0.99997	0.99997	0.0	0.00218	0.0	0.98302	0.0	0.78539	0.0	1.31262
434.0	0.99997	0.99997	0.0	0.00208	0.0	0.98302	0.0	0.78539	0.0	1.34096
435.0	0.99997	0.99997	0.0	0.00199	0.0	0.98302	0.0	0.78539	0.0	1.36932
436.0	0.99997	0.99997	0.0	0.00189	0.0	0.98302	0.0	0.78539	0.0	1.39767
437.0	0.99997	0.99997	0.0	0.00180	0.0	0.98302	0.0	0.78539	0.0	1.42602
438.0	0.99997	0.99997	0.0	0.00171	0.0	0.98302	0.0	0.78539	0.0	1.45434
439.0	0.99997	0.99997	0.0	0.00162	0.0	0.98302	0.0	0.78539	0.0	1.48265
440.0	0.99997	0.99997	0.0	0.00153	0.0	0.98302	0.0	0.78539	0.0	1.51091
441.0	0.99997	0.99997	0.0	0.00145	0.0	0.98302	0.0	0.78539	0.0	1.53912
442.0	0.99997	0.99997	0.0	0.00137	0.0	0.98302	0.0	0.78539	0.0	1.56727
443.0	0.99997	0.99997	0.0	0.00129	0.0	0.98302	0.0	0.78539	0.0	1.59535
444.0	0.99997	0.99997	0.0	0.00121	0.0	0.98302	0.0	0.78539	0.0	1.62336
445.0	0.99997	0.99997	0.0	0.00114	0.0	0.98302	0.0	0.78539	0.0	1.65127
446.0	0.99997	0.99997	0.0	0.00106	0.0	0.98302	0.0	0.78539	0.0	1.67909
447.0	0.99997	0.99997	0.0	0.00099	0.0	0.98302	0.0	0.78539	0.0	1.70680
448.0	0.99997	0.99997	0.0	0.00093	0.0	0.98302	0.0	0.78539	0.0	1.73440
449.0	0.99997	0.99997	0.0	0.00086	0.0	0.98302	0.0	0.78539	0.0	1.76187
450.0	0.99997	0.99997	0.0	0.00080	0.0	0.98302	0.0	0.78539	0.0	1.78921
451.0	0.99997	0.99997	0.0	0.00074	0.0	0.98302	0.0	0.78539	0.0	1.81641
452.0	0.99997	0.99997	0.0	0.00068	0.0	0.98302	0.0	0.78539	0.0	1.84346
453.0	0.99997	0.99997	0.0	0.00063	0.0	0.98302	0.0	0.78539	0.0	1.87035
454.0	0.99997	0.99997	0.0	0.00057	0.0	0.98302	0.0	0 78539	0.0	1.89708
455.0	0.99997	0.99997	0.0	0.00052	0.0	0.98302	0.0	0.78539	0.0	1.92363
456.0	0.99997	0.99997	0.0	0.00047	0.0	0.98302	0.0	0.78539	0.0	1.95000
457.0	0.99997	0.99997	0.0	0.00043	0.0	0.98302	0.0	0.78539	0.0	1.97619
458.0	0.99997	0.99997	0.0	0.00038	0.0	0.98302	0.0	0.78539	0.0	2.00218
459.0	0.99997	0.99997	0.0	0.00034	0.0	0.98302	0.0	0.78539	0.0	2.02797
460.0	0.99997	0.99997	0.0	0.00030	0.0	0.98302	0.0	0.78539	0.0	2.05356
461.0	0.99997	0.99997	0.0	0.00027	0.0	0.98302	0.0	0.78539	0.0	2.07893
462.0	0.99997	0.99997	0.0	0.00023	0.0	0.98302	0.0	0.78539	0.0	2.10407

463.0	0.99997	0.99997	0.0	0.00020	0.0	0.98302	0.0	0.78539	0.0	2.12899
464.0	0.99997	0.99997	0.0	0.00017	0.0	0.98302	0.0	0.78539	0.0	2.15368
465.0	0.99997	0.99997	0.0	0.00014	0.0	0.98302	0.0	0.78539	0.0	2.17812
466.0	0.99997	0.99997	0.0	0.00012	0.0	0.98302	0.0	0.78539	0.0	2.20233
467.0	0.99997	0.99997	0.0	0.00010	0.0	0.98302	0.0	0.78539	0.0	2.22628
468.0	0.99997	0.99997	0.0	0.00008	0.0	0.98302	0.0	0.78539	0.0	2.24998
469.0	0.99997	0.99997	0.0	0.00006	0.0	0.98302	0.0	0.78539	0.0	2.27342
470.0	0.99997	0.99997	0.0	0.00004	0.0	0.98302	0.0	0.78539	0.0	2.29660
471.0	0.99997	0.99997	0.0	0.00003	0.0	0.98302	0.0	0.78539	0.0	2.31950
472.0	0.99997	0.99997	0.0	0.00002	0.0	0.98302	0.0	0.78539	0.0	2.34213
473.0	0.99997	0.99997	0.0	0.00001	0.0	0.98302	0.0	0.78539	0.0	2.36449
474.0	0.99997	0.99997	0.0	0.00000	0.0	0.98302	0.0	0.78539	0.0	2.38656
475.0	0.99997	0.99997	0.0	0.00000	0.0	0.98302	0.0	0.78539	0.0	2.40835
476.0	0.99997	0.99997	0.0	0.0	0.0	0.98302	0.0	0.78539	0.0	2.42985

1

ADIABATIC CORE / BOUNDARY LAYER DATA

CA	YAC	YBL	VACONV	VBLONV	DBLONB	TWALLB	TB	TAC	TBLAYR
344.0	0.000098	0.000002	0.000361	0.000004	0.001303	400.0	2352.7	2367.8	1376.3
345.0	0.000112	0.000003	0.000409	0.000006	0.001609	400.0	2354.4	2373.2	1377.2
346.0	0.000164	0.000004	0.000600	0.000008	0.001510	400.0	2356.1	2373.8	1378.1
347.0	0.000283	0.000006	0.001034	0.000012	0.001263	400.0	2357.8	2372.6	1378.9
348.0	0.000528	0.000009	0.001920	0.000018	0.001056	400.0	2359.5	2371.9	1379.7
349.0	0.001014	0.000015	0.003674	0.000030	0.000922	400.0	2361.2	2372.0	1380.6
350.0	0.001922	0.000026	0.006930	0.000054	0.000868	400.0	2363.0	2373.1	1381.5
351.0	0.003442	0.000046	0.012329	0.000094	0.000907	400.0	2365.0	2375.0	1382.5
352.0	0.005865	0.000079	0.020821	0.000161	0.000945	400.0	2367.6	2377.7	1383.8
353.0	0.009593	0.000133	0.033646	0.000268	0.000989	400.0	2370.8	2381.2	1385.4
354.0	0.015017	0.000217	0.051797	0.000430	0.001061	400.0	2374.8	2385.7	1387.4
355.0	0.022663	0.000342	0.076446	0.000662	0.001132	400.0	2380.0	2391.4	1390.0
356.0	0.033162	0.000525	0.108642	0.000985	0.001210	400.0	2386.6	2398.6	1393.3
357.0	0.047248	0.000777	0.149131	0.001404	0.001315	400.0	2395.0	2407.4	1397.5
358.0	0.065780	0.001120	0.198221	0.001930	0.001404	400.0	2405.3	2418.2	1402.6
359.0	0.089107	0.001607	0.254221	0.002618	0.001309	400.0	2416.9	2430.7	1408.5
360.0	0.117341	0.002372	0.314754	0.003626	0.001269	400.0	2429.0	2444.4	1414.5
361.0	0.150143	0.003473	0.376850	0.004958	0.001349	400.0	2441.1	2458.9	1420.6
362.0	0.187037	0.004970	0.438143	0.006607	0.001442	400.0	2453.0	2473.4	1426.5
363.0	0.227683	0.006932	0.497209	0.008569	0.001555	400.0	2464.3	2487.8	1432.1
364.0	0.271777	0.009457	0.553203	0.010870	0.001659	400.0	2474.7	2501.6	1437.3
365.0	0.318965	0.012615	0.605612	0.013488	0.001796	400.0	2484.0	2514.7	1442.0
366.0	0.368834	0.016434	0.654170	0.016371	0.001956	400.0	2492.3	2527.0	1446.2
367.0	0.420833	0.020929	0.698722	0.019465	0.002127	400.0	2499.5	2538.3	1449.7
368.0	0.474001	0.026121	0.738993	0.022753	0.002307	400.0	2505.3	2548.3	1452.6
369.0	0.527410	0.032025	0.774955	0.026223	0.002494	400.0	2509.5	2557.1	1454.8
370.0	0.580019	0.038639	0.806643	0.029869	0.002692	400.0	2512.2	2564.4	1456.1
371.0	0.630814	0.045963	0.834179	0.033699	0.002880	400.0	2513.1	2570.2	1456.5
372.0	0.678176	0.053970	0.857417	0.037733	0.003095	400.0	2512.0	2574.3	1456.0
373.0	0.719654	0.062632	0.875886	0.042041	0.003298	400.0	2508.3	2576.5	1454.2
374.0	0.753570	0.071911	0.889559	0.046684	0.003543	400.0	2501.9	2576.5	1450.9
375.0	0.779479	0.081574	0.898927	0.051583	0.003853	400.0	2492.8	2574.4	1446.4
376.0	0.799361	0.091437	0.905308	0.056612	0.004192	400.0	2481.9	2570.7	1440.9

377.0	0.814453	0.101394	0.909471	0.061711	0.004544	400.0	2469.4	2565.8	1434.7
378.0	0.824793	0.111351	0.911588	0.066874	0.004914	400.0	2455.5	2559.6	1427.7
379.0	0.830679	0.121257	0.911879	0.072109	0.005265	400.0	2440.1	2552.2	1420.1
380.0	0.832323	0.131289	0.910415	0.077545	0.005511	400.0	2423.2	2543.7	1411.6
381.0	0.831097	0.141114	0.907867	0.082970	0.005991	400.0	2405.3	2534.4	1402.6
382.0	0.828297	0.150575	0.904794	0.088255	0.006477	400.0	2386.9	2524.4	1393.5
383.0	0.824607	0.159671	0.901459	0.093377	0.006966	400.0	2368.4	2514.1	1384.2
384.0	0.820183	0.168411	0.897913	0.098344	0.007458	400.0	2349.6	2503.4	1374.8
385.0	0.815171	0.176803	0.894205	0.103162	0.007955	400.0	2330.7	2492.3	1365.3
386.0	0.809647	0.184857	0.890358	0.107840	0.008455	400.0	2311.6	2480.9	1355.8
387.0	0.803688	0.192585	0.886392	0.112385	0.008960	400.0	2292.4	2469.2	1346.2
388.0	0.797437	0.199998	0.882359	0.116798	0.009469	400.0	2273.1	2457.2	1336.5
389.0	0.791097	0.207110	0.878336	0.121074	0.009981	400.0	2253.8	2445.0	1326.9
390.0	0.784791	0.213935	0.874368	0.125213	0.010495	400.0	2234.6	2432.7	1317.3
391.0	0.778589	0.220488	0.870480	0.129216	0.011011	400.0	2215.5	2420.3	1307.8
392.0	0.772532	0.226787	0.866686	0.133089	0.011530	400.0	2196.6	2407.8	1298.3
393.0	0.766641	0.232845	0.862994	0.136836	0.012049	400.0	2177.9	2395 3	1288.9
394.0	0.760926	0.238676	0.859403	0.140465	0.012570	400.0	2159.3	2382.7	1279.7
395.0	0.755390	0.244295	0.855915	0.143981	0.013093	400.0	2141.0	2370.2	1270.5
396.0	0.750030	0.249715	0.852525	0.147390	0.013617	400.0	2122.8	2357.6	1261.4
397.0	0.744840	0.254947	0.849230	0.150699	0.014142	400.0	2104.9	2345.1	1252.5
398.0	0.739815	0.260002	0.846027	0.153913	0.014668	400.0	2087.2	2332.6	1243.6
399.0	0.734948	0.264892	0.842910	0.157037	0.015195	400.0	2069.8	2320.1	1234.9
400.0	0.730230	0.269627	0.839876	0.160077	0.015723	400.0	2052.6	2307.7	1226.3
401.0	0.725655	0.274215	0.836919	0.163038	0.016251	400.0	2035.6	2295.3	1217.8
402.0	0.721215	0.278664	0.834036	0.165923	0.016781	400.0	2018.9	2283.0	1209.5
403.0	0.716902	0.282984	0.831223	0.168739	0.017310	400.0	2002.5	2270.8	1201.2
404.0	0.712710	0.287182	0.828476	0.171488	0.017840	400.0	1986.3	2258.7	1193.1
405.0	0.708632	0.291264	0.825791	0.174174	0.018371	400.0	1970.3	2246.7	1185.2
406.0	0.704662	0.295237	0.823165	0.176801	0.018901	400.0	1954.6	2234.7	1177.3
407.0	0.700795	0.299107	0.820594	0.179372	0.019431	400.0	1939.1	2222.9	1169.6
408.0	0.697024	0.302880	0.818077	0.181891	0.019961	400.0	1923.9	2211.2	1162.0
409.0	0.693345	0.306560	0.815609	0.184359	0.020491	400.0	1909.0	2199.5	1154.5
410.0	0.689753	0.310154	0.813189	0.186779	0.021020	400.0	1894.3	2188.0	1147.1
411.0	0.686243	0.313664	0.810814	0.189155	0.021549	400.0	1879.9	2176.6	1139.9
412.0	0.682811	0.317097	0.808481	0.191488	0.022076	400.0	1865.7	2165.4	1132.8
413.0	0.679454	0.320454	0.806189	0.193780	0.022603	400.0	1851.7	2154.2	1125.9
414.0	0.676168	0.323741	0.803936	0.196033	0.023129	400.0	1838.0	2143.2	1119.0
415.0	0.672949	0.326960	0.801719	0.198250	0.023653	400.0	1824.5	2132.3	1112.3
416.0	0.669795	0.330115	0.799538	0.200431	0.024176	400.0	1811.3	2121.6	1105.7
417.0	0.666701	0.333209	0.797390	0.202580	0.024697	400.0	1798.3	2111.0	1099.2
418.0	0.663665	0.336245	0.795272	0.204698	0.025217	400.0	1785.6	2100.5	1092.8
419.0	0.660683	0.339227	0.793184	0.206786	0.025736	400.0	1773.1	2090.1	1086.5
420.0	0.657753	0.342158	0.791124	0.208846	0.026253	400.0	1760.8	2079.9	1080.4
421.0	0.654873	0.345038	0.789091	0.210879	0.026767	400.0	1748.7	2069.8	1074.4
422.0	0.652040	0.347871	0.787085	0.212885	0.027280	400.0	1736.9	2059.9	1068.4
423.0	0.649253	0.350658	0.785104	0.214866	0.027791	400.0	1725.3	2050.1	1062.6
424.0	0.646510	0.353402	0.783148	0.216822	0.028299	400.0	1713.9	2040.4	1056.9
425.0	0.643809	0.356102	0.781215	0.218755	0.028805	400.0	1702.7	2030.9	1051.3
426.0	0.641149	0.358763	0.779304	0.220666	0.029309	400.0	1691.7	2021.5	1045.8
427.0	0.638528	0.361384	0.777415	0.222555	0.029810	400.0	1680.9	2012.2	1040.5
428.0	0.635945	0.363966	0.775548	0.224422	0.030308	400.0	1670.4	2003.1	1035.2
429.0	0.633399	0.366513	0.773702	0.226268	0.030804	400.0	1660.0	1994.1	1030.0
430.0	0.630888	0.369023	0.771876	0.228094	0.031297	400.0	1649.8	1985.3	1024.9
431.0	0.628412	0.371499	0.770069	0.229901	0.031787	400.0	1639.8	1976.6	1019.9
432.0	0.625970	0.373942	0.768282	0.231688	0.032274	400.0	1630.0	1968.0	1015.0
433.0	0.623559	0.376352	0.766513	0.233456	0.032758	400.0	1620.4	1959.6	1010.2
434.0	0.621181	0.378731	0.764762	0.235207	0.033239	400.0	1611.0	1951.3	1005.5

435.0	0.618833	0.381079	0.763030	0.236940	0.033716	400.0	1601.7	1943.1	1000.9
436.0	0.616515	0.383397	0.761316	0.238654	0.034190	400.0	1592.6	1935.1	996.3
437.0	0.614227	0.385684	0.759619	0.240350	0.034661	400.0	1583.7	1927.3	991.9
438.0	0.611969	0.387942	0.757941	0.242029	0.035128	400.0	1575.0	1919.6	987.5
439.0	0.609740	0.390172	0.756279	0.243690	0.035592	400.0	1566.4	1912.0	983.2
440.0	0.607538	0.392373	0.754634	0.245335	0.036052	400.0	1558.0	1904.5	979.0
441.0	0.605364	0.394547	0.753006	0.246963	0.036508	400.0	1549.8	1897.2	974.9
442.0	0.603217	0.396695	0.751394	0.248576	0.036961	400.0	1541.7	1890.0	970.8
443.0	0.601096	0.398816	0.749797	0.250173	0.037410	400.0	1533.7	1882.9	966.9
444.0	0.599000	0.400912	0.748215	0.251754	0.037855	400.0	1525.9	1876.0	963.0
445.0	0.596929	0.402982	0.746650	0.253319	0.038297	400.0	1518.3	1869.1	959.1
446.0	0.594883	0.405028	0.745099	0.254870	0.038734	400.0	1510.8	1862.4	955.4
447.0	0.592861	0.407051	0.743564	0.256406	0.039168	400.0	1503.4	1855.8	951.7
448.0	0.590863	0.409049	0.742042	0.257927	0.039598	400.0	1496.2	1849.3	948.1
449.0	0.588887	0.411024	0.740537	0.259432	0.040024	400.0	1489.1	1843.0	944.5
450.0	0.586935	0.412977	0.739044	0.260925	0.040446	400.0	1482.1	1836.7	941.1
451.0	0.585004	0.414907	0.737567	0.262403	0.040864	400.0	1475.3	1830.6	937.7
452.0	0.583096	0.416816	0.736104	0.263866	0.041278	400.0	1468.6	1824.6	934.3
453.0	0.581209	0.418703	0.734653	0.265316	0.041689	400.0	1462.0	1818.7	931.0
454.0	0.579343	0.420568	0.733217	0.266752	0.042095	400.0	1455.6	1812.9	927.8
455.0	0.577498	0.422413	0.731794	0.268175	0.042497	400.0	1449.3	1807.2	924.6
456.0	0.575674	0.424238	0.730385	0.269584	0.042896	400.0	1443.1	1801.6	921.5
457.0	0.573869	0.426042	0.728988	0.270981	0.043290	400.0	1437.0	1796.1	918.5
458.0	0.572085	0.427827	0.727606	0.272364	0.043680	400.0	1431.0	1790.8	915.5
459.0	0.570320	0.429592	0.726235	0.273733	0.044067	400.0	1425.1	1785.5	912.6
460.0	0.568574	0.431338	0.724879	0.275090	0.044449	400.0	1419.3	1780.3	909.7
461.0	0.566847	0.433065	0.723535	0.276435	0.044828	400.0	1413.7	1775.2	906.8
462.0	0.565139	0.434773	0.722203	0.277766	0.045202	400.0	1408.1	1770.2	904.1
463.0	0.563449	0.436463	0.720883	0.279086	0.045572	400.0	1402.7	1765.4	901.3
464.0	0.561777	0.438135	0.719576	0.280393	0.045939	400.0	1397.4	1760.6	898.7
465.0	0.560123	0.439789	0.718281	0.281688	0.046301	400.0	1392.1	1755.9	896.1
466.0	0.558487	0.441425	0.716999	0.282970	0.046660	400.0	1387.0	1751.3	893.5
467.0	0.556867	0.443044	0.715728	0.284241	0.047014	400.0	1381.9	1746.8	891.0
468.0	0.555265	0.444646	0.714470	0.285499	0.047365	400.0	1376.9	1742.3	888.5
469.0	0.553680	0.446232	0.713223	0.286746	0.047712	400.0	1372.1	1738.0	886.0
470.0	0.552111	0.447800	0.711988	0.287981	0.048054	400.0	1367.3	1733.8	883.7
471.0	0.550559	0.449353	0.710764	0.289205	0.048393	400.0	1362.6	1729.6	881.3
472.0	0.549023	0.450889	0.709553	0.290416	0.048728	400.0	1358.0	1725.5	879.0
473.0	0.547503	0.452409	0.708352	0.291617	0.049059	400.0	1353.5	1721.5	876.7
474.0	0.545998	0.453913	0.707163	0.292806	0.049387	400.0	1349.1	1717.6	874.5
475.0	0.544509	0.455402	0.705985	0.293984	0.049710	400.0	1344.7	1713.8	872.4
476.0	0.543036	0.456876	0.704818	0.295151	0.050030	400.0	1340.4	1710.0	870.2

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NOX FORMATION

CA	YAC	YBL	YNOAC	YNOBL	YNO	XNOAC	XNOBL	XNO	PPMAC	PPMBL	PPMNO
344.0	0.000098	0.000002	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
345.0	0.000112	0.000003	0.001949	0.000350	0.000000	0.001844	0.000015	0.000000	1844.13	14.79	0.22
346.0	0.000164	0.000004	0.002705	0.001125	0.000000	0.002560	0.000048	0.000000	2560.26	47.56	0.44
347.0	0.000283	0.000006	0.002861	0.002156	0.000001	0.002708	0.000091	0.000001	2707.93	91.11	0.82
348.0	0.000528	0.000009	0.002877	0.003426	0.000002	0.002723	0.000145	0.000002	2723.44	144.75	1.53

349.0	0.001014	0.000015	0.002872	0.004913	0.000003	0.002718	0.000208	0.000003	2718.03	207.58	2.94
350.0	0.001922	0.000026	0.002868	0.006555	0.000006	0.002715	0.000277	0.000006	2715.11	276.95	5.56
351.0	0.003442	0.000046	0.002874	0.008191	0.000010	0.002720	0.000346	0.000010	2720.40	346.08	9.98
352.0	0.005865	0.000079	0.002888	0.009759	0.000018	0.002733	0.000412	0.000017	2733.27	412.32	17.10
353.0	0.009593	0.000133	0.002909	0.011267	0.000029	0.002753	0.000476	0.000028	2753.07	475.98	28.18
354.0	0.015017	0.000217	0.002939	0.012697	0.000047	0.002781	0.000536	0.000045	2781.12	536.36	44.56
355.0	0.022663	0.000342	0.002979	0.014043	0.000072	0.002819	0.000593	0.000068	2819.17	593.20	68.17
356.0	0.033162	0.000525	0.003033	0.015326	0.000109	0.002870	0.000647	0.000102	2869.53	647.33	101.52
357.0	0.047248	0.000777	0.003103	0.016532	0.000159	0.002935	0.000698	0.000148	2935.23	698.14	147.90
358.0	0.065780	0.001120	0.003192	0.017680	0.000230	0.003019	0.000747	0.000212	3018.96	746.51	211.63
359.0	0.089107	0.001607	0.003300	0.018851	0.000324	0.003121	0.000796	0.000296	3120.74	795.85	296.08
360.0	0.117341	0.002372	0.003425	0.020161	0.000450	0.003238	0.000851	0.000404	3238.04	850.97	404.24
361.0	0.150143	0.003473	0.003563	0.021492	0.000610	0.003367	0.000907	0.000537	3367.24	907.02	537.39
362.0	0.187037	0.004970	0.003706	0.022794	0.000806	0.003502	0.000962	0.000695	3501.66	961.80	695.45
363.0	0.227683	0.006932	0.003849	0.024051	0.001043	0.003636	0.001015	0.000878	3636.27	1014.65	878.07
364.0	0.271777	0.009457	0.003989	0.025268	0.001323	0.003768	0.001066	0.001085	3767.59	1065.87	1084.53
365.0	0.318965	0.012615	0.004123	0.026437	0.001649	0.003893	0.001115	0.001313	3893.34	1115.01	1313.37
366.0	0.368834	0.016434	0.004249	0.027544	0.002020	0.004012	0.001162	0.001562	4011.52	1161.57	1562.20
367.0	0.420833	0.020929	0.004366	0.028585	0.002435	0.004120	0.001205	0.001827	4120.42	1205.37	1827.46
368.0	0.474001	0.026121	0.004470	0.029564	0.002891	0.004218	0.001247	0.002103	4217.70	1246.56	2102.87
369.0	0.527410	0.032025	0.004559	0.030484	0.003381	0.004302	0.001285	0.002382	4301.66	1285.28	2381.77
370.0	0.580019	0.038639	0.004633	0.031348	0.003899	0.004371	0.001322	0.002657	4370.98	1321.63	2656.68
371.0	0.630814	0.045963	0.004690	0.032157	0.004437	0.004425	0.001356	0.002920	4424.55	1355.74	2920.01
372.0	0.678176	0.053970	0.004729	0.032913	0.004983	0.004461	0.001388	0.003161	4460.83	1387.67	3161.10
373.0	0.719654	0.062632	0.004745	0.033619	0.005521	0.004476	0.001417	0.003364	4476.22	1417.48	3364.21
374.0	0.753570	0.071911	0.004737	0.034274	0.006035	0.004469	0.001445	0.003519	4469.14	1445.25	3518.62
375.0	0.779479	0.081574	0.004706	0.034870	0.006513	0.004440	0.001471	0.003621	4440.10	1470.56	3620.99
376.0	0.799361	0.091437	0.004657	0.035404	0.006960	0.004394	0.001493	0.003683	4394.00	1493.34	3682.76
377.0	0.814453	0.101394	0.004593	0.035883	0.007379	0.004335	0.001514	0.003712	4334.81	1513.79	3712.23
378.0	0.824793	0.111351	0.004517	0.036309	0.007769	0.004263	0.001532	0.003711	4263.42	1532.11	3710.58
379.0	0.830679	0.121257	0.004429	0.036691	0.008128	0.004181	0.001549	0.003681	4180.81	1548.55	3680.50
380.0	0.832323	0.131289	0.004329	0.037039	0.008466	0.004088	0.001564	0.003625	4087.91	1563.64	3624.80
381.0	0.831097	0.141114	0.004222	0.037348	0.008780	0.003988	0.001577	0.003552	3988.11	1577.09	3552.06
382.0	0.828297	0.150575	0.004111	0.037618	0.009070	0.003884	0.001589	0.003470	3884.08	1588.95	3469.83
383.0	0.824607	0.159671	0.003998	0.037856	0.009341	0.003778	0.001599	0.003383	3777.73	1599.45	3382.60
384.0	0.820183	0.168411	0.003883	0.038066	0.009595	0.003670	0.001609	0.003292	3670.08	1608.79	3292.06
385.0	0.815171	0.176803	0.003767	0.038252	0.009834	0.003562	0.001617	0.003199	3561.59	1617.13	3199.29
386.0	0.809647	0.184857	0.003651	0.038417	0.010058	0.003453	0.001625	0.003105	3452.81	1624.60	3105.20
387.0	0.803688	0.192585	0.003535	0.038564	0.010268	0.003344	0.001631	0.003011	3344.30	1631.33	3010.64
388.0	0.797437	0.199998	0.003421	0.038696	0.010467	0.003237	0.001637	0.002917	3236.57	1637.40	2916.60
389.0	0.791097	0.207110	0.003308	0.038813	0.010655	0.003130	0.001643	0.002824	3130.41	1642.90	2824.40
390.0	0.784791	0.213935	0.003197	0.038919	0.010835	0.003026	0.001648	0.002735	3026.46	1647.89	2734.89
391.0	0.778589	0.220488	0.003089	0.039014	0.011007	0.002925	0.001652	0.002649	2925.26	1652.44	2648.67
392.0	0.772532	0.226787	0.002985	0.039099	0.011173	0.002827	0.001657	0.002566	2827.22	1656.60	2566.11
393.0	0.766641	0.232845	0.002884	0.039177	0.011333	0.002733	0.001660	0.002487	2732.67	1660.42	2487.44
394.0	0.760926	0.238676	0.002788	0.039247	0.011489	0.002642	0.001664	0.002413	2641.87	1663.95	2412.80
395.0	0.755390	0.244295	0.002696	0.039311	0.011640	0.002555	0.001667	0.002342	2555.01	1667.20	2342.26
396.0	0.750030	0.249715	0.002608	0.039369	0.011787	0.002472	0.001670	0.002276	2472.27	1670.23	2275.85
397.0	0.744840	0.254947	0.002524	0.039422	0.011931	0.002394	0.001673	0.002214	2393.75	1673.04	2213.57
398.0	0.739815	0.260002	0.002445	0.039471	0.012072	0.002320	0.001676	0.002155	2319.52	1675.67	2155.35
399.0	0.734948	0.264892	0.002371	0.039516	0.012210	0.002250	0.001678	0.002101	2249.61	1678.14	2101.13
400.0	0.730230	0.269627	0.002302	0.039557	0.012346	0.002184	0.001680	0.002051	2184.00	1680.46	2050.80
401.0	0.725655	0.274215	0.002237	0.039595	0.012481	0.002123	0.001683	0.002004	2122.66	1682.65	2004.25
402.0	0.721215	0.278664	0.002176	0.039631	0.012613	0.002065	0.001685	0.001961	2065.48	1684.73	1961.31
403.0	0.716902	0.282984	0.002120	0.039664	0.012744	0.002012	0.001687	0.001922	2012.37	1686.70	1921.85
404.0	0.712710	0.287182	0.002067	0.039695	0.012873	0.001963	0.001689	0.001886	1963.16	1688.58	1885.67
405.0	0.708632	0.291264	0.002019	0.039724	0.013001	0.001918	0.001690	0.001853	1917.70	1690.38	1852.59
406.0	0.704662	0.295237	0.001975	0.039751	0.013127	0.001876	0.001692	0.001822	1875.81	1692.10	1822.43

