A PERFORMANCE MODEL OF A SPARK IGNITION WANKEL ENGINE: INCLUDING THE EFFECTS OF CREVICE VOLUMES, GAS LEAKAGE, AND HEAT TRANSFER

by

TIMOTHY JOHN NORMAN

B.S.M.E. University of Massachusetts, Amherst
(1981)

Submitted to the Department of
Mechanical Engineering
in Partial Fulfillment of the
Requirments of the Degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 1983

© Massachusetts Institute of Technology

Signature of Author: ______________________________
Department of Mechanical Engineering, 1 March 1983

Certified by: ______________________________
Jack Ekchian
Thesis Supervisor

Accepted by: ______________________________
Warren M. Rohsenow
Chairman, Mechanical Engineering Department Committee

MASSACHUSETTS INSTITUTE
OF TECHNOLOGY
JUN 23 1983
LIBRARIES
Archives

A PERFORMANCE MODEL OF A SPARK IGNITION WANKEL ENGINE: INCLUDING THE EFFECTS OF CREVICE VOLUMES, GAS LEAKAGE, AND HEAT TRANSFER

by

TIMOTHY JOHN NORMAN

Submitted to the Department of Mechanical Engineering on
March 1, 1983 in partial fulfillment of the requirements
for the Degree of Master of Science in Mechanical Engineering

ABSTRACT

Recent aviation gasoline price and supply problems have created a need for general aviation airplane engines that burn kerosene. N.A.S.A. researchers have determined that a stratified charge Wankel engine is a likely engine choice for this purpose. This paper describes the initial work towards modelling such an engine.

A zero-dimensional (or thermodynamic) model of a spark ignition engine has been constructed. Three engine performance loss submodels have been included; they are heat transfer, gas leakage, and crevice volumes. Previous models of the Wankel engine have not included a model of performance loss resulting from crevice volumes.

Preliminary rotary engine performance testing is being conducted by N.A.S.A. on a gasoline, spark ignition Wankel engine. Motoring data from this engine was used to calibrate the computer model. A shortage of firing engine data has made the calibration incomplete but the reported values of crevice volume and leakage area are 0.875 cm^3/apex and 1.0 mm^2/apex respectively. A parametric study on the effects of reducing leakage, heat transfer, and crevice volumes was performed for light load and motoring. As was predicted, gas leakage is the predominant effect in these operating regimes. Crevice volumes and heat transfer have little effect on engine performance at very light load but can be expected to become more significant at higher loads and speeds.

Thesis Supervisor: Professor John B. Heywood

Title: Professor of Mechanical Engineering

Director Sloan Automotive Laboratory

Thesis Supervisor: Dr. Jack A. Ekchian

Title: Manager Sloan Automotive Laboratory.

ACKNOWLEDGEMENTS

This is the bittersweet part of any research thesis. Sweet because my work is complete but bittersweet because it means I must say goodbye to my good friends and family at M.I.T. and in the Boston area.

I want to first thank Professor John Heywood for all his expert help with the research and my career at M.I.T. It has been a privilege to work with such an outstanding engineer and person. I would also like to thank Jack Ekchian, my surrogate advisor these last few months, for his help in finishing the research and thesis. Thanks also to Professor Gyftopoulos for getting me started at M.I.T. Steve Poulos and Hossein Mansouri were both helpful in explaining their work from which this research started.

I would also like to thank my wife (and starter motor) Moni for her typing, love, and devotion . Pat Condon and Karla Stryker deserve recognition for all the help they have provided me. Thanks also to Bruce Marcham (drafting and late nights), Rick Babikian, Yi-Chung Doo, Pepper White, Harry Katz, Chris Shea and Craig Noble (and all the others that I'm forgetting) for all of your friendship. Special thanks to my parents Les and Janet for Sunday dinners and being there, Mona and Tom Widmer for their love and balanced perspective (no more horse-hair sweaters?), and Stanley Cath for his guidance, objectivity, and friendship.

This research has been sponsored by N.A.S.A. and all their help is greatly appreciated.

I would like to dedicate this thesis to my brother Anthony and his children Luke, and Zoe. Peace.