407.0	0.700795	0.299107	0.001934	0.039776	0.013252	0.001837	0.001694	0.001795	1837.27	1693.76	1794.98
408.0	0.697024	0.302880	0.001896	0.039800	0.013376	0.001802	0.001695	0.001770	1801.88	1695.35	1770.05
409.0	0.693345	0.306560	0.001862	0.039823	0.013499	0.001769	0.001697	0.001747	1769.42	1696.88	1747.43
410.0	0.689753	0.310154	0.001830	0.039844	0.013620	0.001740	0.001698	0.001727	1739.69	1698.37	1726.95
411.0	0.686243	0.313664	0.001801	0.039865	0.013740	0.001712	0.001700	0.001708	1712.46	1699.81	1708.41
412.0	0.682811	0.317097	0.001775	0.039884	0.013859	0.001688	0.001701	0.001692	1687.52	1701.20	1691.64
413.0	0.679454	0.320454	0.001751	0.039903	0.013977	0.001665	0.001703	0.001676	1664.69	1702.56	1676.47
414.0	0.676168	0.323741	0.001728	0.039920	0.014093	0.001644	0.001704	0.001663	1643.75	1703.88	1662.75
415.0	0.672949	0.326960	0.001708	0.039937	0.014207	0.001625	0.001705	0.001650	1624.55	1705.17	1650.33
416.0	0.669795	0.330115	0.001689	0.039954	0.014321	0.001607	0.001706	0.001639	1606.89	1706.42	1639.08
417.0	0.666701	0.333209	0.001672	0.039969	0.014433	0.001591	0.001708	0.001629	1590.64	1707.70	1628.89
418.0	0.663665	0.336245	0.001656	0.039985	0.014544	0.001576	0.001709	0.001620	1575.65	1709.31	1619.75
419.0	0.660683	0.339227	0.001641	0.039999	0.014653	0.001562	0.001711	0.001611	1561.77	1710.87	1611.44
420.0	0.657753	0.342158	0.001628	0.040013	0.014761	0.001549	0.001712	0.001604	1548.89	1712.40	1603.86
421.0	0.654873	0.345038	0.001615	0.040027	0.014868	0.001537	0.001714	0.001597	1536.91	1713.89	1596.93
422.0	0.652040	0.347871	0.001603	0.040040	0.014974	0.001526	0.001715	0.001591	1525.73	1715.34	1590.58
423.0	0.649253	0.350658	0.001592	0.040053	0.015078	0.001515	0.001717	0.001585	1515.25	1716.76	1584.75
424.0	0.646510	0.353402	0.001582	0.040065	0.015182	0.001505	0.001718	0.001579	1505.40	1718.14	1579.37
425.0	0.643809	0.356102	0.001572	0.040077	0.015283	0.001496	0.001719	0.001574	1496.12	1719.48	1574.40
426.0	0.641149	0.358763	0.001562	0.040089	0.015384	0.001487	0.001721	0.001570	1487.33	1720.80	1569.78
427.0	0.638528	0.361384	0.001554	0.040100	0.015483	0.001479	0.001722	0.001565	1478.99	1722.08	1565.48
428.0	0.635945	0.363966	0.001545	0.040111	0.015582	0.001471	0.001723	0.001561	1471.04	1723.33	1561.47
429.0	0.633399	0.366513	0.001537	0.040122	0.015679	0.001463	0.001725	0.001558	1463.44	1724.55	1557.71
430.0	0.630888	0.369023	0.001529	0.040132	0.015775	0.001456	0.001726	0.001554	1456.16	1725.74	1554.17
431.0	0.628412	0.371499	0.001522	0.040142	0.015869	0.001449	0.001727	0.001551	1449.16	1726.90	1550.83
432.0	0.625970	0.373942	0.001515	0.040152	0.015963	0.001442	0.001728	0.001548	1442.41	1728.03	1547.67
433.0	0.623559	0.376352	0.001508	0.040162	0.016055	0.001436	0.001729	0.001545	1435.89	1729.14	1544.67
434.0	0.621181	0.378731	0.001501	0.040172	0.016147	0.001430	0.001730	0.001542	1429.57	1730.21	1541.82
435.0	0.618833	0.381079	0.001495	0.040181	0.016237	0.001423	0.001731	0.001539	1423.44	1731.26	1539.09
436.0	0.616515	0.383397	0.001488	0.040190	0.016326	0.001417	0.001732	0.001536	1417.48	1732.10	1536.42
437.0	0.614227	0.385684	0.001482	0.040199	0.016414	0.001412	0.001733	0.001534	1411.68	1732.87	1533.84
438.0	0.611969	0.387942	0.001476	0.040207	0.016501	0.001406	0.001734	0.001531	1406.01	1733.64	1531.36
439.0	0.609740	0.390172	0.001470	0.040216	0.016588	0.001400	0.001734	0.001529	1400.48	1734.39	1528.98
440.0	0.607538	0.392373	0.001465	0.040224	0.016673	0.001395	0.001735	0.001527	1395.06	1735.12	1526.68
441.0	0.605364	0.394547	0.001459	0.040232	0.016757	0.001390	0.001736	0.001524	1389.76	1735.85	1524.47
442.0	0.603217	0.396695	0.001453	0.040240	0.016840	0.001385	0.001737	0.001522	1384.56	1736.56	1522.33
443.0	0.601096	0.398816	0.001448	0.040248	0.016922	0.001379	0.001737	0.001520	1379.46	1737.26	1520.26
444.0	0.599000	0.400912	0.001443	0.040255	0.017003	0.001374	0.001738	0.001518	1374.45	1737.95	1518.25
445.0	0.596929	0.402982	0.001438	0.040263	0.017083	0.001370	0.001739	0.001516	1369.52	1738.63	1516.30
446.0	0.594883	0.405028	0.001432	0.040270	0.017163	0.001365	0.001739	0.001514	1364.67	1739.30	1514.42
447.0	0.592861	0.407051	0.001427	0.040277	0.017241	0.001360	0.001740	0.001513	1359.90	1739.95	1512.58
448.0	0.590863	0.409049	0.001422	0.040284	0.017319	0.001355	0.001741	0.001511	1355.21	1740.60	1510.80
449.0	0.588887	0.411024	0.001418	0.040291	0.017395	0.001351	0.001741	0.001509	1350.57	1741.24	1509.07
450.0	0.586935	0.412977	0.001413	0.040298	0.017471	0.001346	0.001742	0.001507	1346.01	1741.86	1507.38
451.0	0.585004	0.414907	0.001408	0.040304	0.017546	0.001342	0.001742	0.001506	1341.51	1742.48	1505.73
452.0	0.583096	0.416816	0.001403	0.040311	0.017620	0.001337	0.001743	0.001504	1337.07	1743.08	1504.13
453.0	0.581209	0.418703	0.001399	0.040317	0.017694	0.001333	0.001744	0.001503	1332.68	1743.68	1502.57
454.0	0.579343	0.420568	0.001394	0.040323	0.017766	0.001328	0.001744	0.001501	1328.36	1744.27	1501.04
455.0	0.577498	0.422413	0.001390	0.040329	0.017838	0.001324	0.001745	0.001500	1324.09	1744.84	1499.56
456.0	0.575674	0.424238	0.001385	0.040335	0.017909	0.001320	0.001745	0.001498	1319.87	1745.41	1498.11
457.0	0.573869	0.426042	0.001381	0.040341	0.017979	0.001316	0.001746	0.001497	1315.70	1745.97	1496.69
458.0	0.572085	0.427827	0.001376	0.040347	0.018049	0.001312	0.001747	0.001495	1311.58	1746.52	1495.31
459.0	0.570320	0.429592	0.001372	0.040353	0.018118	0.001308	0.001747	0.001494	1307.51	1747.06	1493.96
460.0	0.568574	0.431338	0.001368	0.040358	0.018186	0.001303	0.001748	0.001493	1303.49	1747.60	1492.64
461.0	0.566847	0.433065	0.001364	0.040364	0.018253	0.001300	0.001748	0.001491	1299.51	1748.13	1491.35
462.0	0.565139	0.434773	0.001360	0.040369	0.018320	0.001296	0.001749	0.001490	1295.58	1748.64	1490.08
463.0	0.563449	0.436463	0.001355	0.040374	0.018386	0.001292	0.001749	0.001489	1291.70	1749.15	1488.85
464.0	0.561777	0.438135	0.001351	0.040379	0.018451	0.001288	0.001750	0.001488	1287.85	1749.65	1487.65

465.0	0.560123	0.439789	0.001347	0.040385	0.018515	0.001284	0.001750	0.001486	1284.05	1750.15	1486.47
466.0	0.558487	0.441425	0.001343	0.040390	0.018579	0.001280	0.001751	0.001485	1280.29	1750.64	1485.32
467.0	0.556867	0.443044	0.001340	0.040394	0.018642	0.001277	0.001751	0.001484	1276.58	1751.11	1484.19
468.0	0.555265	0.444646	0.001336	0.040399	0.018705	0.001273	0.001752	0.001483	1272.90	1751.59	1483.08
469.0	0.553680	0.446232	0.001332	0.040404	0.018767	0.001269	0.001752	0.001482	1269.26	1752.05	1482.00
470.0	0.552111	0.447800	0.001328	0.040409	0.018828	0.001266	0.001753	0.001481	1265.66	1752.51	1480.95
471.0	0.550559	0.449353	0.001324	0.040413	0.018889	0.001262	0.001753	0.001480	1262.10	1752.96	1479.92
472.0	0.549023	0.450889	0.001321	0.040418	0.018949	0.001259	0.001753	0.001479	1258.58	1753.40	1478.90
473.0	0.547503	0.452409	0.001317	0.040422	0.019008	0.001255	0.001754	0.001478	1255.09	1753.84	1477.91
474.0	0.545998	0.453913	0.001313	0.040427	0.019067	0.001252	0.001754	0.001477	1251.64	1754.27	1476.94
475.0	0.544509	0.455402	0.001310	0.040431	0.019125	0.001248	0.001755	0.001476	1248.23	1754.70	1476.00
476.0	0.543036	0.456876	0.001306	0.040435	0.019183	0.001245	0.001755	0.001475	1244.85	1755.11	1475.07

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TURBULENT FLOW MODEL

CA (DEG)	MEANKE (ERG)	TURBKE (ERG)	VMKE (CM/SEC)	UPRIME (CM/SEC)	MACRSC (CM)	MICRSC (CM)	SSUBL (CM/SEC)	BTIMSC (MS)
-14.0	158.9	1997.7	117.38	240.29	1.212	0.0	0.0	0.0
-12.0	149.6	1880.4	115.80	237.01	1.172	0.0	0.0	0.0
-10.0	141.3	1775.3	114.22	233.71	1.139	0.0	0.0	0.0
-8.0	134.1	1682.9	112.64	230.42	1.111	0.0	0.0	0.0
-6.0	322.9	1599.0	176.51	226.79	1.089	0.0	0.0	0.0
-4.0	5564.8	1556.2	739.90	225.90	1.073	0.0	0.0	0.0
-2.0	35921.4	1952.9	1901.48	255.97	1.064	0.0	0.0	0.0
0.0	126700.4	4789.2	3627.32	407.16	1.061	0.0	0.0	0.0
2.0	299615.3	19460.6	5703.50	839.22	1.064	0.0	0.0	0.0
4.0	511952.9	72991.8	7684.38	1675.22	1.073	0.0	0.0	0.0
6.0	651550.5	187412.2	8993.31	2784.74	1.089	0.0	0.0	0.0
8.0	639142.8	318043.6	9227.89	3758.26	1.111	0.0	0.0	0.0
9.3	562814.4	376540.0	8765.25	4139.30	1.128	0.0	0.0	0.0
11.3	393680.6	399938.1	7198.65	4189.05	1.160	0.0	0.0	0.0
13.3	272734.8	357769.7	5842.11	3863.15	1.198	0.0	0.0	0.0
15.3	208142.4	306317.4	4967.38	3479.16	1.242	0.0	0.0	0.0
17.3	171219.5	262827.0	4383.44	3135.55	1.291	0.0	0.0	0.0
19.3	149589.0	229215.8	3985.59	2848.43	1.347	0.0	0.0	0.0
21.3	137238.8	203977.4	3712.62	2613.21	1.408	0.0	0.0	0.0
23.3	130876.2	185238.1	3525.06	2421.26	1.475	0.0	0.0	0.0
25.3	128548.9	171429.0	3396.09	2264.27	1.547	0.0	0.0	0.0
27.3	129054.8	161356.7	3307.45	2135.21	1.624	0.0	0.0	0.0
29.0	131195.3	154947.1	3253.36	2041.29	1.695	0.0	0.0	0.0
31.0	173919.1	152194.3	3550.90	1917.81	1.782	0.0	0.0	0.0
33.0	197984.7	154817.0	3607.25	1841.66	1.874	0.0	0.0	0.0
35.0	213968.7	159150.7	3588.07	1786.62	1.970	0.0	0.0	0.0
37.0	228134.5	164299.3	3554.33	1741.49	2.071	0.0	0.0	0.0
39.0	241433.7	169936.6	3515.44	1702.80	2.176	0.0	0.0	0.0
41.0	254104.9	175863.0	3474.18	1668.68	2.285	0.0	0.0	0.0
43.0	266477.4	181962.7	3433.13	1637.92	2.398	0.0	0.0	0.0
45.0	278657.3	188166.4	3393.09	1609.80	2.515	0.0	0.0	0.0
47.0	290689.9	194427.6	3354.36	1583.85	2.635	0.0	0.0	0.0

49.0	302644.0	200713.5	3317.38	1559.76	2.758	0.0	0.0	0.0
51.0	314569.3	207005.4	3282.26	1537.26	2.885	0.0	0.0	0.0
53.0	326419.6	213288.8	3248.67	1516.15	3.014	0.0	0.0	0.0
55.0	338134.6	219548.6	3216.27	1496.28	3.146	0.0	0.0	0.0
57.0	349627.2	225770.5	3184.70	1477.54	3.280	0.0	0.0	0.0
59.0	360874.1	231939.4	3153.86	1459.80	3.416	0.0	0.0	0.0
61.0	371831.2	238041.6	3123.62	1442.95	3.554	0.0	0.0	0.0
63.0	382459.5	244065.1	3093.86	1426.92	3.693	0.0	0.0	0.0
65.0	392750.6	249998.8	3064.59	1411.64	3.834	0.0	0.0	0.0
67.0	402635.3	255834.4	3035.62	1397.05	3.976	0.0	0.0	0.0
69.0	411913.6	261630.1	3006.25	1383.27	4.000	0.0	0.0	0.0
71.0	420150.1	267477.2	2975.04	1370.48	4.000	0.0	0.0	0.0
73.0	427354.4	273332.4	2942.26	1358.54	4.000	0.0	0.0	0.0
75.0	433598.3	279151.7	2908.28	1347.27	4.000	0.0	0.0	0.0
77.0	438891.6	284896.8	2873.29	1336.55	4.000	0.0	0.0	0.0
79.0	443258.1	290533.5	2837.46	1326.30	4.000	0.0	0.0	0.0
81.0	446747.0	296030.4	2801.00	1316.41	4.000	0.0	0.0	0.0
83.0	449390.8	301359.2	2764.04	1306.82	4.000	0.0	0.0	0.0
85.0	451232.5	306495.4	2726.74	1297.46	4.000	0.0	0.0	0.0
87.0	452303.1	311417.8	2689.19	1288.31	4.000	0.0	0.0	0.0
89.0	452643.6	316107.7	2651.50	1279.30	4.000	0.0	0.0	0.0
91.0	452296.3	320548.6	2613.77	1270.41	4.000	0.0	0.0	0.0
93.0	451290.9	324727.7	2576.06	1261.62	4.000	0.0	0.0	0.0
95.0	449642.9	328634.3	2538.37	1252.90	4.000	0.0	0.0	0.0
97.0	447433.7	332258.8	2500.86	1244.24	4.000	0.0	0.0	0.0
99.0	444701.4	335593.6	2463.60	1235.62	4.000	0.0	0.0	0.0
101.0	441447.1	338634.9	2426.56	1227.04	4.000	0.0	0.0	0.0
103.0	437833.6	341382.3	2390.09	1218.48	4.000	0.0	0.0	0.0
105.0	433736.8	343835.3	2353.81	1209.97	4.000	0.0	0.0	0.0
107.0	429233.9	345993.7	2317.86	1201.48	4.000	0.0	0.0	0.0
109.0	424358.2	347857.7	2282.26	1193.00	4.000	0.0	0.0	0.0
111.0	419114.1	349430.0	2246.97	1184.55	4.000	0.0	0.0	0.0
113.0	413528.6	350713.5	2212.01	1176.12	4.000	0.0	0.0	0.0
115.0	407665.0	351711.5	2177.46	1167.70	4.000	0.0	0.0	0.0
117.0	401523.4	352430.0	2143.28	1159.31	4.000	0.0	0.0	0.0
119.0	395149.2	352874.1	2109.52	1150.94	4.000	0.0	0.0	0.0
121.0	388568.2	353050.4	2076.18	1142.59	4.000	0.0	0.0	0.0
123.0	381783.3	352966.7	2043.23	1134.27	4.000	0.0	0.0	0.0
125.0	374836.0	352630.4	2010.71	1125.98	4.000	0.0	0.0	0.0
127.0	367735.4	352049.8	1978.60	1117.72	4.000	0.0	0.0	0.0
129.0	360507.2	351233.4	1946.90	1109.50	4.000	0.0	0.0	0.0
131.0	353184.3	350189.6	1915.65	1101.31	4.000	0.0	0.0	0.0
133.0	345788.4	348927.4	1884.85	1093.15	4.000	0.0	0.0	0.0
135.0	338321.3	347456.4	1854.47	1085.04	4.000	0.0	0.0	0.0
137.0	330807.6	345785.7	1824.52	1076.98	4.000	0.0	0.0	0.0
139.0	323248.5	343924.9	1794.97	1068.96	4.000	0.0	0.0	0.0
141.0	315660.8	341883.2	1765.82	1061.00	4.000	0.0	0.0	0.0
143.0	308082.1	339669.2	1737.11	1053.08	4.000	0.0	0.0	0.0
145.0	300513.7	337292.5	1708.82	1045.22	4.000	0.0	0.0	0.0
147.0	292975.3	334761.7	1680.95	1037.41	4.000	0.0	0.0	0.0
149.0	285422.3	332087.2	1653.39	1029.67	4.000	0.0	0.0	0.0
151.0	277906.2	329276.3	1626.21	1022.00	4.000	0.0	0.0	0.0
153.0	270461.4	326337.2	1599.46	1014.37	4.000	0.0	0.0	0.0
155.0	263046.7	323279.1	1573.04	1006.82	4.000	0.0	0.0	0.0
157.0	255719.6	320109.4	1547.04	999.33	4.000	0.0	0.0	0.0
159.0	248443.0	316837.3	1521.37	991.93	4.000	0.0	0.0	0.0
161.0	241285.0	313469.6	1496.16	984.58	4.000	0.0	0.0	0.0
163.0	234208.8	310015.5	1471.33	977.33	4.000	0.0	0.0	0.0

165.0	227256.1	306482.0	1446.94	970.14	4.000	0.0	0.0	0.0
167.0	220419.5	302877.3	1422.97	963.04	4.000	0.0	0.0	0.0
169.0	213722.1	299208.9	1399.48	956.03	4.000	0.0	0.0	0.0
171.0	207168.9	295484.7	1376.49	949.11	4.000	0.0	0.0	0.0
173.0	200776.3	291712.2	1354.06	942.32	4.000	0.0	0.0	0.0
175.0	194576.3	287898.9	1332.20	935.59	4.000	0.0	0.0	0.0
177.0	188570.7	284052.6	1310.96	928.95	4.000	0.0	0.0	0.0
178.1	185620.8	282114.7	1300.46	925.63	4.000	0.0	0.0	0.0
180.0	180056.3	278284.5	1280.93	919.40	4.000	0.0	0.0	0.0
182.0	174517.9	274303.0	1261.28	912.95	4.000	0.0	0.0	0.0
184.0	169138.4	270240.3	1242.06	906.44	4.000	0.0	0.0	0.0
186.0	163920.6	266117.6	1223.27	899.88	4.000	0.0	0.0	0.0
188.0	158864.4	261951.6	1204.91	893.29	4.000	0.0	0.0	0.0
190.0	153973.5	257764.6	1186.94	886.66	4.000	0.0	0.0	0.0
192.0	149249.0	253575.1	1169.38	880.02	4.000	0.0	0.0	0.0
194.0	144692.6	249402.5	1152.21	873.37	4.000	0.0	0.0	0.0
196.0	140305.6	245265.2	1135.41	866.71	4.000	0.0	0.0	0.0
198.0	136087.3	241178.0	1118.99	860.06	4.000	0.0	0.0	0.0
200.0	132036.4	237154.4	1102.93	853.41	4.000	0.0	0.0	0.0
202.0	128150.5	233205.1	1087.22	846.77	4.000	0.0	0.0	0.0
204.0	124425.3	229337.2	1071.85	840.15	4.000	0.0	0.0	0.0
206.0	120853.9	225552.2	1056.82	833.56	4.000	0.0	0.0	0.0
208.0	117429.8	221851.4	1042.12	826.99	4.000	0.0	0.0	0.0
210.0	114146.2	218234.8	1027.73	820.45	4.000	0.0	0.0	0.0
212.0	110994.4	214697.6	1013.65	813.94	4.000	0.0	0.0	0.0
214.0	107966.9	211236.8	999.88	807.47	4.000	0.0	0.0	0.0
216.0	105057.5	207850.6	986.40	801.04	4.000	0.0	0.0	0.0
218.0	102259.8	204536.3	973.21	794.66	4.000	0.0	0.0	0.0
220.0	99564.2	201284.1	960.30	788.31	4.000	0.0	0.0	0.0
222.0	96960.3	198081.6	947.66	782.02	4.000	0.0	0.0	0.0
224.0	94444.5	194929.0	935.28	775.77	4.000	0.0	0.0	0.0
226.0	92013.4	191826.7	923.16	769.57	4.000	0.0	0.0	0.0
228.0	89663.5	188774.6	911.30	763.42	4.000	0.0	0.0	0.0
230.0	87391.6	185772.8	899.68	757.33	4.000	0.0	0.0	0.0
232.0	85194.8	182821.2	888.30	751.29	4.000	0.0	0.0	0.0
234.0	83070.0	179919.8	877.15	745.30	4.000	0.0	0.0	0.0
236.0	81014.6	177068.1	866.23	739.37	4.000	0.0	0.0	0.0
238.0	79025.7	174266.0	855.54	733.50	4.000	0.0	0.0	0.0
240.0	77100.9	171513.0	845.05	727.68	4.000	0.0	0.0	0.0
242.0	75237.6	168808.7	834.78	721.92	4.000	0.0	0.0	0.0
244.0	73433.6	166152.7	824.71	716.22	4.000	0.0	0.0	0.0
246.0	71686.5	163544.4	814.84	710.58	4.000	0.0	0.0	0.0
248.0	69994.3	160983.4	805.17	704.99	4.000	0.0	0.0	0.0
250.0	68354.9	158468.9	795.68	699.47	4.000	0.0	0.0	0.0
252.0	66766.2	156000.5	786.38	694.00	4.000	0.0	0.0	0.0
254.0	65226.4	153577.5	777.26	688.59	4.000	0.0	0.0	0.0
256.0	63733.7	151199.2	768.31	683.23	4.000	0.0	0.0	0.0
258.0	62286.4	148865.0	759.54	677.94	4.000	0.0	0.0	0.0
260.0	60882.8	146574.3	750.93	672.70	4.000	0.0	0.0	0.0
262.0	59521.2	144326.2	742.49	667.52	4.000	0.0	0.0	0.0
264.0	58200.2	142120.1	734.20	662.40	4.000	0.0	0.0	0.0
266.0	56918.3	139955.4	726.07	657.34	4.000	0.0	0.0	0.0
268.0	55674.1	137831.2	718.09	652.33	4.000	0.0	0.0	0.0
270.0	54466.3	135747.0	710.26	647.38	4.000	0.0	0.0	0.0
272.0	53293.5	133702.0	702.57	642.49	4.000	0.0	0.0	0.0
274.0	52154.6	131695.4	695.02	637.65	4.000	0.0	0.0	0.0
276.0	51048.2	129726.6	687.61	632.86	4.000	0.0	0.0	0.0
278.0	49973.4	127794.9	680.34	628.13	4.000	0.0	0.0	0.0