TABLE OF CONTENTS

page

TITLE PAGE 1

ABSTRACT 2

ACKNOWLEDGEMENTS 3

TABLE OF CONTENTS 4

LIST OF TABLES 8

LIST OF FIGURES 10

CHAPTER

1.0 INTRODUCTION 13

1.1 BACKGROUND 13

1.1.1 OVERALL N.A.S.A. GOAL 13

1.1.2 ENGINES UNDER CONSIDERATION BY N.A.S.A. 14

1.2 THE WANKEL ENGINE 16

1.2.1 WANKEL ENGINE DESCRIPTION 16

1.2.2 ADVANTAGES AND DISADVANTAGES OF THE WANKEL ENGINE 17

1.3 PROGRAM 18

1.4 DESCRIPTION OF PROJECT TASKS 19

1.4.1 DEFINITION OF TASKS 19

1.4.2 OUTLINE OF CODE 19

1.4.3 CHANGE IN GEOMETRY 21

1.4.4 COMBUSTION ROUTINE CHANGES 21

1.4.5 ADDITION OF GAS LEAKAGE MODEL 22

1.4.6 ADDITION OF CREVICE VOLUME MODEL 22

1.4.7 CHANGES TO HEAT TRANSFER MODEL 23

2.0 COMPUTER MODEL 24

2.1 BACKGROUND 24

2.2 CALCULATION OF THERMODYNAMIC PROPERTIES 25

2.2.1 SIMULATION FRAMEWORK AND BASIC ASSUMPTIONS 25

2.2.2 SOLUTION OF THERMODYNAMIC EQUATIONS WITHOUT CREVICE VOLUMES 26

2.3 ENGINE PROCESS MODELS 30

2.3.1 INTAKE AND EXHAUST FLOW PROCESSES 30

2.3.2 COMBUSTION 31

2.3.3 HEAT TRANSFER 32

2.3.4 LEAKAGE 36

2.3.5 CREVICE VOLUME 37

3.0 CREVICE AND LEAKAGE MODEL 39

3.1 CREVICE LOCATIONS AND LEAKAGE POINTS 39

3.2 OPTIONS 40

3.3 THERMODYNAMIC EQUATION OF CREVICE VOLUME AND LEAKAGE MODEL 43

3.4 PROGRAMMING CONSIDERATIONS 52

4.0 MODEL VALIDATION AND CALIBRATION 54

4.1 INTRODUCTION 54

4.2 GEOMETRY VALIDATION 54

4.3 CREVICE AND LEAKAGE MODEL VALIDATION 55

4.4 HEAT TRANSFER VALIDATION 56

4.5 MODEL CALIBRATION 56

4.5.1 INTAKE PORT OPEN AREA 58

4.5.2 FINAL MOTORING CALIBRATION 59
4.5.3 FIRING CASE CALIBRATION 61
4.5.4 COMMENTS ON CALIBRATION 62

5.0 MODEL RESULTS 63
5.1 MOTORING 63
5.1.1 MOTORING VOLUMETRIC EFFICIENCY 63
5.1.2 MOTORING GROSS INDICATED MEAN EFFECTIVE PRESSURE 64
5.1.3 MAXIMUM PRESSURE AND θ_{PEAK} 64
5.2 FIRING 65
5.2.1 FIRING VOLUMETRIC EFFICIENCY 65
5.2.2 FIRING GROSS INDICATED MEAN EFFECTIVE PRESSURE 66
5.2.3 UNBURNED FUEL ENERGY EXHAUSTED 66
5.2.4 RESIDUAL FRACTION 67
5.3 DISCUSSION 68

6.0 SUMMARY AND CONCLUSIONS 69
6.1 SUMMARY 69
6.2 CONCLUSIONS 72

REFERENCES 73
TABLES 76
FIGURES 82

CONTENTS OF SECOND VOLUME

APPENDIX A WANKEL ENGINE CYCLE SIMULATION CODE ....

APPENDIX B SAMPLE INPUT FOR CYCLE SIMULATION ....

APPENDIX C SAMPLE MOTORING OUTPUT ....

APPENDIX D SAMPLE FIRING OUTPUT ....

LIST OF TABLES

page

Table 1. Advanced rotary engine technologies. 76

Table 2. Final engine/airframe rankings for different engine concepts relative to a base general aviation engine. 77

Table 3. Location and size of crevice volumes in a model 12B Mazda Wankel engine. 78

Table 4. Motored engine test matrix with experimental data. 79

Table 5. Basic engine geometry as supplied by N.A.S.A. . 80

Table 6. Motored engine test matrix with computer results and, relative to measured engine data, error. 81

LIST OF FIGURES

page

Figure 1. Side and end views of shaft and rotor showing basic engine dimensions. 82

Figure 2. Side view of rotor and housing detailing engine geometry. 83

Figure 3. Exploded view of typical engine gas seals. 84

Figure 4. Flow chart of reciprocating engine program indicating deletions, additions, and alterations required for transformation to a Wankel engine simulation. 85

Figure 5. Detailed flow chart of Wankel simulation showing the order of subroutine calls. 86

Figure 6. Schematic diagram depicting the coupling of three engine chambers by leakage past the apex seals and the two zone combustion model. 87

Figure 7. Wankel engine surface to volume ratio versus crank angle for several engine geometries. 88

Figure 8. Comparison of true and approximate Wankel engine surface area calculations. 89

Figure 9. Diagram of the assumed flame front propagation. 90

Figure 10. Schematic diagram of side seal leakage path. 91

Figure 11. Diagram of crevice volume locations in the Wankel engine. 92

page

Figure 12. A pictorial schematic of crevice volumes and leakage gas flows. 93

Figure 13. Schematic diagram of a simulation that explicitly models all leakage paths and crevice volumes. 94

Figure 14. Schematic diagram of the crevice volume and leakage model as used in the program. 95

Figure 15. Diagram of crevice gas returning to chamber and being diverted into leakage flow. 96

Figure 16. Motion of Apex seal as resultant pressure forces reverse direction. 97

Figure 17. Schematic diagram of crevice volume and leakage model with a thermodynamic system imposed and positive mass flows shown. 98

Figure 18. Comparison of intake chamber pressure for different intake port area profiles and experimental data. 99

Figure 19. Comparison plot of intake port area profiles used during model calibration. 100

Figure 20. Comparison of intake chamber pressure between calibrated model and experimental data. 101

Figure 21. Comparison of measured and calibrated compression-expansion pressure trace for median engine speed and throttle setting. 102

page

Figure 22. Log P versus normalized log V for motoring runs at three engine speeds: measured and predicted. 103

Figure 23. Comparison of predicted and measured pressure versus crank angle for low engine load and speed. 104

Figure 24. Effect of parametric variation on motoring volumetric efficiency. 105

Figure 25. Effect of parametric variation on motoring gross IMEP. 106

Figure 26. Effect of reducing crevice volumes on compression - expansion pressure trace (motoring). 107

Figure 27. Effect of reducing leakage area on compression - expansion pressure trace (motoring). 108

Figure 28. Effect of reducing leakage area on compression - expansion pressure trace (motoring). 109

Figure 29. Effect of parametric variation on maximum motoring pressure. 110

Figure 30. Effect of parametric variation on motoring θ_{peak}. 111

Figure 31. Effect of parametric variation on firing volumetric efficiency. 112

Figure 32. Effect of parametric variation on mean exhaust gas temperature at light load. 113

page

Figure 33. Effect of parametric variation on light load gross mean effective pressure. 114

Figure 34. Effect of parametric variation on unburned fuel energy escaping to exhaust at light load. 115

Figure 35. Effect of parametric variation on residual gas fraction at light load. 116

1.0 INTRODUCTION

This chapter outlines the structure of the computer simulation developed in this project and the steps necessary for completion of the simulation. Background material is presented to acquaint the reader with the goals and some of the peculiarities of the engine under study. The second chapter discusses the specifics of the simulation and derives the differential equations for a closed system. Chapter Three investigates, in detail, the crevice and leakage model and then presents the derivation of the differential equations for an open system. The validation and calibration of the model through the use of engine data supplied by N.A.S.A. is discussed in Chapter Four. The fifth chapter presents the results from a parametric study on the effects of varying heat transfer, crevice volumes, and leakage areas. Chapter Six summarizes the results and presents a set of conclusions and recommendations.

1.1 BACKGROUND

1.1.1 OVERALL N.A.S.A. GOAL

N.A.S.A. has begun a development process that will by the end of this decade produce an engine for lightweight general aviation airplanes that will not require aviation gasoline. Distributors of high octane aviation gasoline have determined that continued supply to remote locations is no longer profitable. Uncertainty over fuel availability and price have worked to limit the commuter aircraft market (1).

The general aviation community has proposed that any new powerplant should burn the same fuel that powers commercial aircraft (aviation kerosene or jet fuel). This will reduce the uncertainty over fuel availability and minimize the inevitable dislocations within the fuel distribution network.

N.A.S.A. has begun a preliminary engineering program to determine the best engine for this application. Powerplants that have been considered include gas turbines, diesel engines, spark ignition reciprocating engines, and Wankel engines (2&3). Since the engine is to be used in light aircraft beginning in the 1990's, each powerplant choice has been rated for various operating characteristics, using assumed advanced technologies, and engine/airplane system requirements such as range and load capability (Tables 1 and 2).

1.1.2 ENGINES UNDER CONSIDERATION BY N.A.S.A.

Each design characteristic of the various engines being considered was weighted according to importance and a total score was assigned to each type of engine. From these studies N.A.S.A. has decided to concentrate on two choices:

1) a light-weight, turbo-charged, turbo compound, two-stroke diesel engine.
2) a turbo-charged, turbo-compound, stratified charge Wankel engine.

A primary design factor in an aircraft engine is the power density (power to weight ratio). Turbo-charging increases power density and will also allow the engines to operate at higher elevations. Reduction of engine weight, for the same power output, will increase the power density. Consequently, the two stroke engine, which has twice the power density of an equivalent four stroke engine is more desirable for this application. Some early studies of the two engines (no turbo-compounding) predict a power density of 1.25 hp/lb for the rotary engine and 0.98 hp/lb for the diesel. This advantage for the Wankel engine is somewhat offset by a slightly higher brake specific fuel consumption.

Both engines will use turbo-compounding which recovers more of the exhaust gas enthalpy, by driving a heat engine coupled to the engine shaft, which increases power output. This results in a higher thermal efficiency for the engine/compound cycle system. With the use of ceramic materials to reduce heat transfer losses within the engines, turbo-compounding could become more effective as the thermodynamic availability of the exhaust gases from the cylinder will be increased. Since, approximately one third of the fuel energy is converted to work, another one third is lost by heat transfer to the cooling system (in a conventional engine), and the remaining one third is exhausted; a turbo-compounding system that recovers 50% of the exhaust enthalpy of a truly adiabatic engine would double the power output or alternatively halve the engine size for the identical power.

In order for the Wankel engine to burn aviation kerosene the engine will have to be of a stratified charge design. In this engine, fuel is injected directly into the combustion chamber and ignition is insured through the use of one or more spark plugs. Past work by Curtiss-Wright has demonstrated the feasibility and advantages of a rotary stratified charge engine (4). The most significant advantages over a spark ignition rotary engine are:

improved fuel tolerance

higher thermal efficiency, η_{th} (higher compression ratio)

lower emissions (except at light load)

reduced throttling losses

1.2 THE WANKEL ENGINE

1.2.1 WANKEL ENGINE DESCRIPTION

In the Wankel engine a three-sided rotor is mounted on an eccentric shaft that is centered at the geometric center of the rotor housing (figs. 1 & 2). The rotor and housing assembly simultaneously form three isolated chambers. As the crank rotates, an internal gear on the rotor face mates with an external gear on the side plate (1:3 ratio), and forces the rotor to revolve at one third of the crank's angular velocity. This means that one chamber requires three crank shaft revolutions to complete the four strokes of an equivalent reciprocating engine cycle. However, because there are three chambers per rotor there is one induction process and one power "stroke" per crank revolution. Thus a single rotor Wankel engine is equivalent to one, two-cylinder, 4-stroke reciprocating engine. The rotary engine does not require mechanically complex valve trains but instead relies on intake and exhaust ports that are opened and closed by the action of the rotor. The intake ports are typically located on the side plate (known as side intake ports), and there are usually two intake ports per rotor. An exhaust port is located in the rotor housing (a peripheral exhaust port).

There are gas seals at each corner of the rotor (apex seals), along the edges of the rotor (side seals), and at the junctions between the apex and side seals (corner seals) (fig.3) . Oil is introduced into the intake system in order to lubricate these gas seals. The rotor is oil cooled and a set of oil seals prevent the flow of oil from the rotor to the chambers. The spark plugs and fuel injectors (for a stratified charge engine) are located near the top dead center position. The basic geometric design parameters are the rotor radius, which is the distance from the center of the rotor to the apex, the eccentricity of the shaft, and the depth or height of the rotor housing. With these dimensions and the volume of the cutout in the rotor, the theoretical compression ratio can be calculated as can the displacement per rotor.