280.0	48928.9	125899.6	673.19	623.46	4.000	0.0	0.0	0.0
282.0	47913.8	124040.0	666.17	618.84	4.000	0.0	0.0	0.0
284.0	46927.1	122215.3	659.27	614.27	4.000	0.0	0.0	0.0
286.0	45967.7	120425.0	652.50	609.75	4.000	0.0	0.0	0.0
288.0	45034.7	118668.3	645.84	605.29	4.000	0.0	0.0	0.0
290.0	44127.3	116944.5	639.30	600.87	4.000	0.0	0.0	0.0
292.0	43244.6	115253.1	632.88	596.51	4.000	0.0	0.0	0.0
294.0	42377.3	113577.0	626.50	592.16	3.902	0.0	0.0	0.0
296.0	41505.5	111877.6	620.02	587.71	3.760	0.0	0.0	0.0
298.0	40625.8	110147.9	613.42	583.15	3.620	0.0	0.0	0.0
300.0	39738.4	108387.4	606.68	578.47	3.481	0.0	0.0	0.0
302.0	38842.9	106594.6	599.80	573.67	3.344	0.0	0.0	0.0
304.0	37939.2	104768.7	592.79	568.73	3.209	0.0	0.0	0.0
306.0	37027.4	102908.7	585.62	563.66	3.076	0.0	0.0	0.0
308.0	36107.4	101013.9	578.30	558.45	2.946	0.0	0.0	0.0
310.0	35179.3	99083.3	570.82	553.09	2.818	0.0	0.0	0.0
312.0	34243.3	97116.6	563.17	547.57	2.693	0.0	0.0	0.0
314.0	33299.6	95113.3	555.36	541.89	2.572	0.0	0.0	0.0
316.0	32348.8	93073.3	547.37	536.05	2.453	0.0	0.0	0.0
318.0	31391.3	90996.7	539.21	530.04	2.339	0.0	0.0	0.0
320.0	30428.0	88884.0	530.87	523.85	2.228	0.0	0.0	0.0
322.0	29459.5	86736.2	522.36	517.48	2.121	0.0	0.0	0.0
324.0	28487.2	84554.6	513.66	510.93	2.018	0.0	0.0	0.0
326.0	27512.2	82341.0	504.80	504.20	1.919	0.0	0.0	0.0
328.0	26536.2	80098.1	495.76	497.28	1.825	0.0	0.0	0.0
330.0	25560.8	77829.1	486.57	490.19	1.736	0.0	0.0	0.0
332.0	24588.3	75537.8	477.22	482.92	1.652	0.0	0.0	0.0
334.0	23620.8	73229.3	467.74	475.48	1.573	0.0	0.0	0.0
336.0	22661.1	70909.0	458.14	467.89	1.499	0.0	0.0	0.0
338.0	21711.8	68583.6	448.44	460.16	1.430	0.0	0.0	0.0
340.0	20776.1	66260.6	438.67	452.29	1.367	0.0	0.0	0.0
342.0	19857.2	63948.2	428.86	444.33	1.310	0.0	0.0	0.0
344.0	18958.5	61655.6	419.04	436.30	1.258	0.0	0.0	0.0
345.0	18214.2	61655.6	410.73	746.42	1.250	0.04870	75.503	0.6450
346.0	17490.4	61655.6	402.49	750.98	1.243	0.04802	75.888	0.6328
347.0	16787.2	61655.6	394.32	755.38	1.235	0.04738	76.247	0.6214
348.0	16104.7	61655.6	386.22	759.65	1.228	0.04677	76.581	0.6108
349.0	15442.7	61655.6	378.19	763.84	1.222	0.04619	76.899	0.6006
350.0	14801.1	61655.6	370.25	768.05	1.215	0.04560	77.214	0.5906
351.0	14179.4	61655.6	362.40	772.39	1.208	0.04502	77.540	0.5805
352.0	13577.1	61655.6	354.61	777.05	1.201	0.04440	77.898	0.5699
353.0	12993.1	61655.6	346.90	782.24	1.193	0.04372	78.321	0.5583
354.0	12426.5	61655.6	339.26	788.20	1.184	0.04297	78.832	0.5451
355.0	11875.8	61655.6	331.65	795.21	1.174	0.04211	79.467	0.5300
356.0	11339.5	61655.6	324.08	803.57	1.161	0.04112	80.261	0.5124
357.0	10815.9	61655.6	316.51	813.59	1.147	0.03998	81.247	0.4921
358.0	10303.1	61655.6	308.91	825.55	1.130	0.03868	82.457	0.4692
359.0	9799.5	61655.6	301.27	839.39	1.112	0.03726	83.872	0.4442
360.0	9304.0	61655.6	293.55	854.85	1.092	0.03575	85.462	0.4183
361.0	8815.9	61655.6	285.75	871.44	1.071	0.03423	87.157	0.3927
362.0	8335.6	61655.6	277.86	888.68	1.050	0.03274	88.891	0.3683
363.0	7863.9	61655.6	269.88	906.21	1.030	0.03132	90.615	0.3456
364.0	7401.7	61655.6	261.83	923.78	1.010	0.02998	92.299	0.3248
365.0	6950.5	61655.6	253.72	941.13	0.992	0.02873	93.911	0.3060
366.0	6511.6	61655.6	245.58	958.05	0.974	0.02759	95.424	0.2891
367.0	6086.3	61655.6	237.43	974.35	0.958	0.02654	96.805	0.2742
368.0	5676.1	61655.6	229.29	989.72	0.943	0.02560	98.019	0.2612
369.0	5282.4	61655.6	221.19	1003.96	0.930	0.02477	99.036	0.2501

370.0	4906.2	61655.6	213.17	1016.87	0.918	0.02404	99.833	0.2408
371.0	4548.7	61655.6	205.26	1028.30	0.908	0.02342	100.394	0.2333
372.0	4210.6	61655.6	197.48	1037.97	0.899	0.02291	100.689	0.2275
373.0	3892.7	61655.6	189.88	1045.41	0.893	0.02251	100.680	0.2236
374.0	3595.3	61655.6	182.48	1050.35	0.888	0.02225	100.389	0.2216
375.0	3318.8	61655.6	175.33	1052.89	0.886	0.02210	99.797	0.2214
376.0	3062.9	61655.6	168.43	1053.67	0.886	0.02203	98.952	0.2227
377.0	2826.6	61655.6	161.80	1053.08	0.886	0.02203	97.894	0.2250
378.0	2609.0	61655.6	155.45	1051.23	0.888	0.02208	96.620	0.2285
379.0	2409.1	61655.6	149.38	1048.17	0.890	0.02219	95.189	0.2331
380.0	2225.9	61655.6	143.58	1042.95	0.895	0.02242	94.273	0.2379
381.0	2058.4	61655.6	138.08	1036.42	0.900	0.02274	93.561	0.2431
382.0	1905.5	61655.6	132.85	1029.38	0.907	0.02309	92.791	0.2488
383.0	1765.9	61655.6	127.89	1021.99	0.913	0.02347	91.984	0.2551
384.0	1638.3	61655.6	123.18	1014.33	0.920	0.02386	91.146	0.2618
385.0	1521.7	61655.6	118.72	1006.44	0.927	0.02429	90.283	0.2690
386.0	1415.0	61655.6	114.48	998.36	0.935	0.02473	89.397	0.2766
387.0	1317.4	61655.6	110.46	990.12	0.943	0.02519	88.494	0.2846
388.0	1227.9	61655.6	106.64	981.78	0.951	0.02567	87.578	0.2931
389.0	1145.9	61655.6	103.02	973.39	0.959	0.02617	86.656	0.3020
390.0	1070.6	61655.6	99.58	964.99	0.967	0.02668	85.733	0.3112
391.0	1001.5	61655.6	96.31	956.63	0.976	0.02720	84.812	0.3207
392.0	937.9	61655.6	93.20	948.31	0.984	0.02774	83.896	0.3306
393.0	879.3	61655.6	90.24	940.06	0.993	0.02828	82.986	0.3408
394.0	825.3	61655.6	87.43	931.88	1.001	0.02884	82.084	0.3514
395.0	775.5	61655.6	84.75	923.79	1.010	0.02941	81.190	0.3622
396.0	729.4	61655.6	82.20	915.79	1.019	0.02998	80.306	0.3733
397.0	686.9	61655.6	79.76	907.89	1.028	0.03057	79.432	0.3848
398.0	647.4	61655.6	77.44	900.10	1.037	0.03116	78.569	0.3966
399.0	610.9	61655.6	75.22	892.41	1.046	0.03176	77.717	0.4086
400.0	577.0	61655.6	73.10	884.84	1.055	0.03237	76.878	0.4210
401.0	545.5	61655.6	71.08	877.39	1.064	0.03298	76.050	0.4337
402.0	516.2	61655.6	69.14	870.04	1.073	0.03360	75.235	0.4466
403.0	488.9	61655.6	67.29	862.82	1.082	0.03423	74.432	0.4599
404.0	463.5	61655.6	65.52	855.72	1.091	0.03486	73.643	0.4734
405.0	439.7	61655.6	63.82	848.74	1.100	0.03550	72.866	0.4872
406.0	417.6	61655.6	62.19	841.88	1.108	0.03615	72.102	0.5014
407.0	396.9	61655.6	60.63	835.14	1.117	0.03680	71.351	0.5157
408.0	377.5	61655.6	59.13	828.52	1.126	0.03745	70.613	0.5304
409.0	359.4	61655.6	57.69	822.02	1.135	0.03811	69.888	0.5453
410.0	342.4	61655.6	56.31	815.65	1.144	0.03878	69.177	0.5605
411.0	326.4	61655.6	54.98	809.39	1.153	0.03944	68.478	0.5760
412.0	311.4	61655.6	53.70	803.25	1.162	0.04011	67.792	0.5917
413.0	297.3	61655.6	52.47	797.23	1.171	0.04079	67.119	0.6077
414.0	284.0	61655.6	51.29	791.32	1.179	0.04146	66.458	0.6239
415.0	271.5	61655.6	50.15	785.53	1.188	0.04214	65.811	0.6403
416.0	259.8	61655.6	49.05	779.85	1.197	0.04282	65.175	0.6570
417.0	248.7	61655.6	47.99	774.29	1.205	0.04350	64.552	0.6739
418.0	238.2	61655.6	46.97	768.84	1.214	0.04419	63.941	0.6910
419.0	228.3	61655.6	45.98	763.49	1.222	0.04487	63.342	0.7084
420.0	218.9	61655.6	45.03	758.25	1.231	0.04556	62.755	0.7260
421.0	210.1	61655.6	44.11	753.12	1.239	0.04624	62.179	0.7437
422.0	201.7	61655.6	43.22	748.09	1.247	0.04693	61.615	0.7617
423.0	193.7	61655.6	42.36	743.17	1.256	0.04762	61.062	0.7799
424.0	186.2	61655.6	41.53	738.34	1.264	0.04831	60.521	0.7982
425.0	179.0	61655.6	40.72	733.61	1.272	0.04899	59.990	0.8167
426.0	172.2	61655.6	39.94	728.99	1.280	0.04968	59.470	0.8354
427.0	165.8	61655.6	39.19	724.45	1.288	0.05037	58.960	0.8543

428.0	159.7	61655.6	38.45	720.01	1.296	0.05105	58.461	0.8733
429.0	153.8	61655.6	37.74	715.66	1.304	0.05174	57.972	0.8924
430.0	148.2	61655.6	37.06	711.40	1.312	0.05242	57.493	0.9117
431.0	143.0	61655.6	36.39	707.23	1.320	0.05310	57.024	0.9312
432.0	137.9	61655.6	35.74	703.15	1.327	0.05378	56.565	0.9507
433.0	133.1	61655.6	35.11	699.15	1.335	0.05446	56.115	0.9704
434.0	128.5	61655.6	34.50	695.23	1.342	0.05513	55.674	0.9902
435.0	124.1	61655.6	33.90	691.40	1.350	0.05580	55.242	1.0101
436.0	119.9	61655.6	33.32	687.64	1.357	0.05647	54.820	1.0301
437.0	115.9	61655.6	32.76	683.97	1.364	0.05714	54.406	1.0502
438.0	112.1	61655.6	32.22	680.37	1.372	0.05780	54.000	1.0704
439.0	108.4	61655.6	31.68	676.85	1.379	0.05846	53.603	1.0906
440.0	104.9	61655.6	31.17	673.40	1.386	0.05912	53.215	1.1110
441.0	101.5	61655.6	30.66	670.02	1.393	0.05977	52.834	1.1313
442.0	98.3	61655.6	30.17	666.71	1.400	0.06042	52.461	1.1517
443.0	95.2	61655.6	29.69	663.47	1.407	0.06107	52.096	1.1722
444.0	92.2	61655.6	29.22	660.30	1.413	0.06171	51.739	1.1927
445.0	89.4	61655.6	28.77	657.20	1.420	0.06235	51.389	1.2133
446.0	86.6	61655.6	28.33	654.16	1.427	0.06298	51.046	1.2338
447.0	84.0	61655.6	27.89	651.19	1.433	0.06361	50.711	1.2544
448.0	81.5	61655.6	27.47	648.28	1.440	0.06423	50.382	1.2749
449.0	79.0	61655.6	27.06	645.42	1.446	0.06485	50.061	1.2955
450.0	76.7	61655.6	26.65	642.63	1.452	0.06547	49.746	1.3161
451.0	74.5	61655.6	26.26	639.90	1.458	0.06608	49.438	1.3366
452.0	72.3	61655.6	25.88	637.23	1.464	0.06669	49.136	1.3572
453.0	70.2	61655.6	25.50	634.61	1.471	0.06729	48.841	1.3776
454.0	68.2	61655.6	25.13	632.05	1.476	0.06788	48.552	1.3981
455.0	66.3	61655.6	24.77	629.54	1.482	0.06847	48.269	1.4185
456.0	64.4	61655.6	24.42	627.09	1.488	0.06905	47.992	1.4389
457.0	62.6	61655.6	24.08	624.68	1.494	0.06963	47.721	1.4592
458.0	60.9	61655.6	23.74	622.33	1.500	0.07021	47.455	1.4794
459.0	59.2	61655.6	23.41	620.03	1.505	0.07077	47.195	1.4996
460.0	57.6	61655.6	23.09	617.78	1.511	0.07133	46.941	1.5197
461.0	56.0	61655.6	22.78	615.57	1.516	0.07189	46.692	1.5397
462.0	54.5	61655.6	22.47	613.42	1.521	0.07244	46.448	1.5596
463.0	53.0	61655.6	22.16	611.30	1.527	0.07298	46.210	1.5794
464.0	51.6	61655.6	21.87	609.24	1.532	0.07352	45.977	1.5991
465.0	50.3	61655.6	21.58	607.22	1.537	0.07405	45.748	1.6187
466.0	49.0	61655.6	21.29	605.24	1.542	0.07458	45.525	1.6382
467.0	47.7	61655.6	21.01	603.30	1.547	0.07510	45.306	1.6576
468.0	46.4	61655.6	20.74	601.41	1.552	0.07561	45.093	1.6768
469.0	45.2	61655.6	20.47	599.56	1.557	0.07612	44.883	1.6959
470.0	44.1	61655.6	20.21	597.74	1.561	0.07662	44.679	1.7149
471.0	43.0	61655.6	19.95	595.97	1.566	0.07711	44.478	1.7337
472.0	41.9	61655.6	19.69	594.24	1.570	0.07760	44.283	1.7524
473.0	40.8	61655.6	19.45	592.54	1.575	0.07808	44.092	1.7709
474.0	39.8	61655.6	19.20	590.87	1.579	0.07856	43.909	1.7892
475.0	38.8	61655.6	18.96	589.24	1.584	0.07903	43.729	1.8073
476.0	37.9	61655.6	18.72	587.65	1.588	0.07950	43.554	1.8253
478.0	37.1	109437.2	18.54	581.33	4.000	0.0	0.0	0.0
480.0	36.4	107051.7	18.36	575.14	4.000	0.0	0.0	0.0
482.0	35.6	104686.6	18.18	569.08	4.000	0.0	0.0	0.0
484.0	34.9	102327.8	18.01	563.14	4.000	0.0	0.0	0.0
486.0	34.1	99958.5	17.84	557.33	4.000	0.0	0.0	0.0
488.0	33.4	97560.0	17.68	551.64	4.000	0.0	0.0	0.0
490.0	32.6	95111.4	17.51	546.07	4.000	0.0	0.0	0.0
492.0	31.8	92593.2	17.35	540.60	4.000	0.0	0.0	0.0
494.0	31.0	89986.9	17.20	535.25	4.000	0.0	0.0	0.0

496.0	30.1	87277.4	17.04	529.99	4.000	0.0	0.0	0.0
498.0	29.2	84453.0	16.89	524.85	4.000	0.0	0.0	0.0
500.0	28.2	81509.4	16.74	519.80	4.000	0.0	0.0	0.0
502.0	27.2	78446.5	16.60	514.84	4.000	0.0	0.0	0.0
504.0	26.1	75273.5	16.45	509.98	4.000	0.0	0.0	0.0
506.0	25.0	72013.6	16.31	505.21	4.000	0.0	0.0	0.0
508.0	23.9	68693.6	16.18	500.53	4.000	0.0	0.0	0.0
510.0	22.8	65356.5	16.04	495.94	4.000	0.0	0.0	0.0
512.0	21.7	62054.8	15.91	491.42	4.000	0.0	0.0	0.0
514.0	20.6	58857.0	15.78	486.99	4.000	0.0	0.0	0.0
516.0	19.6	55832.9	15.65	482.64	4.000	0.0	0.0	0.0
518.0	18.6	53055.6	15.52	478.37	4.000	0.0	0.0	0.0
520.0	17.8	50621.4	15.40	474.17	4.000	0.0	0.0	0.0
522.0	17.1	48637.7	15.28	470.04	4.000	0.0	0.0	0.0
524.0	16.7	47244.1	15.16	465.99	4.000	0.0	0.0	0.0
526.0	786.7	46429.7	104.02	461.36	4.000	0.0	0.0	0.0
528.0	1816.7	45667.6	157.77	456.71	4.000	0.0	0.0	0.0
530.0	2460.3	44938.4	183.30	452.29	4.000	0.0	0.0	0.0
532.0	2823.5	44235.5	196.08	448.08	4.000	0.0	0.0	0.0
534.0	3008.3	43554.4	202.14	444.06	4.000	0.0	0.0	0.0
536.0	3084.1	42892.3	204.45	440.21	4.000	0.0	0.0	0.0
538.0	3096.0	42247.0	204.67	436.51	4.000	0.0	0.0	0.0
540.0	3074.3	41617.2	203.82	432.97	4.000	0.0	0.0	0.0
542.0	3037.0	41001.9	202.49	429.56	4.000	0.0	0.0	0.0
544.0	2995.4	40398.8	201.05	426.29	4.000	0.0	0.0	0.0
546.0	2953.3	39802.7	199.63	423.12	4.000	0.0	0.0	0.0
548.0	2910.8	39212.1	198.21	420.03	4.000	0.0	0.0	0.0
550.0	2868.0	38622.6	196.82	417.00	4.000	0.0	0.0	0.0
552.0	2825.0	38031.3	195.44	414.02	4.000	0.0	0.0	0.0
554.0	2781.8	37438.4	194.09	411.08	4.000	0.0	0.0	0.0
556.0	2738.5	36843.8	192.75	408.19	4.000	0.0	0.0	0.0
558.0	2695.1	36248.8	191.43	405.33	4.000	0.0	0.0	0.0
560.0	2651.6	35651.9	190.13	402.51	4.000	0.0	0.0	0.0
562.0	2608.0	35054.6	188.85	399.74	4.000	0.0	0.0	0.0
564.0	2564.3	34456.9	187.58	397.00	4.000	0.0	0.0	0.0
566.0	2520.5	33858.5	186.33	394.30	4.000	0.0	0.0	0.0
568.0	2476.7	33260.4	185.10	391.63	4.000	0.0	0.0	0.0
570.0	2432.9	32661.9	183.89	389.00	4.000	0.0	0.0	0.0
572.0	2389.1	32063.8	182.69	386.41	4.000	0.0	0.0	0.0
574.0	2345.2	31466.1	181.51	383.85	4.000	0.0	0.0	0.0
576.0	2301.4	30868.7	180.34	381.32	4.000	0.0	0.0	0.0
578.0	2257.6	30272.2	179.18	378.83	4.000	0.0	0.0	0.0
580.0	2213.8	29676.6	178.05	376.37	4.000	0.0	0.0	0.0
582.0	2170.0	29081.7	176.92	373.94	4.000	0.0	0.0	0.0
584.0	2126.3	28487.7	175.81	371.54	4.000	0.0	0.0	0.0
586.0	2082.7	27895.5	174.72	369.17	4.000	0.0	0.0	0.0
588.0	2039.1	27304.1	173.64	366.84	4.000	0.0	0.0	0.0
590.0	1995.6	26713.9	172.57	364.53	4.000	0.0	0.0	0.0
592.0	1952.2	26125.5	171.51	362.25	4.000	0.0	0.0	0.0
594.0	1908.9	25539.1	170.47	360.00	4.000	0.0	0.0	0.0
596.0	1865.7	24954.0	169.44	357.78	4.000	0.0	0.0	0.0
598.0	1822.5	24370.4	168.42	355.58	4.000	0.0	0.0	0.0
600.0	1779.5	23788.9	167.42	353.41	4.000	0.0	0.0	0.0
602.0	1736.7	23209.7	166.43	351.27	4.000	0.0	0.0	0.0
604.0	1694.0	22633.0	165.45	349.15	4.000	0.0	0.0	0.0
606.0	1651.3	22057.5	164.48	347.06	4.000	0.0	0.0	0.0
608.0	1608.9	21484.6	163.52	345.00	4.000	0.0	0.0	0.0
610.0	1566.6	20914.7	162.57	342.96	4.000	0.0	0.0	0.0

612.0	1524.5	20347.8	161.64	340.94	4.000	0.0	0.0	0.0
614.0	1482.7	19784.1	160.71	338.95	4.000	0.0	0.0	0.0
616.0	1441.1	19224.1	159.80	336.97	4.000	0.0	0.0	0.0
618.0	1399.6	18667.0	158.90	335.03	4.000	0.0	0.0	0.0
620.0	1358.5	18113.7	158.00	333.10	4.000	0.0	0.0	0.0
622.0	1317.6	17564.5	157.12	331.20	4.000	0.0	0.0	0.0
624.0	1277.1	17019.8	156.25	329.32	4.000	0.0	0.0	0.0
626.0	1236.9	16480.1	155.38	327.46	4.000	0.0	0.0	0.0
628.0	1197.0	15944.9	154.53	325.62	4.000	0.0	0.0	0.0
630.0	1157.5	15415.0	153.68	323.80	4.000	0.0	0.0	0.0
632.0	1118.5	14891.0	152.85	322.00	4.000	0.0	0.0	0.0
634.0	1079.8	14372.9	152.02	320.22	4.000	0.0	0.0	0.0
636.0	1041.6	13861.5	151.21	318.46	4.000	0.0	0.0	0.0
638.0	1003.9	13356.9	150.40	316.72	4.000	0.0	0.0	0.0
640.0	966.8	12859.4	149.60	315.00	4.000	0.0	0.0	0.0
642.0	930.2	12369.3	148.81	313.30	4.000	0.0	0.0	0.0
644.0	894.1	11887.6	148.02	311.62	4.000	0.0	0.0	0.0
646.0	858.7	11413.3	147.25	309.95	4.000	0.0	0.0	0.0
648.0	823.9	10948.1	146.48	308.30	4.000	0.0	0.0	0.0
650.0	789.7	10491.7	145.73	306.67	4.000	0.0	0.0	0.0
652.0	756.2	10044.9	144.98	305.06	4.000	0.0	0.0	0.0
654.0	723.4	9606.7	144.23	303.45	3.902	0.0	0.0	0.0
656.0	691.1	9175.3	143.46	301.80	3.760	0.0	0.0	0.0
658.0	659.3	8751.0	142.67	300.11	3.620	0.0	0.0	0.0
660.0	628.1	8334.8	141.86	298.37	3.481	0.0	0.0	0.0
662.0	597.5	7926.9	141.03	296.58	3.344	0.0	0.0	0.0
664.0	567.6	7527.9	140.17	294.74	3.209	0.0	0.0	0.0
666.0	538.4	7139.0	139.29	292.84	3.076	0.0	0.0	0.0
668.0	510.0	6759.9	138.38	290.89	2.946	0.0	0.0	0.0
670.0	482.3	6391.5	137.45	288.88	2.818	0.0	0.0	0.0
672.0	455.5	6034.5	136.48	286.80	2.693	0.0	0.0	0.0
674.0	429.6	5689.0	135.48	284.66	2.572	0.0	0.0	0.0
676.0	404.5	5355.5	134.46	282.46	2.453	0.0	0.0	0.0
678.0	380.4	5034.9	133.39	280.18	2.339	0.0	0.0	0.0
680.0	357.3	4727.1	132.30	277.82	2.228	0.0	0.0	0.0
682.0	335.2	4432.5	131.17	275.40	2.121	0.0	0.0	0.0
684.0	314.0	4151.5	130.00	272.89	2.018	0.0	0.0	0.0
686.0	293.9	3884.2	128.79	270.31	1.919	0.0	0.0	0.0
688.0	274.8	3630.0	127.55	267.64	1.825	0.0	0.0	0.0
690.0	256.9	3391.9	126.27	264.89	1.736	0.0	0.0	0.0
692.0	240.0	3167.7	124.95	262.07	1.652	0.0	0.0	0.0
694.0	224.2	2957.5	123.59	259.16	1.573	0.0	0.0	0.0
696.0	209.5	2761.6	122.20	256.18	1.499	0.0	0.0	0.0
698.0	195.8	2579.9	120.77	253.12	1.430	0.0	0.0	0.0
700.0	183.1	2412.2	119.31	250.00	1.367	0.0	0.0	0.0
702.0	171.6	2258.6	117.83	246.82	1.310	0.0	0.0	0.0
704.0	161.0	2118.7	116.32	243.59	1.258	0.0	0.0	0.0

1

HEAT TRANSFER DATA

CA (DEG)	CVHTRN (CM/SEC)	HTPAPI (KW/M**2)	HTPAHD (KW/M**2)	HTPACW (KW/M**2)	Q% PI (%)	Q% HD (%)	Q% CW (%)