1.2.2 ADVANTAGES AND DISADVANTAGES OF THE WANKEL ENGINE

The Wankel engine has been considered a dead issue by much of the technical community since the end of Wankel engine development programs at major automobile manufacturers such as General Motors, Toyota, and Ford. In order to determine if the present interest in the engine is justified, it is instructive to look at the reasons for termination of these developmental programs and what if any improvements have been made.

By far the most important reason for discontinuing Wankel engine research was the poor fuel economy of the engine, which became unacceptable after the OPEC oil embargo of 1973 and the subsequent gasoline price increases. This poor fuel economy is generally believed to be caused by unburned fuel/air mixture leaking past the apex seals during compression and combustion to adjacent chambers. This leakage is also thought to be the prime contributor to the high hydrocarbon emissions of the Wankel (5). Other major concerns were the projected high production and tooling costs for an engine which was of such radically different geometry from the conventional automotive engine. Engine reliability was also a consideration as early production models had serious apex seal wear problems. Although most Wankel engine programs were terminated in the mid 1970's a few projects have continued, most notably at Toyo Kogyo (Mazda) and at Curtiss-Wright. These projects have resulted in production tooling and engines with improved fuel economy and proven reliability. The RX-7, Mazda's production sports car model that employs a two rotor Wankel engine, is now rated at 25 mpg by the EPA, and meets all emissions standards (6). Curtiss-Wright's stratified charge rotary engine is not currently in production, but test results have given very promising emissions and fuel economy data (7). These continued efforts have shown that in certain applications such as general aviation airplanes the Wankel may be a good power plant choice.

For light aircraft duty the stratfied charge Wankel has some specific advantages over its diesel engine competitor:

higher power density
better fuel tolerance
smaller package volume
  - lower frontal area
  - easier maintenance access
better low temperature starting
lower noise levels
shorter lift-off
faster climb
reliability (fewer moving parts)

1.3 PROGRAM

The research proposal calls for three phases of activity that are to be completed in series. During the first phase a reciprocating engine cycle simulation was converted to a Wankel engine simulation. A stratified charge combustion model will be added during the second phase, so that more detailed design questions can be considered. In the third phase turbo-charge and turbo-compound models will be incorporated into the cycle simulation.

The author's task has been to complete the first phase, in order for preliminary engine performance and sizing calculations to be made. A secondary research aim, during this phase of the project, was to develop a crevice volume model for the Wankel engine to assess the importance of crevices on engine performance. Experimental data from a Mazda spark ignition engine has been collected by N.A.S.A. to allow a calibration of the computer model developed in this research effort.

1.4 DESCRIPTION OF PROJECT TASKS

1.4.1 DEFINITION OF TASKS

An extant quasi-dimensional model of a reciprocating engine was used as a starting point for the Wankel engine simulation (8). Figure 4 is a flow chart that illustrates the deletions and additions necessary for the conversion. There were five major steps necessary for the conversion process:

a) change in geometry
b) removal of turbulent combustion model
c) addition of leakage model
d) addition of crevice volume model
e) change in heat transfer model

1.4.2 OUTLINE OF CODE

The four engine processes, intake, compression, combustion-expansion, and exhaust are separated into different subroutines (Fig. 5). The Main program controls, through ODERT (a numerical integrator) the program flow. That is, Main decides when each engine process begins and ends or what, if any, numerical data should be outputted.

The program begins by supplying Main the required input data. A calculation is then performed to initialize the thermodynamic state of the chamber gas at the beginning of the intake process, which is defined as the point where the intake port begins to open. The intake routine is then called by ODERT. Intake calls other subroutines where, for a given crank angle the working fluid thermodynamic properties are evaluated, and the direction, composition, and magnitude of mass flow rates through the intake and exhaust ports or valves are computed. The heat transfer rate is then calculated as is the rate of change of chamber volume. Next, leakage and crevice volume mass flow rates are calculated. Finally, Intake has enough information to evaluate the rates of change of pressure, temperature, work, heat transfer, and mass flow. The program control returns to ODERT which integrates the differential variables through time (crank angles) until program flow returns to Main. This interaction between Main and ODERT is repeated until each engine process is finished and the cycle is completed. The final values of chamber pressure, temperature, and mass are compared to the initialized values and if each property is within the error criteria the calculation ends. However, if these criteria are not met, the program begins again with the final property values used as the initial quantities for the second iteration. Convergence occurs quickly, usually requiring three, or at most four iterations.

This segmented style of programming along with good documentation of the code is vital for any lengthy program such as this. This particular code allows end users to quickly find necessary information, and also great flexibility for logic changes similar to those described already.

1.4.3 CHANGE IN GEOMETRY

A major program alteration was the change in the simulation code required to reflect the different engine geometry. Most of these changes were in the geometry subroutine CSAVDV where chamber surface area, volume, and rate of change of volume expressions are evaluated. Other changes were required in the subroutines that evaluate valve open areas and discharge coefficients to reflect the use of ports rather than valves. The Main program also needed to be modified to account for the extra crankshaft revolution per chamber cycle. The geometric equations developed in the texts by Ansdale and Yamamoto were used to define the engine geometry (10&11).

1.4.4 COMBUSTION ROUTINE CHANGES

In order to run a firing case for the rotary engine the combustion subroutine required some minor modifications. A turbulent entrainment combustion model was included in the reciprocating engine simulation that was specific to that geometry. A specified burn rate combustion model was also included as an option. The turbulent entrainment model was removed and therefore the combustion routine required a specified burn rate input in order to operate. In the resulting program the combustion chamber is modeled with two zones; one each for the cool unburned charge and hot burned products (Fig. 6). The NO formation model was also removed.