-14.0	284.3	20.165	20.165	20.165	42.968	53.781	3.251
-12.0	276.6	19.771	19.771	19.771	43.340	54.246	2.414
-10.0	269.2	19.364	19.364	19.364	43.661	54.647	1.692
-8.0	262.5	18.962	18.962	18.962	43.928	54.981	1.091
-6.0	290.4	20.549	20.549	20.549	44.138	55.245	0.617
-4.0	774.1	44.469	44.469	44.469	44.290	55.435	0.275
-2.0	1918.7	88.606	88.606	88.606	44.382	55.550	0.069
0.0	3650.1	137.674	137.674	137.674	44.412	55.588	0.0
2.0	5764.9	175.686	175.686	175.686	44.382	55.550	0.069
4.0	7864.9	188.965	188.965	188.965	44.290	55.435	0.275
6.0	9414.7	174.419	174.419	174.419	44.138	55.245	0.617
8.0	9964.0	143.084	143.084	143.084	43.928	54.981	1.091
9.3	9693.7	122.684	122.684	122.684	43.759	54.771	1.470
11.3	8329.1	100.363	100.363	100.363	43.457	54.392	2.151
13.3	7004.5	83.200	83.200	83.200	43.103	53.949	2.949
15.3	6065.5	71.359	71.359	71.359	42.700	53.444	3.857
17.3	5390.7	62.721	62.721	62.721	42.251	52.883	4.865
19.3	4900.6	56.244	56.244	56.244	41.762	52.271	5.967
21.3	4542.4	51.303	51.303	51.303	41.236	51.612	7.152
23.3	4279.4	47.471	47.471	47.471	40.677	50.913	8.410
25.3	4085.2	44.443	44.443	44.443	40.089	50.177	9.734
27.3	3940.9	42.001	42.001	42.001	39.477	49.411	11.112
29.0	3845.4	40.233	40.233	40.233	38.928	48.724	12.348
31.0	4040.7	34.225	34.225	34.225	38.281	47.914	13.804
33.0	4055.7	30.321	30.321	30.321	37.621	47.088	15.290
35.0	4014.4	26.527	26.527	26.527	36.952	46.250	16.797
37.0	3964.8	23.145	23.145	23.145	36.277	45.405	18.318
39.0	3913.6	20.193	20.193	20.193	35.598	44.556	19.846
41.0	3862.2	17.602	17.602	17.602	34.920	43.707	21.373
43.0	3812.6	15.326	15.326	15.326	34.244	42.861	22.894
45.0	3765.0	13.323	13.323	13.323	33.574	42.022	24.404
47.0	3719.6	11.557	11.557	11.557	32.910	41.191	25.899
49.0	3676.5	9.996	9.996	9.996	32.255	40.372	27.373
51.0	3635.8	8.615	8.615	8.615	31.611	39.565	28.824
53.0	3597.0	7.389	7.389	7.389	30.979	38.774	30.247
55.0	3559.9	6.299	6.299	6.299	30.359	37.999	31.642
57.0	3523.9	5.327	5.327	5.327	29.754	37.241	33.005
59.0	3489.0	4.458	4.458	4.458	29.164	36.502	34.334
61.0	3454.9	3.682	3.682	3.682	28.589	35.782	35.629
63.0	3421.6	2.986	2.986	2.986	28.029	35.082	36.888
65.0	3389.1	2.361	2.361	2.361	27.486	34.403	38.111
67.0	3357.0	1.800	1.800	1.800	26.960	33.744	39.296
69.0	3324.9	1.303	1.303	1.303	26.450	33.106	40.444
71.0	3291.5	0.852	0.852	0.852	25.957	32.488	41.555
73.0	3257.0	0.440	0.440	0.440	25.480	31.892	42.628
75.0	3221.6	0.065	0.065	0.065	25.020	31.316	43.664
77.0	3185.5	-0.276	-0.276	-0.276	24.576	30.760	44.664
79.0	3148.9	-0.587	-0.587	-0.587	24.148	30.225	45.627
81.0	3111.7	-0.869	-0.869	-0.869	23.736	29.709	46.555
83.0	3074.2	-1.125	-1.125	-1.125	23.340	29.212	47.448
85.0	3036.5	-1.358	-1.358	-1.358	22.958	28.735	48.307
87.0	2998.6	-1.568	-1.568	-1.568	22.591	28.276	49.132
89.0	2960.7	-1.759	-1.759	-1.759	22.239	27.835	49.925
91.0	2922.7	-1.931	-1.931	-1.931	21.901	27.412	50.687
93.0	2884.8	-2.087	-2.087	-2.087	21.577	27.006	51.417
95.0	2846.9	-2.227	-2.227	-2.227	21.265	26.617	52.118
97.0	2809.2	-2.352	-2.352	-2.352	20.967	26.243	52.790
99.0	2771.8	-2.465	-2.465	-2.465	20.681	25.885	53.433

101.0	2734.5	-2.565	-2.565	-2.565	20.408	25.543	54.049
103.0	2697.8	-2.655	-2.655	-2.655	20.146	25.215	54.639
105.0	2661.2	-2.734	-2.734	-2.734	19.895	24.901	55.204
107.0	2625.0	-2.804	-2.804	-2.804	19.655	24.601	55.743
109.0	2589.1	-2.865	-2.865	-2.865	19.426	24.315	56.259
111.0	2553.4	-2.918	-2.918	-2.918	19.208	24.041	56.752
113.0	2518.1	-2.964	-2.964	-2.964	18.999	23.779	57.222
115.0	2483.2	-3.003	-3.003	-3.003	18.799	23.530	57.671
117.0	2448.6	-3.035	-3.035	-3.035	18.609	23.292	58.099
119.0	2414.5	-3.062	-3.062	-3.062	18.428	23.065	58.507
121.0	2380.7	-3.084	-3.084	-3.084	18.256	22.849	58.895
123.0	2347.3	-3.100	-3.100	-3.100	18.091	22.644	59.265
125.0	2314.3	-3.113	-3.113	-3.113	17.935	22.448	59.617
127.0	2281.8	-3.121	-3.121	-3.121	17.787	22.263	59.951
129.0	2249.6	-3.125	-3.125	-3.125	17.646	22.086	60.268
131.0	2217.9	-3.125	-3.125	-3.125	17.513	21.919	60.568
133.0	2186.6	-3.123	-3.123	-3.123	17.386	21.761	60.853
135.0	2155.7	-3.117	-3.117	-3.117	17.267	21.611	61.122
137.0	2125.3	-3.108	-3.108	-3.108	17.154	21.470	61.377
139.0	2095.3	-3.097	-3.097	-3.097	17.047	21.337	61.616
141.0	2065.7	-3.084	-3.084	-3.084	16.947	21.211	61.842
143.0	2036.5	-3.068	-3.068	-3.068	16.853	21.093	62.054
145.0	2007.8	-3.050	-3.050	-3.050	16.764	20.983	62.253
147.0	1979.5	-3.030	-3.030	-3.030	16.682	20.879	62.439
149.0	1951.6	-3.008	-3.008	-3.008	16.605	20.783	62.612
151.0	1924.0	-2.985	-2.985	-2.985	16.533	20.693	62.773
153.0	1896.9	-2.960	-2.960	-2.960	16.467	20.611	62.922
155.0	1870.2	-2.934	-2.934	-2.934	16.406	20.534	63.060
157.0	1843.9	-2.906	-2.906	-2.906	16.350	20.464	63.185
159.0	1818.0	-2.877	-2.877	-2.877	16.299	20.401	63.300
161.0	1792.6	-2.847	-2.847	-2.847	16.253	20.343	63.403
163.0	1767.6	-2.816	-2.816	-2.816	16.212	20.292	63.496
165.0	1743.0	-2.784	-2.784	-2.784	16.176	20.246	63.578
167.0	1719.0	-2.751	-2.751	-2.751	16.144	20.207	63.649
169.0	1695.4	-2.718	-2.718	-2.718	16.117	20.173	63.710
171.0	1672.4	-2.684	-2.684	-2.684	16.095	20.145	63.760
173.0	1649.9	-2.649	-2.649	-2.649	16.077	20.123	63.800
175.0	1628.0	-2.614	-2.614	-2.614	16.064	20.106	63.830
177.0	1606.8	-2.578	-2.578	-2.578	16.055	20.095	63.850
178.1	1596.3	-2.562	-2.562	-2.562	16.052	20.091	63.857
180.0	1576.7	-2.525	-2.525	-2.525	16.050	20.089	63.861
182.0	1557.0	-2.490	-2.490	-2.490	16.052	20.091	63.856
184.0	1537.7	-2.455	-2.455	-2.455	16.059	20.100	63.841
186.0	1518.8	-2.419	-2.419	-2.419	16.070	20.114	63.816
188.0	1500.2	-2.381	-2.381	-2.381	16.086	20.134	63.781
190.0	1482.1	-2.342	-2.342	-2.342	16.106	20.159	63.735
192.0	1464.3	-2.300	-2.300	-2.300	16.131	20.190	63.679
194.0	1446.8	-2.255	-2.255	-2.255	16.160	20.227	63.613
196.0	1429.8	-2.207	-2.207	-2.207	16.194	20.269	63.536
198.0	1413.1	-2.154	-2.154	-2.154	16.233	20.318	63.449
200.0	1396.7	-2.096	-2.096	-2.096	16.277	20.373	63.351
202.0	1380.7	-2.034	-2.034	-2.034	16.325	20.433	63.241
204.0	1365.1	-1.966	-1.966	-1.966	16.379	20.500	63.121
206.0	1349.8	-1.892	-1.892	-1.892	16.437	20.573	62.989
208.0	1334.9	-1.812	-1.812	-1.812	16.501	20.653	62.846
210.0	1320.3	-1.726	-1.726	-1.726	16.570	20.739	62.691
212.0	1306.0	-1.635	-1.635	-1.635	16.644	20.833	62.523
214.0	1292.1	-1.537	-1.537	-1.537	16.724	20.932	62.343

216.0	1278.5	-1.434	-1.434	-1.434	16.810	21.040	62.151
218.0	1265.2	-1.324	-1.324	-1.324	16.901	21.154	61.945
220.0	1252.2	-1.208	-1.208	-1.208	16.998	21.276	61.726
222.0	1239.6	-1.087	-1.087	-1.087	17.102	21.405	61.493
224.0	1227.2	-0.960	-0.960	-0.960	17.212	21.543	61.245
226.0	1215.2	-0.827	-0.827	-0.827	17.328	21.689	60.983
228.0	1203.4	-0.687	-0.687	-0.687	17.451	21.843	60.706
230.0	1192.0	-0.540	-0.540	-0.540	17.582	22.006	60.413
232.0	1180.8	-0.385	-0.385	-0.385	17.719	22.177	60.104
234.0	1169.9	-0.222	-0.222	-0.222	17.864	22.359	59.778
236.0	1159.3	-0.051	-0.051	-0.051	18.016	22.549	59.435
238.0	1149.0	0.130	0.130	0.130	18.176	22.750	59.074
240.0	1138.8	0.322	0.322	0.322	18.345	22.961	58.694
242.0	1129.0	0.524	0.524	0.524	18.522	23.182	58.296
244.0	1119.4	0.738	0.738	0.738	18.708	23.415	57.877
246.0	1110.0	0.965	0.965	0.965	18.902	23.659	57.439
248.0	1100.8	1.205	1.205	1.205	19.107	23.915	56.979
250.0	1091.8	1.460	1.460	1.460	19.321	24.183	56.497
252.0	1083.0	1.732	1.732	1.732	19.545	24.463	55.992
254.0	1074.4	2.020	2.020	2.020	19.780	24.757	55.464
256.0	1066.0	2.328	2.328	2.328	20.025	25.064	54.911
258.0	1057.7	2.655	2.655	2.655	20.281	25.385	54.334
260.0	1049.6	3.005	3.005	3.005	20.549	25.720	53.730
262.0	1041.6	3.378	3.378	3.378	20.829	26.071	53.100
264.0	1033.7	3.777	3.777	3.777	21.122	26.437	52.442
266.0	1025.9	4.204	4.204	4.204	21.427	26.818	51.755
268.0	1018.2	4.661	4.661	4.661	21.745	27.216	51.039
270.0	1010.6	5.151	5.151	5.151	22.076	27.631	50.292
272.0	1003.0	5.677	5.677	5.677	22.422	28.064	49.514
274.0	995.4	6.241	6.241	6.241	22.782	28.514	48.704
276.0	987.9	6.847	6.847	6.847	23.156	28.983	47.861
278.0	980.4	7.499	7.499	7.499	23.545	29.470	46.985
280.0	972.9	8.200	8.200	8.200	23.950	29.976	46.074
282.0	965.4	8.955	8.955	8.955	24.370	30.503	45.127
284.0	957.9	9.768	9.768	9.768	24.807	31.049	44.145
286.0	950.3	10.644	10.644	10.644	25.259	31.615	43.126
288.0	942.7	11.589	11.589	11.589	25.728	32.202	42.071
290.0	935.0	12.609	12.609	12.609	26.213	32.809	40.978
292.0	927.3	13.710	13.710	13.710	26.715	33.437	39.848
294.0	919.4	14.973	14.973	14.973	27.234	34.086	38.680
296.0	911.2	16.381	16.381	16.381	27.769	34.756	37.475
298.0	902.7	17.929	17.929	17.929	28.320	35.446	36.234
300.0	893.9	19.614	19.614	19.614	28.888	36.157	34.956
302.0	884.6	21.445	21.445	21.445	29.471	36.887	33.642
304.0	875.1	23.436	23.436	23.436	30.069	37.636	32.295
306.0	865.1	25.599	25.599	25.599	30.682	38.402	30.916
308.0	854.8	27.950	27.950	27.950	31.308	39.186	29.505
310.0	844.1	30.502	30.502	30.502	31.947	39.986	28.067
312.0	833.0	33.268	33.268	33.268	32.597	40.799	26.604
314.0	821.6	36.265	36.265	36.265	33.256	41.625	25.119
316.0	809.8	39.505	39.505	39.505	33.924	42.460	23.615
318.0	797.7	43.001	43.001	43.001	34.598	43.304	22.099
320.0	785.1	46.763	46.763	46.763	35.275	44.151	20.574
322.0	772.3	50.798	50.798	50.798	35.954	45.001	19.045
324.0	759.1	55.111	55.111	55.111	36.631	45.848	17.521
326.0	745.6	59.697	59.697	59.697	37.304	46.690	16.006
328.0	731.8	64.547	64.547	64.547	37.968	47.523	14.509
330.0	717.7	69.641	69.641	69.641	38.622	48.341	13.037

332.0	703.4	74.948	74.948	74.948	39.261	49.140	11.600
334.0	688.9	80.420	80.420	80.420	39.880	49.915	10.204
336.0	674.2	85.997	85.997	85.997	40.477	50.662	8.861
338.0	659.4	91.597	91.597	91.597	41.046	51.375	7.579
340.0	644.5	97.122	97.122	97.122	41.584	52.048	6.367
342.0	629.6	102.453	102.453	102.453	42.087	52.677	5.236
344.0	614.8	107.456	107.456	107.456	42.549	53.256	4.194
344.0	858.9	140.338	140.665	140.338	42.332	53.107	4.561
345.0	858.2	144.193	144.564	144.193	42.611	53.471	3.918
346.0	857.5	147.959	148.502	147.959	42.875	53.860	3.265
347.0	856.8	151.628	152.561	151.628	42.918	54.048	3.035
348.0	856.2	155.215	156.942	155.215	42.903	54.297	2.800
349.0	855.7	158.781	162.088	158.781	42.780	54.660	2.560
350.0	855.5	162.444	168.647	162.444	42.484	55.205	2.311
351.0	855.5	166.334	176.806	166.334	42.028	55.915	2.057
352.0	856.0	170.669	187.961	170.669	41.289	56.914	1.797
353.0	857.1	175.769	203.561	175.769	40.199	58.270	1.531
354.0	859.1	181.950	224.253	181.950	38.831	59.902	1.267
355.0	862.3	189.651	252.319	189.651	37.141	61.849	1.010
356.0	866.9	199.405	289.739	199.405	35.206	64.028	0.766
357.0	873.2	211.843	335.901	211.843	33.323	66.133	0.544
358.0	881.6	227.704	396.952	227.704	31.320	68.339	0.341
359.0	891.8	293.111	474.355	247.320	33.001	66.847	0.151
360.0	903.8	406.102	569.321	0.0	36.302	63.698	0.0
361.0	917.1	521.770	685.712	297.993	37.764	62.118	0.117
362.0	931.2	662.916	827.226	328.260	38.952	60.838	0.210
363.0	945.8	832.080	986.136	373.530	40.149	59.556	0.294
364.0	960.6	1031.482	1178.534	515.584	40.968	58.587	0.446
365.0	975.4	1244.046	1382.509	667.941	41.571	57.822	0.607
366.0	989.9	1462.315	1595.225	849.100	41.940	57.265	0.795
367.0	1004.0	1688.598	1814.906	1042.438	42.216	56.791	0.992
368.0	1017.5	1918.823	2037.894	1231.635	42.423	56.392	1.185
369.0	1029.9	2148.397	2259.629	1414.195	42.578	56.050	1.372
370.0	1041.3	2369.846	2472.442	1592.270	42.692	55.748	1.560
371.0	1051.4	2593.176	2687.118	1775.944	42.773	55.475	1.753
372.0	1059.9	2786.896	2872.121	1937.715	42.821	55.235	1.943
373.0	1066.3	2969.530	3046.216	2111.386	42.841	55.005	2.154
374.0	1070.4	3099.424	3168.074	2245.083	42.835	54.802	2.363
375.0	1072.4	3144.560	3210.664	2324.310	42.627	54.475	2.897
376.0	1072.7	3147.178	3209.781	2376.752	42.411	54.138	3.451
377.0	1071.8	3121.727	3180.383	2401.294	42.191	53.799	4.010
378.0	1069.7	3069.377	3123.983	2397.725	41.968	53.463	4.569
379.0	1066.6	3007.688	3049.761	2495.865	41.703	52.927	5.370
380.0	1061.5	2980.798	2980.798	2980.799	41.584	52.048	6.368
381.0	1055.2	2839.393	2839.392	2839.392	41.319	51.717	6.964
382.0	1048.4	2698.330	2698.330	2698.331	41.046	51.375	7.579
383.0	1041.5	2560.622	2560.621	2560.622	40.765	51.023	8.212
384.0	1034.3	2427.041	2427.041	2427.041	40.477	50.662	8.861
385.0	1027.0	2298.236	2298.236	2298.237	40.182	50.293	9.526
386.0	1019.6	2174.533	2174.533	2174.534	39.880	49.915	10.205
387.0	1012.1	2056.139	2056.139	2056.139	39.573	49.531	10.896
388.0	1004.5	1943.434	1943.434	1943.434	39.261	49.140	11.600
389.0	997.0	1836.848	1836.848	1836.848	38.943	48.743	12.314
390.0	989.5	1736.498	1736.498	1736.498	38.622	48.340	13.038
391.0	982.2	1642.277	1642.277	1642.277	38.297	47.933	13.770
392.0	974.9	1553.978	1553.977	1553.978	37.968	47.522	14.509
393.0	967.7	1471.321	1471.320	1471.321	37.637	47.108	15.255
394.0	960.7	1394.010	1394.010	1394.010	37.303	46.690	16.006

395.0	953.8	1321.723	1321.722	1321.723	36.968	46.270	16.762
396.0	947.0	1254.140	1254.140	1254.140	36.631	45.848	17.521
397.0	940.3	1190.946	1190:946	1190.946	36.293	45.425	18.283
398.0	933.8	1131.853	1131.852	1131.853	35.954	45.001	19.046
399.0	927.4	1076.574	1076.574	1076.574	35.614	44.576	19.810
400.0	921.1	1024.837	1024.837	1024.837	35.275	44.151	20.574
401.0	915.0	976.395	976.395	976.395	34.936	43.727	21.337
402.0	909.0	931.008	931.008	931.008	34.598	43.303	22.099
403.0	903.2	888.466	888.466	888.466	34.260	42.881	22.859
404.0	897.4	848.552	848.552	848.552	33.924	42.460	23.616
405.0	891.8	811.082	811.082	811.082	33.589	42.041	24.369
406.0	886.3	775.882	775.882	775.882	33.256	41.625	25.119
407.0	881.0	742.790	742.790	742.790	32.925	41.211	25.864
408.0	875.7	711.653	711.653	711.653	32.597	40.799	26.604
409.0	870.6	682.333	682.333	682.333	32.270	40.391	27.339
410.0	865.6	654.703	654.703	654.703	31.947	39.986	28.067
411.0	860.7	628.644	628.644	628.644	31.626	39.584	28.790
412.0	855.8	604.045	604.045	604.045	31.308	39.186	29.506
413.0	851.1	580.809	580.809	580.809	30.993	38.792	30.214
414.0	846.5	558.841	558.841	558.841	30.682	38.402	30.916
415.0	842.0	538.055	538.055	538.055	30.374	38.017	31.610
416.0	837.5	518.372	518.372	518.372	30.069	37.635	32.296
417.0	833.2	499.721	499.721	499.721	29.768	37.259	32.973
418.0	828.9	482.033	482.033	482.033	29.471	36.887	33.643
419.0	824.7	465.244	465.244	465.244	29.177	36.519	34.304
420.0	820.5	449.300	449.300	449.300	28.888	36.157	34.956
421.0	816.5	434.144	434.144	434.144	28.602	35.799	35.599
422.0	812.5	419.729	419.729	419.729	28.320	35.446	36.234
423.0	808.5	406.008	406.008	406.008	28.042	35.099	36.859
424.0	804.6	392.941	392.941	392.941	27.769	34.756	37.475
425.0	800.8	380.484	380.484	380.484	27.499	34.419	38.083
426.0	797.0	368.606	368.606	368.606	27.233	34.086	38.680
427.0	793.3	357.270	357.270	357.270	26.972	33.759	39.269
428.0	789.6	346.446	346.446	346.446	26.715	33.437	39.848
429.0	785.9	336.102	336.102	336.102	26.462	33.121	40.418
430.0	782.3	326.214	326.214	326.214	26.213	32.809	40.978
431.0	778.7	316.755	316.755	316.755	25.968	32.503	41.529
432.0	775.2	307.702	307.702	307.702	25.728	32.202	42.071
433.0	771.6	299.032	299.032	299.032	25.491	31.906	42.603
434.0	768.2	290.726	290.726	290.726	25.259	31.615	43.126
435.0	764.7	282.763	282.763	282.763	25.031	31.329	43.640
436.0	761.3	275.126	275.126	275.126	24.806	31.049	44.145
437.0	757.9	267.797	267.797	267.797	24.586	30.773	44.641
438.0	754.5	260.762	260.762	260.762	24.370	30.503	45.127
439.0	751.1	254.005	254.005	254.005	24.158	30.237	45.605
440.0	747.8	247.512	247.512	247.512	23.950	29.976	46.074
441.0	744.4	241.271	241.271	241.271	23.746	29.721	46.534
442.0	741.1	235.268	235.268	235.268	23.545	29.470	46.985
443.0	737.8	229.494	229.494	229.494	23.349	29.224	47.428
444.0	734.5	223.936	223.936	223.936	23.156	28.983	47.862
445.0	731.2	218.585	218.585	218.585	22.967	28.746	48.287
446.0	728.0	213.431	213.431	213.431	22.781	28.514	48.704
447.0	724.7	208.465	208.465	208.465	22.600	28.287	49.113
448.0	721.5	203.679	203.679	203.679	22.422	28.064	49.514
449.0	718.3	199.064	199.064	199.064	22.247	27.845	49.907
450.0	715.1	194.613	194.613	194.613	22.076	27.631	50.292
451.0	711.9	190.319	190.319	190.319	21.909	27.422	50.669
452.0	708.7	186.175	186.175	186.175	21.745	27.216	51.039

453.0	705.5	182.174	182.174	182.174	21.584	27.015	51.401
454.0	702.4	178.311	178.311	178.311	21.427	26.818	51.755
455.0	699.2	174.580	174.580	174.580	21.273	26.625	52.102
456.0	696.1	170.975	170.975	170.975	21.122	26.437	52.442
457.0	693.0	167.491	167.491	167.491	20.974	26.252	52.774
458.0	689.9	164.124	164.124	164.124	20.829	26.071	53.100
459.0	686.8	160.868	160.869	160.869	20.688	25.894	53.418
460.0	683.7	157.720	157.720	157.720	20.549	25.720	53.730
461.0	680.6	154.674	154.674	154.674	20.414	25.551	54.035
462.0	677.6	151.728	151.728	151.728	20.281	25.385	54.334
463.0	674.5	148.876	148.876	148.876	20.152	25.222	54.626
464.0	671.5	146.117	146.117	146.117	20.025	25.064	54.911
465.0	668.5	143.445	143.445	143.446	19.901	24.908	55.191
466.0	665.5	140.859	140.859	140.859	19.779	24.757	55.464
467.0	662.5	138.354	138.354	138.354	19.661	24.608	55.731
468.0	659.6	135.929	135.929	135.929	19.545	24.463	55.992
469.0	656.7	133.579	133.579	133.579	19.432	24.321	56.247
470.0	653.8	131.302	131.302	131.302	19.321	24.183	56.497
471.0	650.9	129.097	129.097	129.097	19.213	24.047	56.740
472.0	648.0	126.959	126.959	126.959	19.107	23.915	56.979
473.0	645.2	124.887	124.887	124.887	19.003	23.785	57.211
474.0	642.4	122.877	122.877	122.877	18.902	23.659	57.439
475.0	639.6	120.930	120.930	120.930	18.804	23.536	57.661
476.0	636.8	119.041	119.041	119.041	18.708	23.415	57.877
478.0	628.5	95.758	95.758	95.758	18.522	23.182	58.296
480.0	620.7	92.732	92.732	92.732	18.345	22.961	58.694
482.0	613.9	89.903	89.903	89.903	18.176	22.750	59.074
484.0	608.5	87.326	87.326	87.326	18.016	22.549	59.435
486.0	605.9	85.090	85.090	85.090	17.864	22.359	59.778
488.0	607.7	83.339	83.339	83.339	17.719	22.177	60.104
490.0	616.4	82.277	82.277	82.277	17.582	22.006	60.413
492.0	634.6	82.083	82.083	82.083	17.451	21.843	60.706
494.0	665.5	82.934	82.934	82.934	17.328	21.689	60.983
496.0	711.4	84.895	84.895	84.895	17.212	21.543	61.245
498.0	773.7	87.855	87.855	87.855	17.102	21.405	61.493
500.0	852.0	91.521	91.521	91.521	16.998	21.276	61.726
502.0	944.8	95.517	95.517	95.517	16.901	21.154	61.945
504.0	1047.9	99.300	99.300	99.300	16.810	21.040	62.151
506.0	1156.6	102.422	102.422	102.422	16.724	20.932	62.343
508.0	1263.2	104.324	104.324	104.324	16.644	20.832	62.523
510.0	1358.0	104.547	104.547	104.547	16.570	20.739	62.691
512.0	1428.4	102.665	102.665	102.665	16.501	20.653	62.846
514.0	1452.8	97.993	97.993	97.993	16.437	20.573	62.989
516.0	1435.8	91.438	91.438	91.438	16.379	20.500	63.121
518.0	1342.3	81.821	81.821	81.821	16.325	20.433	63.241
520.0	1153.0	68.717	68.717	68.717	16.277	20.373	63.351
522.0	856.6	51.938	51.938	51.938	16.233	20.318	63.449
524.0	499.1	32.883	32.883	32.883	16.194	20.269	63.536
526.0	476.1	31.555	31.555	31.555	16.160	20.227	63.613
528.0	485.5	32.010	32.010	32.010	16.131	20.190	63.679
530.0	489.6	32.187	32.187	32.187	16.106	20.159	63.735
532.0	490.1	32.172	32.172	32.172	16.086	20.134	63.781
534.0	488.5	32.044	32.044	32.044	16.070	20.114	63.816
536.0	485.6	31.851	31.851	31.851	16.059	20.100	63.841
538.0	482.2	31.627	31.627	31.627	16.052	20.091	63.856
540.0	478.5	31.393	31.393	31.393	16.050	20.089	63.861
542.0	475.0	31.162	31.162	31.162	16.052	20.092	63.856
544.0	471.6	30.941	30.941	30.941	16.059	20.100	63.841