1.4.5 ADDITION OF GAS LEAKAGE MODEL

The importance of gas leakage as a performance and emissions mechanism in the Wankel is well known. It is crucial, then, to model this mass transfer between adjacent chambers in order to quantify its effect on performance and measure its relative effect vis-a-vis heat transfer and crevice volumes. The leakage and crevice volume models were combined to reduce complications. The implementation and physical justification of this assumption are described in the next section.

1.4.6 ADDITION OF CREVICE VOLUME MODEL

It has been hypothesized that crevice volume effects could be significant not only as a source of hydrocarbon emissions, but also as a mechanism for performance loss. Engine crevices are small volumes associated with gas seals and spark plugs that are connected to the chamber. As chamber pressure rises, working fluid is forced into these crevices which then re-enters the chamber as this pressure falls. Since crevice volumes have a high surface-to-volume ratio, the gas entering the crevice is cooled and the combustion reactions are quenched in these regions.

A subroutine which calculates the leakage and crevice mass flow rates was added to the program. Since the addition of the model makes the chamber an open thermodynamic system throughout the cycle, rather than just during intake and exhaust, the final differential equations governing chamber pressure, temperature, and composition were changed and evaluated within this subroutine. Also in order to evaluate the composition, direction, and magnitude of the crevice and leakage mass flow rates, a history of adjacent chamber pressures and crevice compositions versus crank angle was required. As this cycle pressure history does not exist during the first cycle iteration, the crevice and leakage models are not activated until the second iteration.

1.4.7 CHANGES TO HEAT TRANSFER MODEL

An important concern regarding the Wankel rotary engine has been its high rate of heat transfer. During the combustion process the surface-to-volume ratio of the combustion chamber is higher than in equivalent reciprocating engines (Fig. 7). The charge is also swept along, by the rotor motion, at high velocities which naturally increases the heat transfer to the walls. Obviously a heat transfer model is required to predict engine performance and evaluate the effect of insulating ceramic materials.

2.0 COMPUTER MODEL

2.1 BACKGROUND

Computer models of internal combustion engines can be grouped into three general classifications: zero-dimensional models, quasi-dimensional models, and multidimensional models. Zero-dimensional models use the First Law of Thermodynamics and a specified combustion rate to predict engine operating characteristics. Quasi-dimensional models add a turbulent combustion submodel to predict the burning rate which requires an assumption about flame front shape. Multidimensional models use the conservation equations for mass, energy, momentum and species to predict the flame propagation through the combustion chamber (12).

The research work presented here has used a zero-dimensional model for several reasons. Multi-dimensional models are currently restricted by available computing power to only two dimensional analyses. They are consequently not yet suitable for this application. Also, it was felt that although the initial test data would be from a spark ignition engine, the final goal of the simulation program was the study of a stratified charge plant. Thus, the implementation of a pre-mixed turbulent combustion model, such as the model present in the reciprocating engine simulation was not considered worthwhile.

The model will be able to predict the engine size required for a given task. Parametric studies can then be performed in order to judge the relative merits of different research efforts. For example, questions concerning the importance of reducing heat loss, crevice volumes, and leakage can be addressed.

2.2 CALCULATION OF THERMODYNAMIC PROPERTIES

2.2.1 SIMULATION FRAMEWORK AND BASIC ASSUMPTIONS

The simulation is separated into four distinct but sequential processes: intake, compression, combustion (and expansion), and exhaust. Intake starts as the intake ports begin to open (IPO) and continues until they are completely closed (IPC). The compression process begins at IPC and ends at the spark ignition point (TSPARK). The combustion process is initiated with the occurrence of the spark and continues through expansion until the exhaust port begins to open (EPO). The exhaust process occurs from this point until the intake ports start to open once again (not EVC). The cycle lasts exactly 1080 crank angle degrees.

To solve the differential form of the First Law equation for the chamber contents some basic assumptions must be made. Except during combustion, the chamber contents are assumed to be an homogeneous mixture of non-reacting ideal gases. Therefore the contents have a single mean temperature. During intake and compression chamber contents are characterized as a mixture of fresh charge (air and fuel vapor) and residual burned gas. The intake and exhaust manifolds are assumed to have constant temperatures and pressures. During exhaust only burned product is assumed to be present in the chamber. Unburned gas that leaks into the exhaust chamber is treated as burned product and the amount of fuel energy lost is accounted for. During combustion two zones are created, one each for the unburned gas and the burned product. Each zone is assumed to be homogeneous i.e. of uniform temperature and composition. It is assumed that there are no pressure waves within the chamber so gas pressure is constant throughout the chamber.

2.2.2 SOLUTION OF THERMODYNAMIC EQUATIONS WITHOUT CREVICE VOLUME

In this section the method for generating differential equations to find the thermodynamic state of the chamber's contents is briefly outlined. To be useful the final equation must evaluate the rate of temperature change independently of the rate of change of chamber pressure.

The First Law of Thermodynamics for an open system, in differential form, is:

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

Note that heat loss from the system is positive. From the definition of internal energy:

$$\dot{E} = \frac{d(mh - pV)}{dt} = \dot{m}h + m\dot{h} - \dot{p}V - p\dot{V} \tag{2.2}$$

where;

m : mass

h : enthalpy

p : pressure

v : volume

The First Law equation can be rewritten as:

$$m\dot{h} = \dot{Q}_w - h\Sigma(\dot{m}_j) + \Sigma(\dot{m}_j h_j) + V\dot{p} \tag{2.3}$$

During intake, chamber composition changes as fresh charge is added to the fresh charge/residual gas mixture already present. If fresh charge and residual gas are taken to be the two ideal gas components making up the mixture the change in enthalpy can be expressed as:

$$\dot{h} = \frac{d(x_1h_1 + x_2h_2)}{dt} = \dot{x}_1h_1 + x_1\dot{h}_1 + \dot{x}_2h_2 + x_2\dot{h}_2 \qquad (2.4)$$