546.0	468.4	30.733	30.733	30.733	16.070	20.114	63.816
548.0	466.0	30.564	30.564	30.564	16.086	20.134	63.781
550.0	463.8	30.408	30.408	30.408	16.106	20.159	63.735
552.0	463.2	30.332	30.332	30.332	16.131	20.190	63.679
554.0	462.8	30.272	30.272	30.272	16.160	20.227	63.613
556.0	462.8	30.231	30.231	30.231	16.194	20.269	63.536
558.0	465.0	30.311	30.311	30.311	16.233	20.318	63.449
560.0	465.9	30.313	30.313	30.313	16.277	20.373	63.351
562.0	468.4	30.403	30.403	30.403	16.325	20.433	63.241
564.0	471.8	30.539	30.539	30.539	16.379	20.500	63.121
566.0	474.9	30.660	30.660	30.660	16.437	20.573	62.989
568.0	479.6	30.867	30.867	30.867	16.501	20.653	62.846
570.0	484.4	31.070	31.070	31.070	16.570	20.739	62.691
572.0	489.7	31.301	31.301	31.301	16.644	20.833	62.523
574.0	495.9	31.579	31.579	31.579	16.724	20.933	62.343
576.0	502.1	31.853	31.853	31.853	16.810	21.040	62.151
578.0	509.3	32.177	32.177	32.177	16.901	21.154	61.945
580.0	517.2	32.533	32.533	32.533	16.998	21.276	61.726
582.0	525.0	32.882	32.882	32.882	17.102	21.405	61.493
584.0	533.0	33.238	33.238	33.238	17.212	21.543	61.245
586.0	542.6	33.672	33.672	33.672	17.328	21.689	60.983
588.0	551.4	34.064	34.064	34.064	17.451	21.843	60.706
590.0	560.2	34.456	34.456	34.456	17.582	22.006	60.413
592.0	569.7	34.875	34.875	34.875	17.719	22.177	60.104
594.0	580.4	35.349	35.349	35.349	17.864	22.359	59.778
596.0	590.3	35.786	35.786	35.786	18.016	22.549	59.435
598.0	599.9	36.199	36.199	36.199	18.176	22.750	59.074
600.0	609.8	36.625	36.625	36.625	18.345	22.961	58.694
602.0	620.4	37.078	37.078	37.078	18.522	23.182	58.296
604.0	631.4	37.552	37.552	37.552	18.708	23.415	57.877
606.0	643.4	38.064	38.064	38.064	18.903	23.659	57.439
608.0	652.7	38.443	38.443	38.443	19.107	23.915	56.979
610.0	662.6	38.844	38.844	38.844	19.321	24.183	56.496
612.0	672.6	39.247	39.247	39.247	19.545	24.463	55.992
614.0	682.6	39.650	39.650	39.650	19.780	24.757	55.464
616.0	693.2	40.074	40.074	40.074	20.025	25.064	54.911
618.0	702.4	40.426	40.426	40.426	20.281	25.385	54.334
620.0	711.2	40.754	40.754	40.754	20.549	25.720	53.730
622.0	719.6	41.060	41.060	41.060	20.829	26.071	53.100
624.0	727.9	41.358	41.358	41.358	21.122	26.437	52.442
626.0	736.4	41.660	41.660	41.660	21.427	26.818	51.755
628.0	743.0	41.871	41.871	41.871	21.745	27.217	51.039
630.0	748.9	42.047	42.047	42.047	22.076	27.632	50.292
632.0	754.8	42.218	42.218	42.218	22.422	28.064	49.514
634.0	759.2	42.317	42.317	42.317	22.782	28.514	48.704
636.0	763.5	42.414	42.414	42.414	23.156	28.983	47.861
638.0	767.4	42.491	42.491	42.491	23.545	29.470	46.985
640.0	769.8	42.506	42.506	42.506	23.950	29.977	46.074
642.0	771.4	42.481	42.481	42.481	24.370	30.503	45.127
644.0	773.8	42.490	42.490	42.490	24.807	31.049	44.145
646.0	771.9	42.310	42.310	42.310	25.259	31.615	43.126
648.0	770.9	42.167	42.167	42.167	25.728	32.202	42.071
650.0	768.3	41.950	41.950	41.950	26.213	32.809	40.978
652.0	765.4	41.725	41.725	41.725	26.715	33.437	39.848
654.0	760.8	41.626	41.626	41.626	27.234	34.086	38.680
656.0	755.5	41.596	41.596	41.596	27.769	34.756	37.475
658.0	748.3	41.490	41.490	41.490	28.320	35.446	36.233
660.0	741.3	41.397	41.397	41.397	28.888	36.157	34.956

662.0	732.1	41.206	41.206	41.206	29.471	36.887	33.642
664.0	721.6	40.957	40.957	40.957	30.069	37.636	32.295
666.0	712.6	40.787	40.787	40.787	30.682	38.403	30.915
668.0	700.4	40.465	40.465	40.465	31.308	39.186	29.505
670.0	687.0	40.089	40.089	40.089	31.947	39.986	28.067
672.0	673.6	39.708	39.708	39.708	32.597	40.799	26.604
674.0	658.7	39.253	39.253	39.253	33.257	41.625	25.118
676.0	640.9	38.651	38.651	38.651	33.924	42.461	23.615
678.0	626.1	38.191	38.191	38.191	34.598	43.304	22.099
680.0	608.4	37.580	37.580	37.580	35.275	44.151	20.573
682.0	589.8	36.911	36.911	36.911	35.954	45.001	19.045
684.0	570.2	36.180	36.180	36.180	36.631	45.848	17.521
686.0	549.3	35.360	35.360	35.360	37.304	46.690	16.006
688.0	533.3	34.760	34.760	34.760	37.969	47.523	14.509
690.0	506.0	33.574	33.574	33.574	38.622	48.341	13.037
692.0	487.5	32.823	32.823	32.823	39.261	49.140	11.599
694.0	465.6	31.854	31.854	31.854	39.880	49.915	10.204
696.0	443.3	30.836	30.836	30.836	40.477	50.662	8.861
698.0	420.4	29.740	29.740	29.740	41.046	51.375	7.579
700.0	399.0	28.696	28.696	28.696	41.584	52.048	6.367
702.0	376.9	27.571	27.571	27.571	42.087	52.677	5.236
704.0	355.4	26.440	26.440	26.440	42.550	53.256	4.194

APPENDIX D

GEOMETRIC SIMULATION CODE

MODEL FOR THE GEOMETRIC INTERACTION BETWEEN A SPHERICAL PROPAGATING FLAME AND A COMBUSTION CHAMBER OF ARBITRARY SHAPE

BY

STEPHEN G. POULOS

SLOAN AUTOMOTIVE LABORATORY

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

MARCH 1982

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CAMBRIDGE, MASS 02139

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C                                                   VERSION 1.0__4/26/82___
C
C     PROGRAM CHAMBER
C
C     PURPOSE
C        THIS PROGRAM CALCULATES THE GEOMETRY OF A SPHERICAL FLAME
C        WITH A FIXED CENTER AS IT PROPAGATES THROUGH THE COMBUSTION
C        CHAMBER OF A RECIPROCATING ENGINE.  THE CHAMBER MAY HAVE
C        ANY ARBITRARY SHAPE, AND THE CALCULATION TAKES INTO
C        ACCOUNT THE EFFECT OF PISTON MOTION ON THE INSTANTANEOUS
C        SHAPE OF THE CHAMBER.  GIVEN A DETAILED DESCRIPTION OF
C        THE CHAMBER SHAPE, THE CRANK ANGLE (WHICH TOGETHER WITH
C        THE ENGINE STROKE AND CONNECTING ROD LENGTH DETERMINES THE
C        PISTON POSITION), AND A FLAME RADIUS, THE PROGRAM CALCULATES
C        THE AREAS OF THE CYLINDER HEAD, PISTON, AND CYLINDER WALL ON
C        EACH SIDE OF THE FLAME , AND THE FLAME SURFACE.
C
C     DESCRIPTION OF PARAMETERS
C        PARAMETER  INPUT  OUTPUT  DESCRIPTION
C
C        OFLAME     NO     YES     BASE FLAME AREA ABOVE HIGHEST POINT
C        ------     --     ---     ON PISTON @ TDC
C        AFLAME     NO     YES     TOTAL FLAME AREA
C        AINH       NO     YES     AREA OF HEAD INSIDE FLAME
C        AOUTH      NO     YES     AREA OF HEAD OUTSIDE FLAME
C        AINP       NO     YES     AREA OF PISTON INSIDE FLAME
C        AOUTP      NO     YES     AREA OF PISTON OUTSIDE FLAME
C        AINCW      NO     YES     AREA OF CYL. WALL INSIDE FLAME
C        AOUTCW     NO     YES     AREA OF CYL. WALL OUTSIDE FLAME
C        VIN        NO     YES     VOLUME INSIDE THE FLAME
C        VOUT       NO     YES     VOLUME OUTSIDE THE FLAME
C        VTOTAL     NO     YES     TOTAL CHAMBER VOLUME
C
C     REMARKS
C        NONE
C
C     SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED
C        INPUT      RQUIT      FLAME      CHANGE
C        WALL       REPORT
C
C     METHOD
C        THE SURFACE OF THE COMBUSTION CHAMBER IS APPROXIMATED BY A
C        LARGE NUMBER OF FLAT TRIANGULAR FACETS. THE FACETS WHICH LIE
C        ON THE CYLINDER WALL ARE "STRETCHED" AS THE PISTON MOVES AND
C        THOSE ON THE PISTON CROWN TRANSLATE WITH THE PISTON. AT EACH
C        CRANK ANGLE, SPHERES WITH INCREMENTAL RADII ARE MADE TO INTER-
C        SECT THE INSTANTANEOUS SURFACE OF THE CHAMBER. A LARGE NUMBER
C        OF POINTS ARE DISTRUBUTED RANDOMLY ON THE SURFACE OF EACH
C        SPHERE AND EACH POINT IS TESTED TO SEE IF IT LIES WITHIN THE
C        CHAMBER. THE FRACTION OF POINTS ON THE TEST SPHERE WHICH ARE
C        INSIDE THE CHAMBER TIMES THE SURFACE AREA OF THE TEST SPHERE
C        IS THE TOTAL FLAME AREA. THE SURFACES OF THE 3 ZONES OF THE
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C        CHAMBER (HEAD, PISTON, CYLINDER WALL) ON EACH SIDE OF THE
C        FLAME ARE FOUND BY IDENTIFYING WHICH FACETS LIE ON EACH SIDE
C        OF THE FLAME AND ADDING UP THEIR AREAS TO GET THE TOTALS.
C
C     WRITTEN BY S. G. POULOS
C     EDITED BY S. G. POULOS
C
C
      INTEGER SPNTS, SPMIN, SPMAX, OLDTHT, OLDRAD, ACOUNT, BCOUNT,
     &        CCOUNT
      REAL LIMIT(2,3), OFLAME(50), AINH(30,50), AINP(30,50),
     &     AINCW(30,50), AOUTH(30,50), AOUTP(30,50), AOUTCW(30,50),
     &     AFLAME(30,50), VIN(30,50), VTOTAL(30),VOUT(30,50), MTHETA
      REAL ZLMT(2,3), ZINH(30,50), ZINP(30,50),
     &     ZINCW(30,50), ZOUTH(30,50), ZOUTP(30,50), ZOUTCW(30,50),
     &     ZFLAME(30,50), ZIN(30,50), ZOUT(30,50)
      COMMON/DIMENS/ BORE, STROKE, CONRL
      COMMON/LIMITS/ LIMIT, PISBOT
      COMMON/ACNT/ ACOUNT
      COMMON/BCNT/ BCOUNT
      COMMON/CCNT/ CCOUNT
      COMMON/VOLUMS/ VTOTAL, VIN, VOUT
      COMMON/CNTROL/ DTHETA, MTHETA, RSTEPS, PDENST, SPMIN,
     &               SPMAX, MAXITS
      COMMON/RSEED/ IX
C
      LIMIT(1,1) =  999999.
      LIMIT(2,1) = -999999.
      LIMIT(1,2) =  999999.
      LIMIT(2,2) = -999999.
      LIMIT(1,3) = -999999.
      LIMIT(2,3) = -999999.
      PISBOT = 999999.
C
C        READ IN CHAMBER GEOMETRY AND PARAMETERS FOR CONTROLING
C        CALCULATION.  INPUTS ARE TRANSFERED THROUGH COMMON BLOCKS.
C
      CALL INPUT
C
      WRITE (6,170)
C
C        INITIALIZE TO 0.0 ALL VOLUMES AND AREAS TO BE CALCULATED
C
      DO 10 ITHETA = 1, 30
          VTOTAL(ITHETA) = 0.0
          DO  4 IRAD = 1, 50
              OFLAME(IRAD) = 0.0
              AFLAME(ITHETA,IRAD) = 0.0
              AINH(ITHETA,IRAD) = 0.0
              AOUTH(ITHETA,IRAD) = 0.0
              AINP(ITHETA,IRAD) = 0.0
              AOUTP(ITHETA,IRAD) = 0.0
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            AINCW(ITHETA,IRAD) = 0.0
            AOUTCW(ITHETA,IRAD) = 0.0
            VIN(ITHETA,IRAD) = 0.0
            VOUT(ITHETA,IRAD) = 0.0
    4    CONTINUE
   10 CONTINUE
C
C        CALCULATE MAXIMUM FLAME RADIUS FOR PISTON AT BDC
C
      ACOUNT = 0
C
C        SET INITIAL RANDOM NUMBER SEED FOR SUBROUTINE 'FLAME'
C
      IX = 11261949
      CALL RQUIT (RMAX)
C
C        CALCULATE RADIUS INCREMENT AND NORMALIZE ENGINE DIMENSIONS
C
      DELTAR = RMAX/RSTEPS
      STBRAT = STROKE/BORE
      CTBRAT = CONRL/BORE
      DTBRAT = DELTAR/BORE
      WRITE (8,210) DTHETA, MTHETA, DTBRAT, STBRAT, CTBRAT
C
C        CALCULATE FLAME AREAS FOR BASE CASE: PISTON AT TDC.
C        REGION OF INTEREST FOR BASE CASE IS BETWEEN THE HIGHEST
C        POINT IN THE CHAMBER AND THE HORIZONTAL PLANE PASSING
C        THROUGH THE HIGHEST POINT ON THE PISTON AT TDC.
C
      RADIUS = 0.0
C
      DO 20 IRAD = 1, 50
          IF (IRAD .EQ. 1) GO TO 20
          RADIUS = RADIUS + DELTAR
C
C             CALCULATE NUMBER OF POINTS TO GENERATE ON FLAME SPHERE
C
          SPNTS = INT( 16. * PDENST * (RADIUS/BORE)**2. )
          IF (SPNTS .LT. SPMIN) SPNTS = SPMIN
          IF (SPNTS .GT. SPMAX) SPNTS = SPMAX
C
          CALL FLAME (RADIUS, SPNTS, FSURF, STADEV)
C
          WRITE (7,260) RADIUS, SPNTS, FSURF, STADEV
          OFLAME(IRAD) = FSURF
          IF ((IRAD .GT. 1) .AND. (OFLAME(IRAD) .LE. 0.00001)) GO TO 30
   20 CONTINUE
C
C        BEGIN MAIN CALCULATION LOOP FOR INCREASING VALUES OF THETA.
C        FOR EACH INCRESING VALUE OF THETA, INCREASE RADIUS IN STEPS
C        OF DELTAR.
C
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   30 LIMIT(2,3) = LIMIT(1,3)
      LIMIT(1,3) = PISBOT
      OLDROP = 0.0
      THETA = 0.0
      BCOUNT = 0
C
      DO 100 ITHETA = 1, 30
          IF (ITHETA .LE. 1) GO TO 40
          THETA = THETA + DTHETA
          IF (THETA .GT. MTHETA) GO TO 105
C
C             SHIFT NON-FIXED POINTS ON CHAMBER SURFACE AND OUTER
C             LIMITS OF CHAMBER
C
          CALL CHANGE (THETA,OLDROP)
C
   40     CALL RQUIT (RMAX)
          WRITE (7,240) THETA
          OLDTHT = ITHETA - 1
          RADIUS = 0.0
          CCOUNT = 0
C
          DO 70 IRAD = 1, 50
              WRITE (7,250) RADIUS
              MAXRAD = IRAD
C
C                CALCULATE CHAMBER SURFACE AREAS ON EACH SIDE OF THE
C                FLAME FOR EACH OF THE 3 CHAMBER ZONES.
C
              CALL WALL (ITHETA, IRAD, RADIUS, AINH, AOUTH, AINP,
     &                   AOUTP, AINCW, AOUTCW)
C
              IF (OLDTHT .LT. 1) GO TO 50
C
C                IF FLAME HAS NOT IMPINGED ON PISTON AT THIS RADIUS,
C                FLAME AREA = FLAME AREA FROM PREVIOUS CRANK ANGLE.
C
              IF ((AINP(OLDTHT,IRAD)/BORE**2) .GT. 0.00001) GO TO 50
              AFLAME(ITHETA,IRAD) = AFLAME(OLDTHT,IRAD)
              GO TO 60
   50         IF (IRAD .EQ. 1) GO TO 60
              SPNTS = INT( 16. * PDENST * (RADIUS/BORE)**2. )
              IF (SPNTS .LT. SPMIN) SPNTS = SPMIN
              IF (SPNTS .GT. SPMAX) SPNTS = SPMAX
C
              CALL FLAME (RADIUS, SPNTS, FSURF, STADEV)
C
C                TOTAL AREA = BASE AREA + FSURF
C
              AFLAME(ITHETA,IRAD) = OFLAME(IRAD) + FSURF
   60         OLDRAD = IRAD - 1
              OLDFLM = 0.0
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            OLDVIN = 0.0
            IF (OLDRAD .GE. 1) OLDFLM = AFLAME(ITHETA,OLDRAD)
            IF (OLDRAD .GE. 1) OLDVIN = VIN(ITHETA,OLDRAD)
C
C              CALCULATE INCREMENTAL VOLUME DUE TO DELTAR
C
            IF ((IRAD .GT. 1) .AND.
     &          (AFLAME(ITHETA,IRAD) .LE. 0.000001)) GO TO 80
            DELV = .5 * ( AFLAME(ITHETA,IRAD) + OLDFLM )*DELTAR
            VIN(ITHETA,IRAD) = OLDVIN + DELV
            RADIUS = RADIUS + DELTAR
   70     CONTINUE
C
C           USE REDUCED DELTAR FOR LAST VOLUME INCREMENT
C
   80     DELV = .5 * ( AFLAME(ITHETA,MAXRAD) + OLDFLM )*
     &          (RMAX - FLOAT(MAXRAD - 2)*DELTAR)
          VIN(ITHETA,MAXRAD) = OLDVIN + DELV
          VTOTAL(ITHETA) = VIN(ITHETA,MAXRAD)
          CMRTIO = (VTOTAL(1) + 3.1415926*BORE*BORE*STROKE/4.)/VTOTAL(1)
          IF (ITHETA .EQ. 1) WRITE (7,230) CMRTIO
          WRITE (6,110) THETA
          WRITE (6,120)
          WRITE (6,130)
C
          DO 90 IRAD = 1, MAXRAD
              VOUT(ITHETA,IRAD) = VTOTAL(ITHETA) - VIN(ITHETA,IRAD)
   90     CONTINUE
C
C            COMPLETE SOLUTION MATRIX FOR REMAINING RADII
C
          MXRD1 = MAXRAD + 1
          DO 91 IRAD = MXRD1, 50
              AINH(ITHETA,IRAD) = AINH(ITHETA,MAXRAD)
              AOUTH(ITHETA,IRAD) = AOUTH(ITHETA,MAXRAD)
              AINP(ITHETA,IRAD) = AINP(ITHETA,MAXRAD)
              AOUTP(ITHETA,IRAD) = AOUTP(ITHETA,MAXRAD)
              AINCW(ITHETA,IRAD) = AINCW(ITHETA,MAXRAD)
              AOUTCW(ITHETA,IRAD) = AOUTCW(ITHETA,MAXRAD)
              VIN(ITHETA,IRAD) = VIN(ITHETA,MAXRAD)
              VOUT(ITHETA,IRAD) = VOUT(ITHETA,MAXRAD)
   91     CONTINUE
C
C             NORMALIZE AND PRINT OUT RESULTS
C
          RADIUS = 0.0
          DO 95 IRAD = 1, 50
              ZFLAME(ITHETA,IRAD) = AFLAME(ITHETA,IRAD)/( BORE*BORE )
              ZINH(ITHETA,IRAD) = AINH(ITHETA,IRAD)/( BORE*BORE )
              ZOUTH(ITHETA,IRAD) = AOUTH(ITHETA,IRAD)/( BORE*BORE )
              ZINP(ITHETA,IRAD) = AINP(ITHETA,IRAD)/( BORE*BORE )
              ZOUTP(ITHETA,IRAD) = AOUTP(ITHETA,IRAD)/( BORE*BORE )
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            ZINCW(ITHETA,IRAD) = AINCW(ITHETA,IRAD)/( BORE*BORE )
            ZOUTCW(ITHETA,IRAD) = AOUTCW(ITHETA,IRAD)/( BORE*BORE )
            ZIN(ITHETA,IRAD) = VIN(ITHETA,IRAD)/( BORE*BORE*BORE )
            ZOUT(ITHETA,IRAD) = VOUT(ITHETA,IRAD)/( BORE*BORE*BORE )
            IF (IRAD .GT. MAXRAD) GO TO 93
            WRITE (6,140) RADIUS, ZFLAME(ITHETA,IRAD),
     &                    ZINH(ITHETA,IRAD), ZOUTH(ITHETA,IRAD),
     &                    ZINP(ITHETA,IRAD), ZOUTP(ITHETA,IRAD),
     &                    ZINCW(ITHETA,IRAD), ZOUTCW(ITHETA,IRAD),
     &                    ZIN(ITHETA,IRAD), ZOUT(ITHETA,IRAD)
 93         WRITE (8,160) RADIUS, ZFLAME(ITHETA,IRAD),
     &                    ZINH(ITHETA,IRAD), ZOUTH(ITHETA,IRAD),
     &                    ZINP(ITHETA,IRAD), ZOUTP(ITHETA,IRAD),
     &                    ZINCW(ITHETA,IRAD), ZOUTCW(ITHETA,IRAD),
     &                    ZIN(ITHETA,IRAD), ZOUT(ITHETA,IRAD)
            RADIUS = RADIUS + DTBRAT
 95       CONTINUE
          DO 98 I = 1, 2
            DO 96 J = 1, 3
              ZLMT(I,J) = LIMIT(I,J)/BORE
 96         CONTINUE
 98       CONTINUE
          WRITE (6,190) ((ZLMT(I,J), I = 1, 2), J = 1, 3)
100 CONTINUE
C
105 EOF = 10000.
    WRITE (8,220) EOF
    CMRTIO = (VOUT(1,1) + 3.1415926*BORE*BORE*STROKE/4.)/VOUT(1,1)
    WRITE (6,230) CMRTIO
    WRITE (7,230) CMRTIO
C
110 FORMAT (1H1,////,8X,8HTHETA = ,F6.2)
120 FORMAT (1H ,//,8X,41HRADIUS     AFLAME       AINH        AOUTH,
   & 59H        AINP          AOUTP        AINCW        AOUTCW        ,
   & 19H  VIN          VOUT)
130 FORMAT (1H ,2X,43H___________________________________________,
   &               43H___________________________________________,
   &               43H___________________________________________,/)
140 FORMAT (1H ,/,1X,10(3X,F10.6))
160 FORMAT (1H ,1X,10(3X,F10.6))
170 FORMAT (1H1,/////,46X,37HCOMBUSTION CHAMBER GEOMETRY SIMULATOR)
190 FORMAT (1H ,///,5X,16HLOWER X LIMIT = ,F10.5,/,
   &                5X,16HUPPER X LIMIT = ,F10.5,/,
   &                5X,16HLOWER Y LIMIT = ,F10.5,/,
   &                5X,16HUPPER Y LIMIT = ,F10.5,/,
   &                5X,16HLOWER Z LIMIT = ,F10.5,/,
   &                5X,16HUPPER Z LIMIT = ,F10.5,/)
210 FORMAT (1H ,5(5X,F10.5))
220 FORMAT (1H ,4X,F10.2)
230 FORMAT (//,1H ,10X,'COMPRESSION RATIO = ',F8.3)
240 FORMAT (/,1H ,10X,'THETA  = ',F8.3)
250 FORMAT (1H ,15X,'RADIUS = ',F20.10)
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  260 FORMAT (/,1H ,'RADIUS = ',F13.7,10X,'POINTS = ',I9,/,1X,
     &         'BASE FLAME AREA = ',F13.7,5X,'STND. DEV. = ',
     &         F13.7)
C
      STOP
      END
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C                                                VERSION 1.0__4/26/82___
C
C     SUBROUTINE INPUT
C
C     PURPOSE
C        'INPUT' IS CALLED BY 'MAIN' TO READ IN THE DATA FOR A
C        PARTICULAR COMBUSTION CHAMBER.  THREE TYPES OF DATA ARE
C        READ: 1. BASIC ENGINE DIMENSIONS AND SPARK PLUG LOCATION;
C        2. POINTS ON THE CHAMBER SURFACE AND RELATED DATA; 3. FACETS
C        ON THE CHAMBER SURFACE AND RELATED DATA. IN ADDITION, USER
C        CONTROLS ON THE PRECISION OF THE CALCULATIONS ARE READ IN.
C        AS THE DATA IS BEING READ, THE POINTS AND EACH OF THE THREE
C        TYPES OF FACETS ARE COUNTED.
C
C     USAGE
C        CALL INPUT
C
C     DESCRIPTION OF PARAMETERS
C        PARAMETER  INPUT  OUTPUT  DESCRIPTION
C
C        POINT      YES    NO      POINT NUMBER
C        HOLD       YES    NO      LABELS POINT AS FIXED OR MOVABLE
C        APEX       YES    NO      LABELS THE 3 POINTS ON EACH FACET
C        FACET      YES    NO      FACET NUMBER
C        ZONE       YES    NO      LABELS FACET AS HEAD (1), PISTON (2),
C        ----       ---    --      OR CYLINDER WALL (3)
C        COORD      YES    NO      DUMMY RETURN VARIABLE
C        DTHETA     YES    NO      CRANK ANGLE INCREMENT
C        MTHETA     YES    NO      MAXIMUM CRANK ANGLE
C        RSTEPS     YES    NO      # BY WHICH MAXIMUM ACHIEVABLE RADIUS
C        ------     ---    --      (PISTON @ BDC) IS DIVIDED TO CALCU-
C        ------     ---    --      LATE RADIUS INCREMENT
C        PDENST     YES    NO      RANDOM POINT DENSITY, EXPRESSED AS
C        ------     ---    --      EQUIVALENT POINTS/(AREA OF BORE)
C        SPMIN      YES    NO      MINIMUM # OF POINTS ON A SPHERE
C        SPMAX      YES    NO      MAXIMUM # OF POINTS ON A SPHERE
C        MAXITS     YES    NO      ITERATIONS IN CALCULATING AFLAME
C
C     REMARKS
C        REFERENCE FRAME FOR ALL COORDINATES IS (0,0,0) ON THE AXIS
C        OF THE CYLINDER AND AT THE TOP PLANE OF THE ENGINE BLOCK.
C        Z IS UP, AND X AND Y ARE ANY SET OF ORTHOGONAL AXES.
C
C     SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED
C        ______     ______     ______     ______
C
C     METHOD
C        SEE PURPOSE, ABOVE
C
C     WRITTEN BY S. G. POULOS
C     EDITED BY S. G. POULOS
C
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      SUBROUTINE INPUT
C
      INTEGER POINT(200,3), FACET, POINTS, PNT, FACETS, APEX, AXIS,
     &        HOLD(100), ZONE(200), SPMIN, SPMAX
      REAL LIMIT(2,3), COORD(100,3), MTHETA
      COMMON/DIMENS/ BORE, STROKE, CONRL
      COMMON/SPARK/ XSPARK, YSPARK, ZSPARK
      COMMON/QUANTS/ FACETS, NHEAD, NPIST, NCWALL, POINTS
      COMMON/LIMITS/ LIMIT, PISBOT
      COMMON/FPNTS/ POINT
      COMMON/COORDI/ COORD
      COMMON/FIXPNT/ HOLD
      COMMON/ZONES/ ZONE
      COMMON/CNTROL/ DTHETA, MTHETA, RSTEPS, PDENST, SPMIN,
     &               SPMAX, MAXITS
C
C        READ BASIC ENGINE DIMENSIONS AND SPARK PLUG LOCATION
C
      READ (5,90) BORE, STROKE, CONRL, XSPARK, YSPARK, ZSPARK
      WRITE (6,95) BORE, STROKE, CONRL, XSPARK, YSPARK, ZSPARK
C
C        READ CRANK ANGLE AND RADIUS INTERVALS AND PARAMETERS
C        DETERMINING RANDOM POINT GENERATION
C
      READ (5,100) DTHETA, MTHETA, RSTEPS, PDENST, SPMIN, SPMAX, MAXITS
      WRITE (6,100) DTHETA, MTHETA, RSTEPS, PDENST, SPMIN, SPMAX, MAXITS
C
      POINTS = 0
      FACETS = 0
      NHEAD  = 0
      NPIST  = 0
      NCWALL = 0
C
C        READ IN EACH POINT, IT'S 3 COORDINATES, AND WHETHER IT IS
C        FIXED (HOLD = 1) OR MOVABLE (HOLD = 0).
C
      READ (5,110)
      DO 10 I = 1, 1000
          READ (5,120) PNT, (COORD(PNT,AXIS),AXIS = 1,3), HOLD(PNT)
          WRITE (6,120) PNT, (COORD(PNT,AXIS),AXIS = 1,3), HOLD(PNT)
          IF (HOLD(PNT) .GE. 2) GO TO 20
          POINTS = POINTS + 1
   10 CONTINUE
C
C        READ IN EACH FACET, IT'S 3 POINTS, AND  IT'S LOCATION.
C        ALSO, COUNT HOW MANY FACETS EXIST IN EACH ZONE AND CAL-
C        CULATE THE INITIAL OUTER BOUNDS OF THE CHAMBER (USED TO
C        REDUCE CALCULATION EFFORT).
C
   20 READ (5,130)
      DO 70 J = 1, 1000
          READ (5,140) FACET, (POINT(FACET,APEX),APEX = 1,3),
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     &                    ZONE(FACET)
          WRITE (6,140) FACET, (POINT(FACET,APEX),APEX = 1,3),
     &                    ZONE(FACET)
          IF (ZONE(FACET) .GE. 4) GO TO 80
          IF (ZONE(FACET) .LT. 3) GO TO 30
          NCWALL = NCWALL + 1
          GO TO 70
   30     IF (ZONE(FACET) .EQ. 2) GO TO 50
          NHEAD = NHEAD + 1
C
          DO 40 APEX = 1, 3
              K = POINT(FACET,APEX)
              IF (COORD(K,3) .GT. LIMIT(2,3)) LIMIT(2,3) = COORD(K,3)
              IF (COORD(K,1) .GT. LIMIT(2,1)) LIMIT(2,1) = COORD(K,1)
              IF (COORD(K,1) .LT. LIMIT(1,1)) LIMIT(1,1) = COORD(K,1)
              IF (COORD(K,2) .GT. LIMIT(2,2)) LIMIT(2,2) = COORD(K,2)
              IF (COORD(K,2) .LT. LIMIT(1,2)) LIMIT(1,2) = COORD(K,2)
   40     CONTINUE
C
          GO TO 70
   50     NPIST = NPIST + 1
C
          DO 60 APEX = 1, 3
              L = POINT(FACET,APEX)
              IF (COORD(L,3) .GT. LIMIT(1,3)) LIMIT(1,3) = COORD(L,3)
              IF (COORD(L,3) .LT. PISBOT) PISBOT = COORD(L,3)
   60     CONTINUE
C
   70 CONTINUE
C
C         LASTLY, CALCULATE TOTAL NUMBER OF FACETS ON CHAMBER SURFACE
C
   80 FACETS = NHEAD + NPIST + NCWALL
      WRITE (6,150) NHEAD, NPIST, NCWALL, FACETS
      WRITE (6,160) POINTS
C
   90 FORMAT (//////,2X,6F10.3)
   95 FORMAT (1H ,//,5X,'BORE   = ',F10.3,/,5X,'STROKE = ',F10.3,
     &        /,5X,'CONRL  = ',F10.3,//,5X,'XSPARK = ',F10.3,
     &        /,5X,'YSPARK = ',F10.3,/,5X,'ZSPARK = ',F10.3)
  100 FORMAT (//////,2X,4F10.3,3I8)
  110 FORMAT (///)
  120 FORMAT (2X,I5,3F12.3,I5)
  130 FORMAT (///)
  140 FORMAT (2X,5I5)
  150 FORMAT (1H ,//,5X,'NHEAD  = ',I5,/,5X,'NPIST  = ',I5,
     &        /,5X,'NCWALL = ',I5,/,5X,'FACETS = ',I5)
  160 FORMAT (1H ,//,5X,'POINTS = ',I5)
C
      RETURN
      END
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C                                                VERSION 1.0__4/26/82___
C
C     SUBROUTINE FLAME
C
C     PURPOSE
C        THIS SUBROUTINE CALCULATES THE INTERSECTION BETWEEN A
C        GENERAL CHAMBER SHAPE AND A SPHERE OF GIVEN RADIUS. THE
C        SURFACE OF THE SPHERE WITHIN THE CHAMBER IS FOUND BY
C        GENERATING RANDOM POINTS ON THE SURFACE OF THE SPHERE
C        AND THEN TESTING THE POINTS TO SEE IF THEY LIE INSIDE THE
C        CHAMBER.  THE INTERIOR SPHERE SURFACE IS THEN EQUAL TO THE
C        FRACTION OF POINTS FOUND INSIDE THE CHAMBER TIMES THE
C        TOTAL SURFACE AREA OF A SPHERE OF THE GIVEN RADIUS.
C
C     USAGE
C        CALL FLAME  (RADIUS, SPNTS, FSURF, STADEV)
C
C     DESCRIPTION OF PARAMETERS
C        PARAMETER  INPUT  OUTPUT  DESCRIPTION
C
C        RADIUS     YES    NO      INSTANTANEOUS SPHERE RADIUS
C        SPNTS      YES    NO      NUMBER OF RANDOM POINTS TO BE GENE-
C                   ---    --      RATED ON THE SURFACE OF THE SPHERE
C        FSURF      NO     YES     FLAME SURFACE
C        STADEV     NO     YES     STANDARD DEVIATION OF ITERATIONS
C                   ---    ---     ABOUT MEAN (MEAN IS FSURF)
C
C     REMARKS
C        NONE
C
C     SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED
C        INTERS     ______    ______    ______
C
C     METHOD
C        ALGORITHM FOR GENERATING RANDOM POINTS ON THE SURFACE OF
C        A SPHERE IS TAKEN FROM: MARSAGLIA, GEORGE, "CHOOSING A
C        POINT FROM THE SURFACE OF A SPHERE", THE ANNALS OF MA-
C        THEMATICAL STATISTICS, 1972, VOL. 43, NO. 2, 645-646.
C
C     WRITTEN BY S. G. POULOS
C     EDITED BY S. G. POULOS
C
      SUBROUTINE FLAME (RADIUS, SPNTS, FSURF, STADEV)
C
      INTEGER SPNTS, FACET, FACETS, A, B, C, POINT(200,3),
     &        PNTA, PNTB, PNTC, AA, BB, CC, POINTS
      REAL COORD(100,3), LIMIT(2,3)
      COMMON/DIMENS/ BORE, STROKE, CONRL
      COMMON/SPARK/ XSPARK, YSPARK, ZSPARK
      COMMON/QUANTS/ FACETS, NHEAD, NPIST, NCWALL, POINTS
      COMMON/CNTROL/ DTHETA, MTHETA, RSTEPS, PDENST, SPMIN,
     &               SPMAX, MAXITS
```