Where:

x_i : mass fraction of component i

$i = 1$: refers to fresh charge

$i = 2$: refers to residual gas

$$x_1 + x_2 = 1 \qquad (2.5)$$

Differentiating equation 2.5 yields:

$$\dot{x}_1 = - \dot{x}_2 \qquad (2.6)$$

Substituting this last relationship into equation 2.4 gives:

$$\dot{h} = \dot{x}_1(h_1 - h_2) + x_1\dot{h}_1 + x_2\dot{h}_2 \qquad (2.7)$$

The change in enthalpy for each component can be expressed as changes in the system temperature and pressure:

$$\dot{h}_i = c_{p_i}\dot{T} + c_{T_i}\dot{p} \qquad (2.8)$$

Where:

$$c_p \equiv (\partial h / \partial T)_p \qquad (2.9)$$

$$c_T \equiv (\partial h / \partial p)_T \qquad (2.10)$$

From the ideal gas law :

$$\rho = \frac{p}{R\ T} \tag{2.11}$$

So, differentiating both sides gives:

$$\frac{d\rho}{dt} = \dot{\rho} = (\partial\rho/\partial p)\dot{p} + (\partial\rho/\partial R)\dot{R} + (\partial\rho/\partial T)\dot{T} \tag{2.12}$$

Rearranging equation 2.12 provides a differential equation for pressure in terms of rates of change of density, temperature, and the gas constant:

$$\dot{p} = \frac{\rho}{(\partial\rho/\partial p)} = \left[\ \frac{\dot{\rho}}{\rho} - \frac{\dot{R}}{\rho}(\partial\rho/\partial R) - \frac{\dot{T}}{\rho}(\partial\rho/\partial T)\ \right] \tag{2.13}$$

Referring to equation 2.11 it can be shown that:

$$(\partial\rho/\partial R) = -\frac{\rho}{R} \tag{2.14}$$

From the definition of density:

$$\rho = \frac{m}{V} \tag{2.15}$$

it is apparent that:

$$\frac{\dot{\rho}}{\rho} = \frac{\dot{m}}{m} + \frac{\dot{V}}{V} \tag{2.16}$$

The rate of change of the gas constant is:

$$\dot{R} = \frac{d(x_1R_1 + x_2R_2)}{dt} = \dot{x}_1R_1 + \dot{x}_2R_2 = \dot{x}_1(R_1 - R_2) \tag{2.17}$$

Combining equations 2.13 through 2.17 results in:

$$\dot{p} = \frac{\rho}{(\partial\rho/\partial p)} \left[\left(\frac{R_1 - R_2}{R} \right) \dot{x}_1 + \frac{\dot{m}}{m} - \frac{\dot{V}}{V} - \frac{\partial\rho}{\partial T} \frac{\dot{T}}{\rho} \right] \tag{2.18}$$

Finally substitution of equations (2.2), (2.4), (2.7), (2.8) and(2.18) into the energy equation (2.1) gives an equation for temperature independent of the unknown rate of change of pressure:

$$\dot{T} = \frac{B}{A} \left[\dot{x}_1 \left(\frac{R_1 - R_2}{R} + \frac{h_2 - h_1}{B} \right) + \frac{\dot{m}}{m}\left(1 - \frac{h}{B}\right) - \frac{\dot{V}}{V} + \frac{1}{mB} \left(\sum m_j h_j - \dot{Q} \right) \right] \tag{2.19}$$

Where:

$$A = C_p + \frac{(\partial\rho/\partial T)_p}{(\partial\rho/\partial p)_T} \left(\frac{1}{\rho} - C_T \right) \tag{2.20}$$

$$B = \frac{(1 - \rho C_T)}{(\partial\rho/\partial p)_T} \tag{2.21}$$

$$C_p = x_1 C_{p_1} + x_2 C_{p_2} \tag{2.22a}$$

$$C_T = x_1 C_{T_2} + x_2 C_{T_2} \tag{2.22b}$$

However, equation 2.18 assumes that the rate of mass flow into or out of the chamber is independent of the rate of change of pressure. This is not a valid assumption if a crevice volume is present within the chamber. The thermodynamic implications of the crevice volume model are discussed in Chapter 3.

2.3 ENGINE PROCESS MODELS

2.3.1 INTAKE AND EXHAUST FLOW PROCESSES

A quasi-steady compressible flow model is used to evaluate the mass exchange between the chamber and intake or exhaust manifolds. The manifolds are considered to be infinite plenums with specified pressure, i.e. manifold pipe dynamics are not modeled. The intake gas is a mixture of fresh charge (fuel-air mixture) and recirculated exhaust gas (EGR). If back flow occurs chamber contents are sent back to the intake manifold but are not mixed with the intake charge (a plug flow assumption). Instead, if flow reverses again, all the back mass is assumed to return to the chamber before any additional intake charge enters the chamber. However, at IPO, only intake charge is present in the manifold. Gas in the exhaust manifold is assumed to be completely burned products of combustion at the instantaneous chamber temperature.