```
      COMMON/LIMITS/ LIMIT, PISBOT
      COMMON/FPNTS/ POINT
      COMMON/COORDI/ COORD
      COMMON/RSEED/ IX
C
      SUM = 0.0
      SUMSQ = 0.0
C
      DO 50 ITER = 1, MAXITS
C
      ITERS = ITER
      NCOUNT = 0
      INPTS = 0
C
      DO 40 IPOINT = 1, SPNTS
C
C            GENERATE A SINGLE RANDOM POINT
C
   10     IX = IX*65539
          IF (IX .LT. 0) IX = IX + 2147483647 + 1
          XR = IX
          V1 = 1. - XR*0.9313224E-9
C
          IX = IX*65539
          IF (IX .LT. 0) IX = IX + 2147483647 + 1
          XR = IX
          V2 = 1. - XR*0.9313224E-9
C
          S = (V1*V1) + (V2*V2)
          IF (S .GE. 1.0) GO TO 10
          R = 2.*SQRT(1. - S)
C
          ZTEST = R*V1*RADIUS + ZSPARK
C
C            REJECT THE POINT IF IT IS OUTSIDE OF LIMITING PLANES
C            SURROUNDING THE INSTANTANEOUS CHAMBER.
C
          IF (ZTEST .GT. LIMIT(2,3)) GO TO 40
          IF (ZTEST .LT. LIMIT(1,3)) GO TO 40
          YTEST = R*V2*RADIUS + YSPARK
          IF (YTEST .GT. LIMIT(2,2)) GO TO 40
          IF (YTEST .LT. LIMIT(1,2)) GO TO 40
          XTEST = (S + S - 1.)*RADIUS + XSPARK
          IF (XTEST .GT. LIMIT(2,1)) GO TO 40
          IF (XTEST .LT. LIMIT(1,1)) GO TO 40
C
          NCOUNT = 0
C
          DO 30 FACET = 1, FACETS
C
C                FIND INTERSECTION OF VECTOR THROUGH TEST POINT ON
C                SPHERE AND SPARK LOCATION WITH PLANE OF A FACET
```

```
C
      CALL INTERS (FACET, XTEST, YTEST, ZTEST, XINT, YINT, ZINT)
C
      IF (XINT .EQ. 99999.) GO TO 30
      AA = 3
      BB = 1
      CC = 2
C
C        ENTER LOOP TO DECIDE WHETHER INTERSECTION POINT FOUND
C        ABOVE LIES WHITHIN THE FACET. CONCIDER 2 APICES OF A
C        A FACET.  IF REMAINING APEX IS ON OPPOSITE SIDE OF LINE
C        THROUGH FIRST 2 APICES FROM TEST POINT, THEN TEST POINT
C        IS OUTSIDE OF FACET. REPEAT FOR ALL 3 PAIRS OF APICES.
C        TEST POINT MUST PASS ALL 3 TESTS TO BE INSIDE FACET.
C
      DO 20 L = 1, 3
         A = BB
         B = CC
         C = AA
         AA = A
         BB = B
         CC = C
         PNTA = POINT(FACET,A)
         PNTB = POINT(FACET,B)
         PNTC = POINT(FACET,C)
C
         DNA = COORD(PNTA,1) - COORD(PNTB,1)
         DNB = COORD(PNTA,2) - COORD(PNTB,2)
         DNC = COORD(PNTA,3) - COORD(PNTB,3)
C
         XCA = COORD(PNTC,1) - COORD(PNTA,1)
         YCA = COORD(PNTC,2) - COORD(PNTA,2)
         ZCA = COORD(PNTC,3) - COORD(PNTA,3)
C
         DISTCL = (DNC*YCA - DNB*ZCA)*(DNC*YCA - DNB*ZCA)
     &            + (DNA*ZCA - DNC*XCA)*(DNA*ZCA - DNC*XCA)
     &            + (DNB*XCA - DNA*YCA)*(DNB*XCA - DNA*YCA)
         YIA = YINT - COORD(PNTA,2)
         ZIA = ZINT - COORD(PNTA,3)
         DISTIL = (DNC*YIA - DNB*ZIA)*(DNC*YIA - DNB*ZIA)
         IF (DISTIL .GT. DISTCL) GO TO 30
         XIA = XINT - COORD(PNTA,1)
         DISTIL = DISTIL + (DNA*ZIA - DNC*XIA)*
                           (DNA*ZIA - DNC*XIA)
     &   IF (DISTIL .GT. DISTCL) GO TO 30
         DISTIL = DISTIL + (DNB*XIA - DNA*YIA)*
                           (DNB*XIA - DNA*YIA)
     &   IF (DISTIL .GT. DISTCL) GO TO 30
         XCI = COORD(PNTC,1) - XINT
         YCI = COORD(PNTC,2) - YINT
         ZCI = COORD(PNTC,3) - ZINT
         DISTCI = (DNC*YCI - DNB*ZCI)*(DNC*YCI - DNB*ZCI) +
```

```
     &                    (DNA*ZCI - DNC*XCI)*(DNA*ZCI - DNC*XCI) +
     &                    (DNB*XCI - DNA*YCI)*(DNB*XCI - DNA*YCI)
                 IF (DISTCI .LT. DISTIL) GO TO 20
                 IF (DISTCI .LT. DISTCL) GO TO 20
                 GO TO 30
   20          CONTINUE
C
C                REJECT FACET UNLESS IT IS BETWEEN THE TEST POINT
C                AND THE SPARK LOCATION
C
               ADIST = SQRT( (XTEST - XSPARK)*(XTEST - XSPARK) +
     &                       (YTEST - YSPARK)*(YTEST - YSPARK) +
     &                       (ZTEST - ZSPARK)*(ZTEST - ZSPARK) )
               BDIST = SQRT( (XTEST - XINT)*(XTEST - XINT) +
     &                       (YTEST - YINT)*(YTEST - YINT) +
     &                       (ZTEST - ZINT)*(ZTEST - ZINT) )
               CDIST = SQRT( (XSPARK - XINT)*(XSPARK - XINT) +
     &                       (YSPARK - YINT)*(YSPARK - YINT) +
     &                       (ZSPARK - ZINT)*(ZSPARK - ZINT) )
C
               IF (BDIST .GT. ADIST) GO TO 30
               IF (CDIST .GT. ADIST) GO TO 30
C
C                FACET IS INTERSECTED BY TEST VECTOR; INCREMENT NCOUNT
C
               NCOUNT = NCOUNT + 1
   30       CONTINUE
C
C              IF VECTOR INTERSECTS AN ODD NUMBER OF FACETS, THEN THE
C              TEST POINT IS OUTSIDE THE CHAMBER. OTHERWISE, IT IS
C              INSIDE. TRY A NEW POINT.
C
            IF ( ((NCOUNT/2)*2) .LT. NCOUNT ) GO TO 40
            INPTS = INPTS + 1
C
   40 CONTINUE
C
C         CALCULATE FLAME SURFACE AREA FOR THIS ITERATION
C
      FSURFI = ( 4. * 3.1415926 * RADIUS*RADIUS * FLOAT(INPTS) )
     &         /FLOAT(SPNTS)
      SUM = SUM + FSURFI
      SUMSQ = SUMSQ + ( FSURFI*FSURFI )
C
   50 CONTINUE
C
C         CALCULATE FLAME AREA AVERAGED OVER ALL ITERATIONS.
C
      FSURF = SUM/FLOAT(ITERS)
      STADEV = SQRT(ABS( SUMSQ/FLOAT(ITERS) - (FSURF*FSURF) ))
C
```

```
RETURN
END
```

```
C                                                VERSION 1.0__4/26/82___
C
C     SUBROUTINE WALL
C
C     PURPOSE
C        CALCULATES THE SURFACE AREAS ON EACH SIDE OF THE FLAME
C        FOR EACH OF THE THREE ZONES OF THE CHAMBER (I.E. HEAD,
C        PISTON, CYLINDER WALL).
C
C     USAGE
C        CALL WALL (ITHETA, IRAD, RADIUS, AINH, AOUTH, AINP,
C       &           AOUTP, AINCW, AOUTCW)
C
C     DESCRIPTION OF PARAMETERS
C        PARAMETER  INPUT  OUTPUT  DESCRIPTION
C
C        ITHETA     YES    NO      CRANK ANGLE INDEX
C        IRAD       YES    NO      RADIUS INDEX
C        RADIUS     YES    NO      FLAME RADIUS
C        AINH       NO     YES     HEAD AREA INSIDE THE FLAME
C        AOUTH      NO     YES     HEAD AREA OUTSIDE THE FLAME
C        AINP       NO     YES     PISTON AREA INSIDE THE FLAME
C        AOUTP      NO     YES     PISTON AREA OUTSIDE THE FLAME
C        AINCW      NO     YES     CYL. WALL AREA INSIDE THE FLAME
C        AOUTCW     NO     YES     CYL. WALL AREA OUTSIDE THE FLAME
C        BCOUNT     YES    NO      1 @ START OF THETA LOOP, ELSE > 1
C        CCOUNT     YES    NO      1 @ START OF RADIUS LOOP, ELSE >1
C
C     REMARKS
C        THE PROCEDURE USED IN THIS CALCULATION IS INDEPENDENT OF
C        THE NUMBER OF RANDOM POINTS ON THE SURFACE OF THE SPHERE.
C        ACCURACY DEPENDS MAINLY ON HOW CLOSELY THE CHAMBER IS RE-
C        PRESENTED BY FLAT TRIANGULAR FACETS.
C
C     SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED
C        TRIARE     INTSPH     ______     ______
C
C     METHOD
C        'WALL' CONCIDERS EACH FACET AT A TIME. BY COMPARING THE DIS-
C        TANCE FROM THE FACET APICES TO THE SPARK LOCATION WITH THE
C        FLAME RADIUS, IT DECIDES WHETHER THE FACET LIES INSIDE OR
C        OUTSIDE THE FLAME.  IF 2 OF THE APICES LIE ON ONE SIDE AND
C        THE OTHER APEX LIES ON THE OTHER, 'WALL' CALLS SUBROUTINE
C        'INTSPH' TO LOCATE THE POINTS AT WHICH THE FLAME RADIUS
C        INTERSECTS 2 SIDES OF THE FACET.  IT THEN CALCULATES THE
C        APPROXIMATE AREA OF THE FACET ON EACH SIDE OF THE FLAME.
C        THE TOTAL WALL AREA IN ANY ZONE IS THE SUM OF THE CONTRIBU-
C        TIONS FROM THE INDIVIDUAL FACETS IN THAT ZONE.
C
C     WRITTEN BY S. G. POULOS
C     EDITED BY S. G. POULOS
C
```

```
      SUBROUTINE WALL (ITHETA, IRAD, RADIUS, AINH, AOUTH, AINP,
     &                 AOUTP, AINCW, AOUTCW)
C
      INTEGER FACET, FACETS, ZONE(200), FLAG, BCOUNT, CCOUNT,
     &        A, B, C, AA, BB, CC, FIRST, SECOND, OTHER, APEX,
     &        POINT(200,3), PNT, POINTS
      REAL COORD(100,3), AREAF(200), RADDIF(3), AINH(30,50), AINP(30,50)
     &     , AINCW(30,50), AOUTH(30,50), AOUTP(30,50), AOUTCW(30,50)
      COMMON/DIMENS/ BORE, STROKE, CONRL
      COMMON/SPARK/ XSPARK, YSPARK, ZSPARK
      COMMON/QUANTS/ FACETS, NHEAD, NPIST, NCWALL, POINTS
      COMMON/FPNTS/ POINT
      COMMON/COORDI/ COORD
      COMMON/ZONES/ ZONE
      COMMON/BCNT/ BCOUNT
      COMMON/CCNT/ CCOUNT
C
      AINH(ITHETA,IRAD)    = 0.0
      AOUTH(ITHETA,IRAD)   = 0.0
      AINP(ITHETA,IRAD)    = 0.0
      AOUTP(ITHETA,IRAD)   = 0.0
      AINCW(ITHETA,IRAD)   = 0.0
      AOUTCW(ITHETA,IRAD)  = 0.0
C
      BCOUNT = BCOUNT + 1
      CCOUNT = CCOUNT + 1
C
C        CONCIDER ONE FACET ON THE CHAMBER WALL
C
      DO 110 FACET = 1, FACETS
         IF (ZONE(FACET) .NE. 3) GO TO 10
         IF (CCOUNT .GT. 1) GO TO 20
C
C           RECALCULATE FACET AREA IF FACET HAS JUST BEEN STRETCHED
C
         CALL TRIARE (FACET, TRIA)
C
         AREAF(FACET) = TRIA
         GO TO 20
   10    IF (BCOUNT .GT. 1) GO TO 20
C
C           CALCULATE FACET AREA IF THIS HAS NOT YET BEEN DONE.
C
         CALL TRIARE (FACET, TRIA)
C
         AREAF(FACET) = TRIA
   20    IF (ZONE(FACET) .NE. 1) GO TO 30
         IF (ITHETA .GT. 1) GO TO 110
   30    ADDARE = AREAF(FACET)
         AINSP = 0.0
         AOUTSP = 0.0
         FLAG = 0
```

```
C
C           FIND DIFFERENCE BETWEEN DISTANCE FROM EACH FACET APEX
C           TO SPARK LOCATION AND FLAME RADIUS
C
          DO 40 APEX = 1, 3
              PNT = POINT(FACET,APEX)
              RADDIF(APEX) =
     &         SQRT( (COORD(PNT,1) - XSPARK)*(COORD(PNT,1) - XSPARK) +
     &               (COORD(PNT,2) - YSPARK)*(COORD(PNT,2) - YSPARK) +
     &               (COORD(PNT,3) - ZSPARK)*(COORD(PNT,3) - ZSPARK) )
     &         - RADIUS
   40     CONTINUE
C
          IF ( (RADDIF(1) .GE. 0.0) .AND. (RADDIF(2) .GE. 0.0) .AND.
     &         (RADDIF(3) .GE. 0.0) ) GO TO 100
          IF ( (RADDIF(1) .LE. 0.0) .AND. (RADDIF(2) .LE. 0.0) .AND.
     &         (RADDIF(3) .LE. 0.0) ) GO TO 90
C
C           SET FLAG = 1 IF FACET LIES LIES NEITHER FULLY OUTSIDE
C           NOR FULLY INSIDE OF FLAME
C
          FLAG = 1
          AA = 3
          BB = 1
          CC = 2
C
C           ENTER LOOP TO IDENTIFY WHICH SIDES OF THE FACET ARE
C           INTERSECTED BY THE FLAME RADIUS
C
          DO 50 II = 1, 3
              A = BB
              B = CC
              C = AA
              AA = A
              BB = B
              CC = C
              IF ( (RADDIF(A) .GE. 0.0) .AND. (RADDIF(B) .GE. 0.0) )
     &           GO TO 60
              IF ( (RADDIF(A) .LE. 0.0) .AND. (RADDIF(B) .LE. 0.0) )
     &           GO TO 60
   50     CONTINUE
C
C           POINTS 'FIRST' AND 'SECOND' LIE ON ONE SIDE OF THE FLAME,
C           WHILE POINT 'OTHER' LIES ON THE OTHER SIDE.
C
   60     FIRST = A
          SECOND = B
          OTHER = C
C
C           FIND INTERSECTION BETWEEN FLAME RADIUS AND SIDES OF FACET
C
          CALL INTSPH (RADIUS, FACET, OTHER, FIRST, XX1, YY1, ZZ1)
```

```
      CALL INTSPH (RADIUS, FACET, OTHER, SECOND, XX2, YY2, ZZ2)
C
C        CALCULATE AREA OF MINOR TRIANGLE OF INTERSECTED FACET
C
      PNT = POINT(FACET,OTHER)
      SIDEA = SQRT( (COORD(PNT,1) - XX1)*(COORD(PNT,1) - XX1) +
     &              (COORD(PNT,2) - YY1)*(COORD(PNT,2) - YY1) +
     &              (COORD(PNT,3) - ZZ1)*(COORD(PNT,3) - ZZ1) )
      SIDEB = SQRT( (COORD(PNT,1) - XX2)*(COORD(PNT,1) - XX2) +
     &              (COORD(PNT,2) - YY2)*(COORD(PNT,2) - YY2) +
     &              (COORD(PNT,3) - ZZ2)*(COORD(PNT,3) - ZZ2) )
      SIDEC = SQRT( (XX1 - XX2)*(XX1 - XX2) +
     &              (YY1 - YY2)*(YY1 - YY2) +
     &              (ZZ1 - ZZ2)*(ZZ1 - ZZ2) )
      SDUMY = 0.5*( SIDEA + SIDEB + SIDEC )
      IF (RADDIF(OTHER) .LE. 0.0) GO TO 70
      AOUTSP = SQRT( ABS( SDUMY*(SDUMY - SIDEA)*(SDUMY - SIDEB)
     &              *(SDUMY - SIDEC) ) )
      AINSP = AREAF(FACET) - AOUTSP
      GO TO 80
C
   70 AINSP = SQRT( ABS( SDUMY*(SDUMY - SIDEA)*(SDUMY - SIDEB)
     &              *(SDUMY - SIDEC) ) )
      AOUTSP = AREAF(FACET) - AINSP
   80 ADDARE = 0.0
C
C        ALLOCATE AREA OR SUB-AREAS OF CURRENT FACET TO
C        APPROPRIATE ZONE OF THE CHAMBER
C
   90 IF (ZONE(FACET) .EQ. 1) AINH(ITHETA,IRAD) = AINH(ITHETA,IRAD)
     &                                            + ADDARE + AINSP
      IF (ZONE(FACET) .EQ. 2) AINP(ITHETA,IRAD) = AINP(ITHETA,IRAD)
     &                                            + ADDARE + AINSP
      IF (ZONE(FACET) .EQ. 3) AINCW(ITHETA,IRAD) =
     &                         AINCW(ITHETA,IRAD) + ADDARE + AINSP
      IF (FLAG .LT. 1) GO TO 110
C
  100 IF (ZONE(FACET) .EQ. 1) AOUTH(ITHETA,IRAD) =
     &                        AOUTH(ITHETA,IRAD) + ADDARE + AOUTSP
      IF (ZONE(FACET) .EQ. 2) AOUTP(ITHETA,IRAD) =
     &                        AOUTP(ITHETA,IRAD) + ADDARE + AOUTSP
      IF (ZONE(FACET) .EQ. 3) AOUTCW(ITHETA,IRAD) =
     &                        AOUTCW(ITHETA,IRAD) + ADDARE + AOUTSP
C
  110 CONTINUE
C
C        NO NEED TO RECALCULATE CYLINDER HEAD AREAS IF ALREADY DONE
C
      IF (ITHETA .EQ. 1) GO TO 120
      AINH(ITHETA,IRAD) = AINH(1,IRAD)
      AOUTH(ITHETA,IRAD) = AOUTH(1,IRAD)
C
```

```
120 RETURN
    END
```

```
C                                                VERSION 1.0__4/26/82___
C
C     SUBROUTINE RQUIT
C
C     PURPOSE
C        'RQUIT' IS CALLED EACH TIME THE PISTON POSITION IS CHANGED
C        IN ORDER TO EVALUATE THE SMALLEST RADIUS TO WHICH THE FLAME
C        WILL HAVE TO DEVELOP IN ORDER FOR IT TO SWEEP THROUGH THE
C        ENTIRE CHAMBER.
C
C     USAGE
C        CALL RQUIT (RMAX)
C
C     DESCRIPTION OF PARAMETERS
C        PARAMETER  INPUT  OUTPUT  DESCRIPTION
C
C        RMAX       NO     YES     MAXIMUM FLAME RADIUS FOR FLAME TO
C        ----       --     ---     SWEEP THROUGH INSTANTANEOUS CHAMBER
C        DIST       NO     NO      DISTANCE FROM SPARK TO A CORNER OF
C        ----       --     --      LIMITING VOLUME SURROUNDING CHAMBER
C        ACOUNT     YES    YES     1 FOR FIRST CALL, >1 THEREAFTER
C        POINTS     YES    NO      # OF POINTS ON SURFACE OF CHAMBER
C
C     REMARKS
C        NONE
C
C     SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED
C        ______     ______     ______     ______
C
C     METHOD
C        FOR EACH VALUE OF THETA (CRANK ANGLE), THE DISTANCE FROM THE
C        SPARK LOCATION TO THE 8 CORNERS OF A RECTANGULAR PARALLELEPIPED
C        SURROUNDING THE CHAMBER IS CALCULATED. THE MAXIMUM VALUE FROM
C        AMONG THESE DISTANCES IS THE OUTER LIMIT OF FLAME TRAVEL.
C
C     WRITTEN BY S. G. POULOS
C     EDITED BY S. G. POULOS
C
      SUBROUTINE RQUIT (RMAX)
C
      INTEGER ACOUNT, PNT, POINTS, HOLD(100)
      REAL LIMIT(2,3), COORD(100,3)
      COMMON/DIMENS/ BORE, STROKE, CONRL
      COMMON/QUANTS/ FACETS, NHEAD, NPIST, NCWALL, POINTS
      COMMON/SPARK/ XSPARK, YSPARK, ZSPARK
      COMMON/LIMITS/ LIMIT, PISBOT
      COMMON/COORDI/ COORD
      COMMON/FIXPNT/ HOLD
      COMMON/ACNT/ ACOUNT
C
      RMAX = 0.0
      ACOUNT = ACOUNT + 1
```