The port open areas are determined by assuming that the ports open linearly with crank angle. The discharge coefficients are assumed constant as a function of pressure ratio and equal to 0.75. This value was based on data from two-stroke diesel engines (13). With open area, coefficient of discharge, and the pressure ratio across the port known, the mass flow rate can be calculated from:

$$\dot{m} = C_d A \frac{P_o}{RT_o} \sqrt{\gamma R T_o} \left\{ \frac{2}{\gamma - 1} \left[\left(\frac{P_s}{P_o}\right)^{2/\gamma} - \left(\frac{P_s}{P_o}\right)^{(\gamma+1)/\gamma} \right] \right\} \qquad (2.23)$$

where:

C_d : coefficient of discharge

A : port open area

p_o : upstream stagnation pressure

p_s : static pressure at restriction

T_o : upstream stagnation temperature

γ : ratio of specific heats

R : gas constant

For choked flow the equation is:

$$\dot{m} = C_d A \frac{p_o}{RT_o} A \sqrt{\gamma R T_o} \left(\frac{2}{\gamma + 1} \right)^{(\gamma+1)/2(\gamma-1)} \qquad (2.24)$$

The sign convention adhered to in the model is as follows: intake flow into the chamber is positive and exhaust flow out of the chamber is also positive.

2.3.2 COMBUSTION

During combustion the chamber is divided into two zones. The first containing unburned mixture, the second composed of combustion products. Mass is transferred from the unburned zone to the burned zone according to a specified equation for the mass fraction burned. The equation is of the form proposed by Wiebe (14).

$$x_b = 1 - e^{-a[(\theta - \theta_o)/\Delta\theta_b]^{m+1}} \qquad (2.25)$$

where:

x = mass fraction burned in chamber

a = efficiency parameter

m = form factor

Θ = crank angle

Θ_0 = start of combustion (not spark timing)

$\Delta\Theta_b$ = burn duration

The form factor and efficiency parameter in equation (2.25) are inputs to the program. These constants generally fall between:

$$1 < m < 3 \qquad (2.26a)$$

$$3 < a < 10 \qquad (2.26b)$$

for real engines (15). For a closed system differentiation of Eq. 2.25 would define the rate of combustion. However, with the presence of leakage and crevice volume mass flows, the system is open during combustion and the combustion rate should reflect this change. The combustion rate equation is derived in Chapter 3.

2.3.3 HEAT TRANSFER

Heat transfer in the Wankel rotary engine is a major source of concern. Most heat transfer in an internal combustion engine occurs during the combustion and the expansion stroke. The shape of this engine's combustion chamber, which has a high surface area to volume ratio, leads one to expect high heat transfer rates near the top dead center position. Also since the charge is pushed at high velocities past the housing walls even higher heat transfer rates can be expected. The general area of heat transfer from internal combustion engines is lacking in quantitative equations to describe the phenomenon, and experimental data is necessary to calibrate the model. This is especially difficult for the Wankel engine where little heat transfer data has been published.

The analysis starts with the general forced convective heat transfer equation:

$$Nu = \alpha \, Re^{a} \, Pr^{b} \qquad (2.27)$$

where;

$Nu \equiv hL/k$: Nusselt number

$Re \equiv VL/\nu$: Reynolds number

$Pr \equiv \mu C_p/k$: Prandtl number

α : constant

a : constant

b : constant

h : heat transfer coefficient

L : characteristic length

k : thermal conductivity of fluid

V : characteristic velocity

ν : kinematic viscosity

μ : dynamic viscosity

C_p: specific heat at constant pressure

The Prandtl number is assumed to be unity. The flow pattern is assumed to be similar to that of forced convection over a flat plate. This provides values for the constants in Eq. 2.27 of (16).

$\alpha = 0.037$

$a = 0.8$

In reciprocating engines the cylinder bore is used as the characteristic dimension. In the Wankel an equivalent dimension to the bore is the housing depth. These dimensions are similar in that both are constant throughout the cycle and perpendicular to the primary component of the flow. The last piece of information needed to solve Eq. 2.27 for the heat transfer coefficient is the characteristic gas velocity.

The model uses the approach originally suggested by Woshni, i.e. a velocity composed of two parts (17). The first component velocity is proportional to the mean rotor velocity in the Wankel engine, which turns at one third the crank shaft speed:

$$V_{\text{non-firing}} = \left(\frac{2\pi}{60}\right)\left(\frac{RPM}{3}\right) R \qquad (2.28)$$

The second velocity component is proportional to the combustion intensity. Woschni believed that the rapid expansion of the burning charge caused large velocities within the chamber. The combustion intensity is characterized by the difference in chamber pressure between a firing case and a non-firing case at the same crank angle. A term is added to account for the amount of fuel inducted which affects the pressure trace.

$$V_{\text{fire}} = C_1 V_{\substack{\text{non-}\\\text{fire}}} + C_2 V_s \left(\frac{T}{pV}\right)_{IPC} \left(p - p_{\substack{\text{non-}\\\text{fire}}}\right) \qquad (2.29)$$

Where:

V_s : chamber volume

T_{IPC} : chamber temperature at intake port close

p_{IPC} : chamber pressure at intake port close

V_{IPC} : chamber volume at intake port close

Woschni found that for diesel engines a value for C_2 of .00324 (m / sec K) correctly accounted for the increased heat transfer during combustion. Danieli used a value of unity for the non-firing velocity constant (18). These data were used as starting points for the calibration of the heat transfer model.

In order to evaluate the heat transfer the chamber surface area must be calculated:

$$\dot{Q} = h\, A\, (T - T_{wall}) \qquad (2.30)$$

During combustion heat is transferred from both zones so chamber surface areas for each zone need to be defined.

$$Q = h\, A_u\, (T_u - T_{wall}) + h\, A_b\, (T_b - T_{wall}) \qquad (2.31)$$

The rotor surface area is constant throughout the cycle and is approximated by a circular arc :

$$A_{rotor} = 2\, R_x\, \beta\, b \qquad (2.32)$$

Where:

$$R_x = \frac{R^2 - 2eR + 4e^2}{R - 4e}$$: Radius of circular arc approximation

$$\beta = \arctan\left[\frac{\sqrt{3R}}{\left(\frac{6eR}{R - 4e}\right) + R + 2e} \right]$$:One half the angle subtended by the approximate circular arc