```
C
      DO 20 PNT = 1, POINTS
          DUMYX = COORD(PNT,1)
          DUMYY = COORD(PNT,2)
          DUMYZ = COORD(PNT,3)
C
C            WHEN CALLED FOR THE FIRST TIME (ACOUNT = 1), BASE
C            CALCULATION OF MAXIMUM RADIUS ON BDC PISTON POSITION
C
          IF (ACOUNT .GT. 1) GO TO 10
          IF (HOLD(PNT) .LT. 1) DUMYZ = DUMYZ - STROKE
C
C            FIND DISTANCE FROM SPARK TO CORNER OF LIMITING VOLUME
C
   10     DIST = SQRT( (DUMYX - XSPARK)*(DUMYX - XSPARK) +
     &                 (DUMYY - YSPARK)*(DUMYY - YSPARK) +
     &                 (DUMYZ - ZSPARK)*(DUMYZ - ZSPARK) )
          IF (DIST .GT. RMAX) RMAX = DIST
   20 CONTINUE
C
      RETURN
      END
```

```
C_____________________________________________VERSION 1.0__4/26/82___
C
C     SUBROUTINE CHANGE
C
C     PURPOSE
C        'CHANGE' IS CALLED EACH TIME THE PISTON POSITION IS TO BE
C        CHANGED.  THIS SUBROUTINE CALCULATES THE DISTANCE BY WHICH
C        THE PISTON DROPS AS A FUNCTION OF CRANK ANGLE.  IT THEN
C        LOCATES THOSE POINTS ON THE CHAMBER SURFACE WHICH ARE LA-
C        BELED AS MOVABLE AND SHIFTS THEM APPROPRIATELY. IN ADDITION,
C        'CHANGE' SHIFTS THE LOWER Z LIMIT USED IN SUBROUTINE FLAME.
C
C     USAGE
C        CALL CHANGE (THETA,OLDROP)
C
C     DESCRIPTION OF PARAMETERS
C        PARAMETER  INPUT  OUTPUT  DESCRIPTION
C
C        THETA      YES    NO      CURRENT CRANK ANGLE
C        OLDROP     YES    YES     STORES DISTANCE TRAVELLED BY
C        ------     ---    ---     PISTON FROM TDC POSITION
C
C     REMARKS
C        NONE
C
C     SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED
C        ______     ______     ______     ______
C
C     METHOD
C        SEE PURPOSE, ABOVE
C
C     WRITTEN BY S. G. POULOS
C     EDITED BY S. G. POULOS
C
      SUBROUTINE CHANGE (THETA,OLDROP)
C
      INTEGER APEX, HOLD(100), PNT, POINTS
      REAL LIMIT(2,3), COORD(100,3)
      COMMON/DIMENS/ BORE, STROKE, CONRL
      COMMON/QUANTS/ FACETS, NHEAD, NPIST, NCWALL, POINTS
      COMMON/LIMITS/ LIMIT, PISBOT
      COMMON/COORDI/ COORD
      COMMON/FIXPNT/ HOLD
C
C        CONVERT THETA TO RADIANS
C
      THETAR = 3.1415926*THETA/180.
C
C        CALCULATE DISTANCE TRAVELLED BY PISTON FROM TDC POSITION TO
C        CURRENT CRANK ANGLE POSITION, AND ADJUSTMENT FROM LAST THETA
C
      ZDROP = -(  CONRL + (STROKE/2.)*(1. - COS(THETAR)) - SQRT( CONRL*
```

```
     &       CONRL - (STROKE/2.)*(STROKE/2.)*SIN(THETAR)*SIN(THETAR) ) )
      DELTAZ = ZDROP - OLDROP
C
C        SHIFT LOWER Z LIMIT TO MATCH NEW VALUE OF THETA
C
      LIMIT(1,3) = LIMIT(1,3) + DELTAZ
C
C        SHIFT Z COORDINATE OF ALL NON-FIXED POINTS BY DELTAZ
C
      OLDROP = ZDROP
C
      DO 10 PNT = 1, POINTS
          IF (HOLD(PNT) .GE. 1) GO TO 10
          COORD(PNT,3) = COORD(PNT,3) + DELTAZ
   10 CONTINUE
C
      RETURN
      END
```

```
C                                                  VERSION 1.0__4/26/82___
C
C     SUBROUTINE INTERS
C
C     PURPOSE
C        THIS SUBROUTINE CALCULATES THE INTERSECTION BETWEEN A VECTOR
C        PASSING THROUGH THE SPARK LOCATION AND A TEST POINT ON A
C        FLAME SPHERE AND THE PLANE OF A FACET ON THE CHAMBER WALL.
C
C     USAGE
C        CALL INTERS (FACET, XTEST, YTEST, ZTEST, XINT, YINT, ZINT)
C
C     DESCRIPTION OF PARAMETERS
C        PARAMETER  INPUT  OUTPUT  DESCRIPTION
C
C        FACET      YES    NO      FACET NUMBER
C        XTEST      YES    NO      X COORDINATE OF POINT ON SPHERE
C        YTEST      YES    NO      Y COORDINATE OF POINT ON SPHERE
C        ZTEST      YES    NO      Z COORDINATE OF POINT ON SPHERE
C        XINT       NO     YES     X COORDINATE OF FACET INTERSECTION
C        YINT       NO     YES     Y COORDINATE OF FACET INTERSECTION
C        ZINT       NO     YES     Z COORDINATE OF FACET INTERSECTION
C
C     REMARKS
C        NONE
C
C     SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED
C        ______     ______     ______     ______
C
C     METHOD
C        'INTERS' PERFORMS AN ANALYTICAL SOLUTION OF 2 SIMULTANEOUS
C        EQUATIONS: 1) THE EQUATION OF A VECTOR DEFINED BY THE 3-D
C        COORDINATES OF 2 POINTS (SPARK & TEST); 2) THE EQUATION OF A
C        PLANE DEFINED BY THE 3-D COORDINATES OF THE 3 POINTS OF A
C        TEST FACET (PNT1, PNT2, PNT3)
C
C     WRITTEN BY S. G. POULOS
C     EDITED BY S. G. POULOS
C
C
      SUBROUTINE INTERS (FACET, XTEST, YTEST, ZTEST, XINT, YINT, ZINT)
C
      INTEGER FACET, POINT(200,3), PNT1, PNT2, PNT3
      REAL COORD(100,3)
      COMMON/SPARK/ XSPARK, YSPARK, ZSPARK
      COMMON/FPNTS/ POINT
      COMMON/COORDI/ COORD
C
      XST = XSPARK - XTEST
      IF (ABS(XST) .GE. 0.0000001) GO TO 10
      XINT = 99999.
      GO TO 30
```

```
   10 YST = YSPARK - YTEST
      ZST = ZSPARK - ZTEST
C
      PNT1 = POINT(FACET,1)
      PNT2 = POINT(FACET,2)
      PNT3 = POINT(FACET,3)
C
      YZBAR = ( COORD(PNT2,2) - COORD(PNT1,2) )*( COORD(PNT3,3) -
     1        COORD(PNT1,3) ) - ( COORD(PNT2,3) - COORD(PNT1,3) )*
     2        ( COORD(PNT3,2) - COORD(PNT1,2) )
      ZXBAR = ( COORD(PNT2,3) - COORD(PNT1,3) )*( COORD(PNT3,1) -
     1        COORD(PNT1,1) ) - ( COORD(PNT2,1) - COORD(PNT1,1) )*
     2        ( COORD(PNT3,3) - COORD(PNT1,3) )
      XYBAR = ( COORD(PNT2,1) - COORD(PNT1,1) )*( COORD(PNT3,2) -
     1        COORD(PNT1,2) ) - ( COORD(PNT2,2) - COORD(PNT1,2) )*
     2        ( COORD(PNT3,1) - COORD(PNT1,1) )
C
C        IN THE EVENT THAT BOT = 0.0 (AN EXTREMELY UNLIKELY EVENT),
C        NEGLECT THIS FACET TO AVOID DIVISION BY ZERO
C
      BOT = (ZXBAR * YST) + (XYBAR * ZST) + (YZBAR * XST)
      IF (ABS(BOT) .GE. 0.0000001) GO TO 20
      XINT = 99999.
      GO TO 30
C
   20 A = (YST * XTEST) + XST*( COORD(PNT1,2) - YTEST )
      B = (ZST * XTEST) + XST*( COORD(PNT1,3) - ZTEST )
      C = XST * COORD(PNT1,1)
C
      TOP = (ZXBAR * A) + (XYBAR * B) + (YZBAR * C)
C
C        CALCULATE COORDINATES OF INTERSECTION BETWEEN TEST VECTOR
C        PLANE OF TEST FACET
C
      XINT = TOP/BOT
      YINT = YTEST + ( YST/XST )*(XINT - XTEST)
      ZINT = ZTEST + ( ZST/XST )*(XINT - XTEST)
C
   30 RETURN
      END
```

```
C                                                  VERSION 1.0__4/26/82___
C
C     SUBROUTINE INTSPH
C
C     PURPOSE
C        'INTSPH' IS CALLED BY SUBROUTINE 'WALL' WHEN A FACET IS
C        INTERSECTED BY THE FLAME AT THE CURRENT RADIUS.  IN ORDER
C        TO PROPERLY ALLOCATE THE AREA OF THE FACET TO EACH SIDE OF
C        THE FLAME (INSIDE/OUTSIDE), THE POINTS OF INTERSECTION
C        BETWEEN THE RADIUS AND THE 2 INTERSECTED SIDES OF THE FACET
C        MUST BE FOUND.  THIS SUBROUTINE CALCULATES THE COORDINATES
C        OF ONE OF THE INTERSECTING POINTS WHEN GIVEN THE END POINTS
C        OF ONE OF THE INTERSECTED SIDES OF THE FACET.
C
C     USAGE
C        CALL INTSPH (RADIUS, FACET, APEX1, APEX2, XX, YY, ZZ)
C
C     DESCRIPTION OF PARAMETERS
C        PARAMETER  INPUT  OUTPUT  DESCRIPTION
C
C        RADIUS     YES    NO      CURRENT FLAME RADIUS
C        FACET      YES    NO      FACET NUMBER
C        APEX1      YES    NO      POINT ON INTERSECTED SIDE OF FACET
C        APEX2      YES    NO      POINT ON INTERSECTED SIDE OF FACET
C        XX         NO     YES     X COORDINATE OF INTERSECTION POINT
C        YY         NO     YES     Y COORDINATE OF INTERSECTING POINT
C        ZZ         NO     YES     Z COORDINATE OF INTERSECTING POINT
C
C     REMARKS
C        NONE
C
C     SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED
C        ______     ______     ______     ______
C
C     METHOD
C        TO FIND THE POINT WHERE THE RADIUS INTERSECTS A GIVEN SIDE OF
C        THE FACET, FIRST FIND WHICH OF THE TWO POINTS ON THE ENDS
C        OF THE SIDE OF THE FACET IS OUTSIDE THE FLAME.  THIS IS
C        NEEDED TO PLACE THE INPUTS TO THE CALCULATION IN STANDARD
C        FORM.  THEN TAKE A TEST POINT WHICH BISECTS THE SIDE OF THE
C        FACET AND COMPARE IT'S DISTANCE TO THE SPARK LOCATION WITH THE
C        CURRENT FLAME RADIUS. WITH THE RESULT, DECIDE WHICH HALF OF
C        THE FACET SIDE MUST CONTAIN THE SOLUTION POINT.  NEXT, BISECT
C        THIS HALF AND MAKE THE BISECTION THE NEW TEST POINT. REPEAT
C        THIS PROCESS UNTIL THE DISTANCE BETWEEN THE TEST POINT AND
C        THE SPARK PLUG IS SUFFICIENTLY CLOSE TO THE FLAME RADIUS.
C
C     WRITTEN BY S. G. POULOS
C     EDITED BY S. G. POULOS
C
      SUBROUTINE INTSPH (RADIUS, FACET, APEX1, APEX2, XX, YY, ZZ)
C
```

```
      INTEGER PNT, POINT(200,3), APEX1, APEX2, FACET
      REAL COORD(100,3)
      COMMON/SPARK/ XSPARK, YSPARK, ZSPARK
      COMMON/FPNTS/ POINT
      COMMON/COORDI/ COORD
C
      PNT = POINT(FACET, APEX1)
      XA = COORD(PNT,1)
      YA = COORD(PNT,2)
      ZA = COORD(PNT,3)
C
      PNT = POINT(FACET, APEX2)
      XB = COORD(PNT,1)
      YB = COORD(PNT,2)
      ZB = COORD(PNT,3)
C
      ARAD = SQRT( (XA - XSPARK)*(XA - XSPARK) + (YA - YSPARK)*
     &             (YA - YSPARK) + (ZA - ZSPARK)*(ZA - ZSPARK) )
      BRAD = SQRT( (XB - XSPARK)*(XB - XSPARK) + (YB - YSPARK)*
     &             (YB - YSPARK) + (ZB - ZSPARK)*(ZB - ZSPARK) )
C
C        CHECK TO SEE WHICH FACET POINT IS OUTSIDE OF FLAME
C
      IF (ARAD .GT. BRAD) GO TO 10
C
      DUMXA = XA
      DUMYA = YA
      DUMZA = ZA
      XA = XB
      YA = YB
      ZA = ZB
      XB = DUMXA
      YB = DUMYA
      ZB = DUMZA
C
   10 DO 30 I = 1, 30
C
C           NEW TEST POINT BISECTS RANGE WHERE SOLUTION MUST EXIST
C
          TESTX = (XA + XB)/2.
          TESTY = (YA + YB)/2.
          TESTZ = (ZA + ZB)/2.
          TESTR = SQRT( (TESTX - XSPARK)*(TESTX - XSPARK) +
     &                  (TESTY - YSPARK)*(TESTY - YSPARK) +
     &                  (TESTZ - ZSPARK)*(TESTZ - ZSPARK) )
C
C           CHECK FOR CONVERGENCE
C
          IF ( ABS((TESTR - RADIUS)/RADIUS) .LE. 0.0001 ) GO TO 40
          IF (TESTR .GT. RADIUS) GO TO 20
          XB = TESTX
          YB = TESTY
```

```
          ZB = TESTZ
          GO TO 30
   20     XA = TESTX
          YA = TESTY
          ZA = TESTZ
   30 CONTINUE
C
   40 XX = TESTX
      YY = TESTY
      ZZ = TESTZ
C
      RETURN
      END
```

```
C                                                VERSION 1.0__4/26/82___
C
C     SUBROUTINE TRIARE
C
C     PURPOSE
C        THIS SUBROUTINE CALCULATES THE SURFACE AREA OF A TRIANGU-
C        LAR FACET.  GIVEN THE FACET NUMBER, 'TRIARE' OBTAINS THE
C        COORDINATES OF THE 3 APICES OF THE FACET AND THEN USES A
C        STANDARD ANALYTICAL FORMULA TO CALCULATE IT'S SURFACE AREA.
C
C     USAGE
C        CALL TRIARE (FACET, TRIA)
C
C     DESCRIPTION OF PARAMETERS
C        PARAMETER  INPUT  OUTPUT  DESCRIPTION
C
C        FACET      YES    NO      FACET NUMBER
C        TRIA       NO     YES     AREA OF FACET
C
C     REMARKS
C        NONE
C
C     SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED
C        ______     ______     ______     ______
C
C     METHOD
C        CALCULATION OF TRIANGULAR FACET AREA TAKEN FROM: BEYER, W.
C        H., "CRC HANDBOOK OF MATHEMATICAL SCIENCES", 5TH ED., 1978,
C        PP. 222-223.
C
C     WRITTEN BY S. G. POULOS
C     EDITED BY S. G. POULOS
C
      SUBROUTINE TRIARE (FACET, TRIA)
C
      INTEGER PNT1, PNT2, PNT3, POINT(200,3), FACET
      REAL COORD(100,3)
      COMMON/FPNTS/ POINT
      COMMON/COORDI/ COORD
C
      PNT1 = POINT(FACET,1)
      PNT2 = POINT(FACET,2)
      PNT3 = POINT(FACET,3)
C
C        CALCULATE LENGTHS OF SIDES OF TRIANGLE
C
      SIDEA = SQRT(
     & (COORD(PNT1,1) - COORD(PNT2,1))*(COORD(PNT1,1) - COORD(PNT2,1))+
     & (COORD(PNT1,2) - COORD(PNT2,2))*(COORD(PNT1,2) - COORD(PNT2,2))+
     & (COORD(PNT1,3) - COORD(PNT2,3))*(COORD(PNT1,3) - COORD(PNT2,3)))
C
      SIDEB = SQRT(
```

```
     & (COORD(PNT1,1) - COORD(PNT3,1))*(COORD(PNT1,1) - COORD(PNT3,1))+
     & (COORD(PNT1,2) - COORD(PNT3,2))*(COORD(PNT1,2) - COORD(PNT3,2))+
     & (COORD(PNT1,3) - COORD(PNT3,3))*(COORD(PNT1,3) - COORD(PNT3,3)))
C
      SIDEC = SQRT(
     & (COORD(PNT2,1) - COORD(PNT3,1))*(COORD(PNT2,1) - COORD(PNT3,1))+
     & (COORD(PNT2,2) - COORD(PNT3,2))*(COORD(PNT2,2) - COORD(PNT3,2))+
     & (COORD(PNT2,3) - COORD(PNT3,3))*(COORD(PNT2,3) - COORD(PNT3,3)))
C
      SDUMY = 0.5 * (SIDEA + SIDEB + SIDEC)
C
      TRIA = SQRT( ABS( SDUMY*(SDUMY - SIDEA)*(SDUMY - SIDEB)
     &        *(SDUMY - SIDEC) ) )
C
      RETURN
      END
```

APPENDIX E

SAMPLE INPUT TO GEOMETRIC SIMULATION

```
C
C   BASIC ENGINE DIMENSIONS AND SPARK PLUG LOCATION;
C
C   BORE, STROKE, CONNECTING-ROD LENGTH, XSPARK, YSPARK, & ZSPARK:
C
C *         **          **          **          **          **
  8.000       7.95775   14.0        2.92768     0.0         0.860
C
C   CRANK ANGLE INTERVAL; MAXIMUM CRANK ANGLE; RADIUS STEP SIZE;
C   RANDOM POINT DENSITY; MINIMUM # OF RANDOM POINTS; MAXIMUN #
C   OF RANDOM POINTS; # OF ITERATIONS IN AFLAME CALCULATION
C                                                       RJ->      RJ->      RJ->
C *         **          **          **          **        **        **         *
    14.0        70.0    25.700      300.0         200     2200         9
C
C   POINTS:
C  RJ->                                                  RJ->
C *   **          **          **          **             *
      1     3.97414     0.79050   0.00000          1
      2     3.97414    -0.79050   0.00000          1
      3    -3.97414     0.79050   0.00000          1
      4    -3.97414    -0.79050   0.00000          1
      5     3.36912     2.25117   0.00000          1
      6     3.36912    -2.25117   0.00000          1
      7    -3.36912     2.25117   0.00000          1
      8    -3.36912    -2.25117   0.00000          1
      9     2.25117     3.36912   0.00000          1
     10     2.25117    -3.36912   0.00000          1
     11    -2.25117     3.36912   0.00000          1
     12    -2.25117    -3.36912   0.00000          1
     13     0.79050     3.97414   0.00000          1
     14     0.79050    -3.97414   0.00000          1
     15    -0.79050     3.97414   0.00000          1
     16    -0.79050    -3.97414   0.00000          1
     17     3.97414     0.79050   0.00000          0
     18     3.97414    -0.79050   0.00000          0
     19    -3.97414     0.79050   0.00000          0
     20    -3.97414    -0.79050   0.00000          0
     21     3.36912     2.25117   0.00000          0
     22     3.36912    -2.25117   0.00000          0
     23    -3.36912     2.25117   0.00000          0
     24    -3.36912    -2.25117   0.00000          0
     25     2.25117     3.36912   0.00000          0
     26     2.25117    -3.36912   0.00000          0
     27    -2.25117     3.36912   0.00000          0
     28    -2.25117    -3.36912   0.00000          0
     29     0.79050     3.97414   0.00000          0
     30     0.79050    -3.97414   0.00000          0
     31    -0.79050     3.97414   0.00000          0
     32    -0.79050    -3.97414   0.00000          0
     33     2.70482     1.12038   1.11000          1
     34     2.70482    -1.12038   1.11000          1
```

35	-2.70482	1.12038	1.11000	1
36	-2.70482	-1.12038	1.11000	1
37	2.07019	2.07019	1.11000	1
38	2.07019	-2.07019	1.11000	1
39	-2.07019	2.07019	1.11000	1
40	-2.07019	-2.07019	1.11000	1
41	1.12038	2.70482	1.11000	1
42	1.12038	-2.70482	1.11000	1
43	-1.12038	2.70482	1.11000	1
44	-1.12038	-2.70482	1.11000	1
45	2.92768	0.00000	1.11000	1
46	-2.92768	0.00000	1.11000	1
47	0.00000	-2.92768	1.11000	1
48	0.00000	2.92768	1.11000	1
49	1.08494	1.08494	1.80500	1
50	1.08494	-1.08494	1.80500	1
51	-1.08494	1.08494	1.80500	1
52	-1.08494	-1.08494	1.80500	1
53	1.53434	0.00000	1.80500	1
54	-1.53434	0.00000	1.80500	1
55	0.00000	1.53434	1.80500	1
56	0.00000	-1.53434	1.80500	1
57	0.00000	0.00000	2.04000	1
58	0.00000	0.00000	0.00000	0
59	0.00000	0.00000	0.00000	2

```
C
C   FACETS:
C
C *   **   **   **   **   *
      1   17    1    2    3
      2   17    1   21    3
      3    5    1   21    3
      4    5   25   21    3
      5    5   25    9    3
      6   29   25    9    3
      7   29   13    9    3
      8   29   13   31    3
      9   15   13   31    3
     10   15   31   27    3
     11   15   11   27    3
     12   23   11   27    3
     13   23   11    7    3
     14   23   19    7    3
     15    3   19    7    3
     16    3   19   20    3
     17    3    4   20    3
     18   24    4   20    3
     19   24    4    8    3
     20   24   28    8    3
     21   12   28    8    3
     22   12   28   32    3
     23   12   16   32    3
```

24	30	16	32	3
25	30	16	14	3
26	30	26	14	3
27	10	26	14	3
28	10	26	22	3
29	10	6	22	3
30	18	6	22	3
31	18	6	2	3
32	18	17	2	3
33	45	1	2	1
34	45	1	33	1
35	5	1	33	1
36	5	37	33	1
37	5	37	9	1
38	41	37	9	1
39	41	13	9	1
40	41	13	48	1
41	15	13	48	1
42	15	43	48	1
43	15	43	11	1
44	39	43	11	1
45	39	7	11	1
46	39	7	35	1
47	3	7	35	1
48	3	46	35	1
49	3	46	4	1
50	36	46	4	1
51	36	8	4	1
52	36	8	40	1
53	12	8	40	1
54	12	44	40	1
55	12	44	16	1
56	47	44	16	1
57	47	14	16	1
58	47	14	42	1
59	10	14	42	1
60	10	38	42	1
61	10	38	6	1
62	34	38	6	1
63	34	2	6	1
64	34	2	45	1
65	53	33	45	1
66	53	33	49	1
67	37	33	49	1
68	37	41	49	1
69	55	41	49	1
70	55	41	48	1
71	55	43	48	1
72	55	43	51	1
73	39	43	51	1
74	39	35	51	1
75	54	35	51	1

76	54	35	46	1
77	54	36	46	1
78	54	36	52	1
79	40	36	52	1
80	40	44	52	1
81	56	44	52	1
82	56	44	47	1
83	56	42	47	1
84	56	42	50	1
85	38	42	50	1
86	38	34	50	1
87	53	34	50	1
88	53	34	45	1
89	53	57	49	1
90	55	57	49	1
91	55	57	51	1
92	54	57	51	1
93	54	57	52	1
94	56	57	52	1
95	56	57	50	1
96	53	57	50	1
97	18	17	58	2
98	21	17	58	2
99	21	25	58	2
100	29	25	58	2
101	29	31	58	2
102	27	31	58	2
103	27	23	58	2
104	19	23	58	2
105	19	20	58	2
106	24	20	58	2
107	24	28	58	2
108	32	28	58	2
109	32	30	58	2
110	26	30	58	2
111	26	22	58	2
112	18	22	58	2
113	1	1	1	4

APPENDIX F

SAMPLE OUTPUT FROM GEOMETRIC SIMULATION

BORE = 8.000
STROKE = 7.958
CONRL = 14.000

XSPARK = 2.928
YSPARK = 0.0
ZSPARK = 0.860

14.000	70.000	25.700	300.000	200	2200	9
1	3.974	0.790	0.0	1		
2	3.974	-0.790	0.0	1		
3	-3.974	0.790	0.0	1		
4	-3.974	-0.790	0.0	1		
5	3.369	2.251	0.0	1		
6	3.369	-2.251	0.0	1		
7	-3.369	2.251	0.0	1		
8	-3.369	-2.251	0.0	1		
9	2.251	3.369	0.0	1		
10	2.251	-3.369	0.0	1		
11	-2.251	3.369	0.0	1		
12	-2.251	-3.369	0.0	1		
13	0.790	3.974	0.0	1		
14	0.790	-3.974	0.0	1		
15	-0.790	3.974	0.0	1		
16	-0.790	-3.974	0.0	1		
17	3.974	0.790	0.0	0		
18	3.974	-0.790	0.0	0		
19	-3.974	0.790	0.0	0		
20	-3.974	-0.790	0.0	0		
21	3.369	2.251	0.0	0		
22	3.369	-2.251	0.0	0		
23	-3.369	2.251	0.0	0		
24	-3.369	-2.251	0.0	0		
25	2.251	3.369	0.0	0		
26	2.251	-3.369	0.0	0		
27	-2.251	3.369	0.0	0		
28	-2.251	-3.369	0.0	0		
29	0.790	3.974	0.0	0		
30	0.790	-3.974	0.0	0		
31	-0.790	3.974	0.0	0		
32	-0.790	-3.974	0.0	0		
33	2.705	1.120	1.110	1		
34	2.705	-1.120	1.110	1		
35	-2.705	1.120	1.110	1		
36	-2.705	-1.120	1.110	1		
37	2.070	2.070	1.110	1		
38	2.070	-2.070	1.110	1		
39	-2.070	2.070	1.110	1		
40	-2.070	-2.070	1.110	1		
41	1.120	2.705	1.110	1		
42	1.120	-2.705	1.110	1		

43	-1.120	2.705	1.110	1
44	-1.120	-2.705	1.110	1
45	2.928	0.0	1.110	1
46	-2.928	0.0	1.110	1
47	0.0	-2.928	1.110	1
48	0.0	2.928	1.110	1
49	1.085	1.085	1.805	1
50	1.085	-1.085	1.805	1
51	-1.085	1.085	1.805	1
52	-1.085	-1.085	1.805	1
53	1.534	0.0	1.805	1
54	-1.534	0.0	1.805	1
55	0.0	1.534	1.805	1
56	0.0	-1.534	1.805	1
57	0.0	0.0	2.040	1
58	0.0	0.0	0.0	0
59	0.0	0.0	0.0	2

1	17	1	2	3
2	17	1	21	3
3	5	1	21	3
4	5	25	21	3
5	5	25	9	3
6	29	25	9	3
7	29	13	9	3
8	29	13	31	3
9	15	13	31	3
10	15	31	27	3
11	15	11	27	3
12	23	11	27	3
13	23	11	7	3
14	23	19	7	3
15	3	19	7	3
16	3	19	20	3
17	3	4	20	3
18	24	4	20	3
19	24	4	8	3
20	24	28	8	3
21	12	28	8	3
22	12	28	32	3
23	12	16	32	3
24	30	16	32	3
25	30	16	14	3
26	30	26	14	3
27	10	26	14	3
28	10	26	22	3
29	10	6	22	3
30	18	6	22	3
31	18	6	2	3
32	18	17	2	3
33	45	1	2	1
34	45	1	33	1
35	5	1	33	1
36	5	37	33	1
37	5	37	9	1
38	41	37	9	1
39	41	13	9	1
40	41	13	48	1
41	15	13	48	1

42	15	43	48	1
43	15	43	11	1
44	39	43	11	1
45	39	7	11	1
46	39	7	35	1
47	3	7	35	1
48	3	46	35	1
49	3	46	4	1
50	36	46	4	1
51	36	8	4	1
52	36	8	40	1
53	12	8	40	1
54	12	44	40	1
55	12	44	16	1
56	47	44	16	1
57	47	14	16	1
58	47	14	42	1
59	10	14	42	1
60	10	38	42	1
61	10	38	6	1
62	34	38	6	1
63	34	2	6	1
64	34	2	45	1
65	53	33	45	1
66	53	33	49	1
67	37	33	49	1
68	37	41	49	1
69	55	41	49	1
70	55	41	48	1
71	55	43	48	1
72	55	43	51	1
73	39	43	51	1
74	39	35	51	1
75	54	35	51	1
76	54	35	46	1
77	54	36	46	1
78	54	36	52	1
79	40	36	52	1
80	40	44	52	1
81	56	44	52	1
82	56	44	47	1
83	56	42	47	1
84	56	42	50	1
85	38	42	50	1
86	38	34	50	1
87	53	34	50	1
88	53	34	45	1
89	53	57	49	1
90	55	57	49	1
91	55	57	51	1
92	54	57	51	1
93	54	57	52	1
94	56	57	52	1
95	56	57	50	1
96	53	57	50	1
97	18	17	58	2
98	21	17	58	2
99	21	25	58	2

100	29	25	58	2
101	29	31	58	2
102	27	31	58	2
103	27	23	58	2
104	19	23	58	2
105	19	20	58	2
106	24	20	58	2
107	24	28	58	2
108	32	28	58	2
109	32	30	58	2
110	26	30	58	2
111	26	22	58	2
112	18	22	58	2
113	1	1	1	4

NHEAD = 64
NPIST = 16
NCWALL = 32
FACETS = 112

POINTS = 58

1

COMBUSTION CHAMBER GEOMETRY SIMULATOR

1

THETA = 0.0

RADIUS	AFLAME	AINH	AOUTH	AINP	AOUTP	AINCW	AOUTCW	VIN	VOUT
0.0	0.0	0.0	0.979253	0.0	0.785393	0.0	0.0	0.0	0.104537
0.054599	0.024599	0.006341	0.972913	0.0	0.785393	0.0	0.0	0.000672	0.103865
0.109198	0.080832	0.028512	0.950741	0.0	0.785393	0.0	0.0	0.003550	0.100987
0.163797	0.103954	0.077497	0.901756	0.0	0.785393	0.0	0.0	0.008594	0.095942
0.218396	0.129689	0.137710	0.841544	0.062860	0.722534	0.000000	-0.000000	0.014973	0.089564
0.272995	0.163228	0.194147	0.785107	0.104708	0.680685	0.0	0.0	0.022969	0.081567
0.327594	0.170210	0.265260	0.713993	0.161209	0.624185	0.0	0.0	0.032072	0.072465
0.382192	0.181842	0.332803	0.646451	0.261019	0.524375	0.000000	-0.000000	0.041683	0.062854
0.436791	0.187491	0.407822	0.571430	0.328884	0.456510	-0.000000	0.000000	0.051765	0.052771

0.491390	0.184719	0.490586	0.488667	0.399302	0.386091	-0.000000	0.000000	0.061926	0.042610
0.545989	0.190652	0.571307	0.407947	0.465646	0.319748	0.0	0.0	0.072174	0.032363
0.600588	0.163516	0.653215	0.326038	0.533354	0.252039	0.0	0.0	0.081842	0.022694
0.655187	0.141988	0.734873	0.244381	0.597488	0.187905	0.0	0.0	0.090182	0.014354
0.709786	0.098800	0.812286	0.166968	0.659034	0.126360	0.0	0.0	0.096756	0.007781
0.764385	0.066378	0.885437	0.093816	0.712945	0.072448	0.0	0.0	0.101265	0.003272
0.818984	0.026393	0.945127	0.034125	0.758334	0.027059	0.0	0.0	0.103797	0.000739
0.873583	0.0	0.978912	0.000341	0.785099	0.000295	-0.000000	0.000000	0.104537	0.0

LOWER X LIMIT = -0.49677
UPPER X LIMIT = 0.49677
LOWER Y LIMIT = -0.49677
UPPER Y LIMIT = 0.49677
LOWER Z LIMIT = 0.0
UPPER Z LIMIT = 0.0

1

THETA = 14.00

RADIUS	AFLAME	AINH	AOUTH	AINP	AOUTP	AINCW	AOUTCW	VIN	VOUT
0.0	0.0	0.0	0.979253	0.0	0.785393	0.0	0.059809	0.0	0.118008
0.054599	0.024599	0.006341	0.972913	0.0	0.785393	0.0	0.059809	0.000672	0.117336
0.109198	0.080832	0.028512	0.950741	0.0	0.785393	0.0	0.059809	0.003550	0.114458
0.163797	0.103954	0.077497	0.901756	0.0	0.785393	0.0	0.059809	0.008594	0.109414
0.218396	0.151596	0.137710	0.841544	0.053843	0.731551	0.005707	0.054102	0.015571	0.102437
0.272995	0.179551	0.194147	0.785107	0.098517	0.686877	0.009315	0.050494	0.024611	0.093397
0.327594	0.192905	0.265260	0.713993	0.155432	0.629962	0.012431	0.047379	0.034779	0.083229
0.382192	0.207445	0.332803	0.646451	0.201724	0.583670	0.015571	0.044238	0.045708	0.072300
0.436791	0.212820	0.407822	0.571430	0.322764	0,462630	0.018289	0.041520	0.057181	0.060827
0.491390	0.207699	0.490586	0.488667	0.393726	0.391668	0.021630	0.038180	0.068661	0.049347
0.545989	0.210444	0.571307	0.407947	0.460764	0.324630	0.024632	0.035177	0.080076	0.037932

0.600588	0.186501	0.653215	0.326038	0.528783	0.256610	0.028037	0.031772	0.090912	0.027096
0.655187	0.161482	0.734873	0.244381	0.593678	0.191716	0.031600	0.028210	0.100412	0.017596
0.709786	0.119903	0.812286	0.166968	0.655609	0.129785	0.035588	0.024221	0.108094	0.009914
0.764385	0.079727	0.885437	0.093816	0.710299	0.075094	0.039957	0.019852	0.113543	0.004464
0.818984	0.040866	0.945127	0.034125	0.756503	0.028891	0.046174	0.013636	0.116836	0.001172
0.873583	0.001937	0.978912	0.000341	0.784573	0.000821	0.055695	0.004114	0.118004	0.000004
0.928182	0.0	0.978912	0.000341	0.785393	0.0	0.059809	0.0	0.118008	0.0

LOWER X LIMIT = -0.49677
UPPER X LIMIT = 0.49677
LOWER Y LIMIT = -0.49677
UPPER Y LIMIT = 0.49677
LOWER Z LIMIT = -0.01891
UPPER Z LIMIT = 0.0

1

THETA = 28.00

RADIUS	AFLAME	AINH	AOUTH	AINP	AOUTP	AINCW	AOUTCW	VIN	VOUT
0.0	0.0	0.0	0.979253	0.0	0.785393	0.0	0.233560	0.0	0.158561
0.054599	0.024599	0.006341	0.972913	0.0	0.785393	0.0	0.233560	0.000672	0.157890
0.109198	0.080832	0.028512	0.950741	0.0	0.785393	0.0	0.233560	0.003550	0.155012
0.163797	0.103954	0.077497	0.901756	0.0	0.785393	0.0	0.233560	0.008594	0.149967
0.218396	0.214104	0.137710	0.841544	0.0	0.785393	0.011857	0.221703	0.017277	0.141284
0.272995	0.243676	0.194147	0.785107	0.072613	0.712781	0.032826	0.200734	0.029774	0.128787
0.327594	0.255170	0.265260	0.713993	0.120141	0.665253	0.045381	0.188179	0.043392	0.115169
0.382192	0.262143	0.332803	0.646451	0.182542	0.602852	0.058586	0.174973	0.057515	0.101047
0.436791	0.270173	0.407822	0.571430	0.298623	0.486771	0.069593	0.163967	0.072047	0.086515
0.491390	0.287405	0.490586	0.488667	0.371338	0.414056	0.082548	0.151011	0.087268	0.071293
0.545989	0.288743	0.571307	0.407947	0.441671	0.343722	0.094664	0.138895	0.102997	0.055565
0.600588	0.255457	0.653215	0.326038	0.510644	0.274749	0.107500	0.126060	0.117853	0.040708

0.655187	0.219964	0.734873	0.244381	0.578670	0.206724	0.121949	0.111610	0.130832	0.027730
0.709786	0.181293	0.812286	0.166968	0.641973	0.143421	0.136783	0.096777	0.141786	0.016775
0.764385	0.135351	0.885437	0.093816	0.699860	0.085533	0.154534	0.079026	0.150430	0.008131
0.818984	0.072793	0.945127	0.034125	0.749048	0.036346	0.178228	0.055332	0.156112	0.002449
0.873583	0.013562	0.978912	0.000341	0.781980	0.003413	0.214558	0.019002	0.158470	0.000092
0.928182	0.0	0.978912	0.000341	0.785393	0.0	0.233560	0.0	0.158561	0.0

LOWER X LIMIT = -0.49677
UPPER X LIMIT = 0.49677
LOWER Y LIMIT = -0.49677
UPPER Y LIMIT = 0.49677
LOWER Z LIMIT = -0.07386
UPPER Z LIMIT = 0.0

1

THETA = 42.00

RADIUS	AFLAME	AINH	AOUTH	AINP	AOUTP	AINCW	AOUTCW	VIN	VOUT
0.0	0.0	0.0	0.979253	0.0	0.785393	0.0	0.504925	0.0	0.222599
0.054599	0.024599	0.006341	0.972913	0.0	0.785393	0.0	0.504925	0.000672	0.221927
0.109198	0.080832	0.028512	0.950741	0.0	0.785393	0.0	0.504925	0.003550	0.219049
0.163797	0.103954	0.077497	0.901756	0.0	0.785393	0.0	0.504925	0.008594	0.214005
0.218396	0.214104	0.137710	0.841544	0.0	0.785393	0.012721	0.492204	0.017277	0.205322
0.272995	0.350357	0.194147	0.785107	0.0	0.785393	0.042299	0.462626	0.032687	0.189912
0.327594	0.361370	0.265260	0.713993	0.062468	0.722925	0.083127	0.421799	0.052116	0.170483
0.382192	0.380267	0.332803	0.646451	0.120480	0.664914	0.113087	0.391838	0.072363	0.150236
0.436791	0.403804	0.407822	0.571430	0.189737	0.595657	0.140760	0.364166	0.093767	0.128832
0.491390	0.393000	0.490586	0.488667	0.316123	0.469270	0.168456	0.336470	0.115520	0.107079
0.545989	0.398476	0.571307	0.407947	0.395288	0.390105	0.196985	0.307941	0.137126	0.085472
0.600588	0.361655	0.653215	0.326038	0.468695	0.316698	0.224302	0.280625	0.157878	0.064721
0.655187	0.322091	0.734873	0.244381	0.542190	0.243204	0.256417	0.248510	0.176543	0.046055

0.709786	0.277216	0.812286	0.166968	0.610031	0.175362	0.287328	0.217599	0.192904	0.029695
0.764385	0.208033	0.885437	0.093816	0.674138	0.111255	0.326523	0.178403	0.206151	0.016448
0.818984	0.157506	0.945127	0.034125	0.728629	0.056765	0.373967	0.130959	0.216130	0.006469
0.873583	0.048434	0.978912	0.000341	0.770572	0.014822	0.441922	0.063003	0.221752	0.000847
0.928182	0.0	0.978912	0.000341	0.785393	0.0	0.504925	0.0	0.222599	0.0

LOWER X LIMIT = -0.49677
UPPER X LIMIT = 0.49677
LOWER Y LIMIT = -0.49677
UPPER Y LIMIT = 0.49677
LOWER Z LIMIT = -0.15968
UPPER Z LIMIT = 0.0

1

THETA = 56.00

RADIUS	AFLAME	AINH	AOUTH	AINP	AOUTP	AINCW	AOUTCW	VIN	VOUT
0.0	0.0	0.0	0.979253	0.0	0.785393	0.0	0.849028	0.0	0.304548
0.054599	0.024599	0.006341	0.972913	0.0	0.785393	0.0	0.849028	0.000672	0.303876
0.109198	0.080832	0.028512	0.950741	0.0	0.785393	0.0	0.849028	0.003550	0.300998
0.163797	0.103954	0.077497	0.901756	0.0	0.785393	0.0	0.849028	0.008594	0.295953
0.218396	0.214104	0.137710	0.841544	0.0	0.785393	0.011863	0.837166	0.017277	0.287271
0.272995	0.350357	0.194147	0.785107	0.0	0.785393	0.042786	0.806242	0.032687	0.271861
0.327594	0.470479	0.265260	0.713993	0.0	0.785393	0.088708	0.760321	0.055095	0.249453
0.382192	0.561236	0.332803	0.646451	0.0	0.785393	0.144309	0.704719	0.083260	0.221288
0.436791	0.560143	0.407822	0.571430	0.085070	0.700323	0.202037	0.646992	0.113873	0.190675
0.491390	0.531757	0.490586	0.488667	0.166697	0.618697	0.257335	0.591694	0.143681	0.160866
0.545989	0.548960	0.571307	0.407947	0.296865	0.488529	0.303824	0.545204	0.173184	0.131363
0.600588	0.503931	0.653215	0.326038	0.385718	0.399676	0.355590	0.493439	0.201928	0.102620
0.655187	0.472807	0.734873	0.244381	0.467141	0.318252	0.405878	0.443151	0.228592	0.075956
0.709786	0.429093	0.812286	0.166968	0.546686	0.238707	0.462665	0.386364	0.253214	0.051334

0.764385	0.343012	0.885437	0.093816	0.618777	0.166617	0.521758	0.327271	0.274292	0.030256
0.818984	0.245198	0.945127	0.034125	0.685469	0.099924	0.599921	0.249108	0.290349	0.014198
0.873583	0.128351	0.978912	0.000341	0.741229	0.044164	0.706046	0.142983	0.300547	0.004001
0.928182	0.013669	0.978912	0.000341	0.779956	0.005438	0.836192	0.012836	0.304424	0.000124
0.982781	0.0	0.978912	0.000341	0.785393	0.0	0.849028	0.0	0.304548	0.0

LOWER X LIMIT = -0.49677
UPPER X LIMIT = 0.49677
LOWER Y LIMIT = -0.49677
UPPER Y LIMIT = 0.49677
LOWER Z LIMIT = -0.26851
UPPER Z LIMIT = 0.0

1

THETA = 70.00

RADIUS	AFLAME	AINH	AOUTH	AINP	AOUTP	AINCW	AOUTCW	VIN	VOUT
0.0	0.0	0.0	0.979253	0.0	0.785393	0.0	1.235760	0.0	0.404053
0.054599	0.024599	0.006341	0.972913	0.0	0.785393	0.0	1.235760	0.000672	0.403381
0.109198	0.080832	0.028512	0.950741	0.0	0.785393	0.0	1.235760	0.003550	0.400503
0.163797	0.103954	0.077497	0.901756	0.0	0.785393	0.0	1.235760	0.008594	0.395458
0.218396	0.214104	0.137710	0.841544	0.0	0.785393	0.011185	1.224575	0.017277	0.386775
0.272995	0.350357	0.194147	0.785107	0.0	0.785393	0.042268	1.193492	0.032687	0.371366
0.327594	0.470479	0.265260	0.713993	0.0	0.785393	0.088612	1.147148	0.055095	0.348958
0.382192	0.561236	0.332803	0.646451	0.0	0.785393	0.146294	1.089466	0.083260	0.320792
0.436791	0.689116	0.407822	0.571430	0.0	0.785393	0.210837	1.024923	0.117394	0.286658
0.491390	0.807525	0.490586	0.488667	0.0	0.785393	0.299058	0.936702	0.158252	0.245801
0.545989	0.764643	0.571307	0.407947	0.085713	0.699680	0.386869	0.848891	0.201171	0.202882
0.600588	0.712835	0.653215	0.326038	0.181570	0.603824	0.469272	0.766489	0.241505	0.162547
0.655187	0.675604	0.734873	0.244381	0.331244	0.454150	0.544892	0.690868	0.279409	0.124644
0.709786	0.627013	0.812286	0.166968	0.430378	0.355015	0.629412	0.606348	0.314970	0.089083

0.764385	0.509884	0.885437	0.093816	0.519576	0.265818	0.715916	0.519845	0.346006	0.058046
0.818984	0.416752	0.945127	0.034125	0.601577	0.183817	0.822562	0.413198	0.371303	0.032750
0.873583	0.282372	0.978912	0.000341	0.675513	0.109881	0.963672	0.272088	0.390389	0.013664
0.928182	0.100060	0.978912	0.000341	0.736666	0.048728	1.139559	0.096201	0.400829	0.003224
0.982781	0.013486	0.978912	0.000341	0.779361	0.006033	1.224974	0.010786	0.403928	0.000124
1.037379	0.0	0.978912	0.000341	0.785393	0.0	1.235760	0.0	0.404053	0.0

LOWER X LIMIT = -0.49677
UPPER X LIMIT = 0.49677
LOWER Y LIMIT = -0.49677
UPPER Y LIMIT = 0.49677
LOWER Z LIMIT = -0.39081
UPPER Z LIMIT = 0.0

COMPRESSION RATIO = 8.473

APPENDIX G

CYCLE SIMULATION LOG SHEETS

SI Engine Cycle Simulation Log Sheet

2 combustion chamber geometries: disk/side plug, disk/center plug

Model Performance and Sensitivity Study

All runs at the following conditions unless otherwise stated:

engine speed:	1500 RPM
fuel:	Isooctane
Phi:	1.0
EGR:	0%
spark timing:	MBT
Pim:	0.5 Atm
Tim:	350 K
Pem:	1.0 Atm
Twall:	400 K

Run #	shape	sp-loc	spark	0-10%	10-90%	0-90%	GIthef	Q/A max (KW/m**2)	u' max (m/sec)	NOppm	Comments
J- 1	disk	center	340	22.11	16.85	38.96	34.5	2.496	6.52	1442	base disk/center
J- 2	disk	center	324	31.41	28.24	59.65	34.4	1.495	7.93	434	=J-1, but EGR = 20%
J- 3	disk	center	330	21.98	14.32	36.30	32.9	3.540	8.10	1511	=J-1, but timing advanced 10 CA
J- 4	disk	center	350	23.75	21.42	45.17	32.1	1.496	5.02	1344	=J-1, but timing retarded 10 CA
J- 5	disk	side	329	25.33	29.67	55.00	33.3	1.884	7.47	1453	base disk/side
J- 6	disk	side	319	26.13	24.91	51.04	31.4	3.112	9.37	1514	=J-5, but timing advanced 10 CA
J- 7	disk	side	339	25.74	37.82	63.56	31.5	1.027	5.69	1358	=J-5, but timing retarded 10 CA
J- 8	disk	side	313	37.09	38.67	75.76	33.0	1.363	9.05	471	=J-5, but EGR = 20%
J- 9	disk	side	331	24.10	29.24	53.34	33.1	1.261	4.80	1329	=J-5, but @ 1000 RPM
J- 10	disk	side	329	26.27	30.85	57.12	33.4	2.280	9.87	1520	=J-5, but @ 2000 RPM
J- 11	disk	side	324	29.25	32.85	62.10	35.5	1.125	7.77	3472	=J-5, but PHI = 0.8
J- 12	disk	side	329	25.59	28.91	54.50	28.2	1.486	7.59	137	=J-5, but PHI = 1.2
J- 13	disk	side	324	31.25	35.11	66.36	32.9	0.916	7.72	1099	=J-5, but Pim = 0.3 Atm
J- 14	disk	side	331	23.51	28.95	52.52	33.6	2.659	7.30	1571	=J-5, but Pim = 0.7 Atm
J- 15	disk	side									=J-5, but PROPANE (not performed)

J- 16	disk	center	342	21.08	16.32	37.40	34.3	1.679	4.18	1317	=J-1, but @ 1000 RPM
J- 17	disk	center	337	22.81	16.95	39.76	34.7	3.491	9.27	1534	=J-1, but @ 2000 RPM
J- 18	disk	center	336	25.50	20.73	46.23	37.0	1.349	6.61	3686	=J-1, but PHI = 0.8
J- 19	disk	center	340	22.37	16.58	38.95	29.1	1.895	6.60	133	=J-1, but PHI = 1.2
J- 20	disk	center	333	27.31	22.77	50.08	34.2	1.216	7.01	1080	=J-1, but Pim = 0.3 Atm
J- 21	disk	center	342	20.54	15.81	36.35	34.9	3.518	6.39	1558	=J-1, but Pim = 0.7 Atm
J- 22	disk	center									=J-1, but PROPANE (not performed)
J- 23	disk	center	340	23.25	18.07	41.32	32.0	3.117	6.41	1325	=J-1, but Conht = 0.105 (1.5*base)
J- 24	disk	center	337	20.69	14.91	35.60	37.8	1.698	7.11	1524	=J-1, but Conht = 0.035 (0.5*base)
J- 25	disk	center	345	19.21	14.83	34.04	32.3	3.407	7.95	1365	=J-1, but Cbeta = 0.75 (0.5*base)
J- 26	disk	center	336	25.02	18.87	43.89	35.3	2.092	5.55	1459	=J-1, but Cbeta = 3.0 (2.0*base)
J- 27	disk	side	331	26.38	32.55	58.93	30.7	1.987	6.96	1345	=J-5, but Conht = 0.105 (0.5*base)
J- 28	disk	side	328	24.09	27.52	51.61	36.7	1.307	7.84	1509	=J-5, but Conht = 0.035 (0.5*base)
J- 29	disk	side	337	21.90	27.17	49.07	31.5	2.211	8.42	1387	=J-5, but Cbeta = 0.75 (0.5*base)
J- 30	disk	side	324	28.95	33.20	62.15	33.9	1.577	6.45	1466	=J-5, but Cbeta = 3.0 (2.0*base)
J- 31	disk	side	346	16.28	20.80	37.08	31.6	2.813	11.50	1410	=J-5, but Cmult = 2.0 (2.0*base)
J- 32	disk	center	354	14.76	11.82	26.58	32.2	3.409	10.49	1390	=J-1, but Cmult = 2.0 (2.0*base)

Study of 10 different combustion chamber geometries

All runs at the following conditions unless otherwise stated:

engine speed: 1500 RPM
fuel: Isooctane
Phi: 1.0
EGR: 0% / 20%
spark timing: MBT
Pim: 0.5 Atm
Tim: 350 K
Pem: 1.0 Atm
Twall: 400 K

Run #	shape	sp-loc	spark	0-10%	10-90%	0-90%	GIthef	Q/A max (KW/m**2)	u' max (m/sec)	NOppm	Comments
K- 1	bowl	center	338	20.87	14.53	35.40	34.4	3.001	7.00	1502	Base case for bowl w/ center plug
K- 2	bowl	center	327	29.80	26.28	56.08	34.8	1.565	7.67	430	=K-1, but EGR = 20%
K- 3	bowl	side	333	23.09	25.87	48.96	32.4	1.972	7.19	1426	Base case for bowl w/ side plug
K- 4	bowl	side	319	33.35	37.48	70.83	33.2	1.275	8.45	420	=K-3, but EGR = 20%
K- 5	hemi	side	331	23.89	26.84	50.73	34.2	2.019	7.38	1459	Base case for hemi w/ side plug
K- 6	hemi	side	319	34.60	37.60	72.20	34.2	1.241	8.27	508	=K-5, but EGR = 20%
K- 7	hemi	center	338	21.47	17.87	39.34	35.3	2.626	6.83	1482	Base case for hemi w/ center plug
K- 8	hemi	center	325	30.82	28.24	59.06	35.3	1.545	7.84	546	=K-7, but EGR = 20%
K- 9	hemi	1/3	335	21.67	24.00	45.67	34.5	2.150	7.00	1478	Base case for hemi w/ 1/3 plug
K- 10	hemi	1/3	321	31.65	32.63	64.28	34.8	1.390	8.30	579	=K-9, but EGR = 20%
K- 11	open	side	333	22.85	25.79	48.64	34.6	2.126	7.15	1480	Base case for open w/ side plug
K- 12	open	side	319	32.89	34.57	67.46	34.8	1.441	8.45	603	=K-11, but EGR = 20%
K- 13	open	top	338	20.79	15.86	36.65	35.5	2.860	6.94	1498	Base case for open w/ top plug
K- 14	open	top	325	29.81	26.00	55.81	35.7	1.664	7.94	630	=K-13, but EGR = 20%
K- 15	open	center	338	19.14	16.01	35.15	35.4	3.044	6.98	1546	Base case for open w/ center plug
K- 16	open	center	329	27.58	28.10	55.68	35.9	1.491	7.35	585	=K-15, but EGR = 20%

Study of turbulence vs. chamber design to achieve fast burn

All runs at the following conditions unless otherwise stated:

engine speed: 1500 RPM
fuel: Isooctane
Phi: 1.0
EGR: 0%
spark timing: MBT
Pim: 0.5 Atm
Tim: 350 K
Pem: 1.0 Atm
Twall: 400 K

Run #	shape	sp-loc	spark	0-10%	10-90%	0-90%	GIthef	Q/A max (KW/m**2)	u' max (m/sec)	NOppm	Comments
L- 1	hemi	side	342	17.85	21.67	39.52	33.3	2.516	9.60	1442	=K-5, but cmult set to match K-7 burn
L- 2	bowl	side	344	16.52	19.34	35.86	31.8	2.693	10.35	1428	=K-3, but cmult set to match K-1 burn