It is assumed that the rotor cutout adds negligible surface area. The side plate surface is calculated during the volume calculation and is :

$$A_{side} = 2V / \text{depth} \tag{2.33}$$

To find the exact housing surface area would require a double integration. It was decided instead to follow Danieli's approach by devising a rectangular box of the same volume as the chamber (Fig. 8). From this the housing area is approximated as:

$$\begin{aligned} A_{housing} &= A - A_{rotor} - 2\,A_{side} \\ &= 2\frac{V}{2} + bL + C \end{aligned} \tag{2.34}$$

Where :

$A = 2(\frac{V}{b} + \frac{V}{L} + bL) + C$: Total surface area

$L = 2\,R_x\,\beta$: Arc length of rotor face

C : A correction factor

During combustion the following approximation is used to divide the individual surface areas between the burned and unburned zones :

$$\frac{A_b}{A_u} = \left(\frac{V_b}{V_u}\right)^{2/3} \tag{2.35}$$

2.3.4 LEAKAGE

Leakage past the apex and side seals is a major problem for the Wankel engine. It has been estimated that side seal leakage accounts for one quarter to as much as one third of the total leakage mass flow (19). Previous computer models have neglected side seal leakage and modeled apex seal leakage only (20&21). These models have assumed that leakage during combustion is composed of unburned gas alone, while at the end of combustion only burned product is leaked. This results from the assumption of a linearly propagating flame front, which implies that the apices do not "see" burned gas until combustion is complete (Fig. 9). These models have also used the overall chamber or zone (during combustion) temperature as the upstream temperature.

It was felt that some effort should be made to model the significant leakage past the side seals. The gas that passes the side seals enters the volume between the oil seals, rotor side, side plate, and side seals (Fig. 10). This mass then enters the side intake ports as the rotor passes over them and so indirectly enters the intake chamber.

By using bulk gas temperatures, previous models may have overestimated the size of the leakage areas . Gas leaking past the apex seals comes from areas with high surface to volume ratios where large gas velocities are believed to exist due to: rotor rotation, vortices set up by the apex seals, and the "squish" of the rotor against the housing. This large surface area and high gas velocity indicates that the leakage mass is likely to be relatively cool and could even approach the wall temperature. Mass that leaks past the side seal must reside in the small clearance volume formed by the rotor side, side seal, and side plate prior to passing the side seal. Again, because of a high surface-to-volume ratio the leakage gas should be relatively cool.

2.3.5 CREVICE VOLUME

Much previous work has concentrated on the effect of crevice volumes on hydrocarbon emissions from spark ignition engines (22). It is now becoming apparent that crevices could also be an important source of performance loss in internal combustion engines. This performance loss is caused by the heat lost from hot combustion products as they enter the crevices and the removal of charge during the useful portion of the cycle.

A brief description of the crevice volume model along with major implications for the cycle simulation program is provided in this section. A more thorough investigation of crevice volumes is given in Chapter 3 .

The leakage and crevice volume models were linked together for two major reasons. First the belief that leakage gas is cooled prior to its transmission from one chamber to the next suggests the use of the crevice temperature as the upstream temperature to reduce the number of independent parameters. Secondly in the Wankel, major crevice volumes and leakage sites occur at the same locations. That is, significant crevice volumes are found in the Wankel adjacent to the side and apex seals .

3.0 CREVICE AND LEAKAGE MODEL

This chapter presents the assumptions made in the model for the analysis of the effects of leakage and crevice volume on engine performance. Engine geometric data is analyzed that suggests crevice volumes in the Wankel are possibly significant factors in performance degradation. The model is then presented and the thermodynamic equations for the open system are derived. Finally, some of the programming considerations for implementing the submodel are discussed.

3.1 CREVICE LOCATIONS AND LEAKAGE POINTS

The author investigated the locations and relative sizes of crevice volumes by taking measurements from a Mazda model (12B) RX-4 engine. The engine was, of course, cold at the time so the absolute magnitude of the crevice volumes should not be considered as final values during operation, as thermal expansion will affect clearances. The major crevices were around the apex seals and side seals; other smaller volumes were associated with spark plugs and transducers (Fig. 11). In typical reciprocating engines the total crevice volume is 3% of the clearance volume and as much as 10% of the cylinder mass is pushed into the crevice at peak pressure. The total measured crevice volume on the Wankel engine was 5% of the clearance volume so a proportionately larger effect should be expected. Table 3 presents the measured and estimated sizes of all the crevices in the rotary engine. It should be noted that the volume associated with the side seal lands and side seals is approximately one half that of the volume behind the apex seals and below the corner seals. This is precisely the same ratio as between apex seal leakage and side seal leakage in the Wankel previously reported.

By ignoring side seal leakage and heat transfer from the leakage gas, leakage areas may have been overestimated in previous models and some effort should be expended to model these effects. After all, one third of the total leakage is significant. The primary difference between the apex and side seal leakage paths is that the side seal will "see" burned gas during combustion in proportion to the surface area "wetted" by the burned gas volume. A secondary difference is the indirect leakage path from the side seal to the rotor side, to the side intake port, and finally to the intake chamber. Therefore, most of the side seal leakage ends up in the intake chamber and not distributed evenly between the leading and trailing chambers as is the case for apex leakage.

3.2 OPTIONS

Figure 12 shows a schematic of a model that includes each leakage path and crevice volume explicitly. This model would be far too complex for the purpose at hand. Separate temperatures, areas, volumes, and compositions leave a virtually unlimited combination of crevice volumes and leakage paths. Most of these combinations are too complex to successfully calibrate with available data (Fig. 13).

The chosen model uses two crevices and two leakage areas per chamber located at each apex seal (Fig. 14). To account for the effect of burned gas entering the side seal crevices, the composition of gas entering the modeled crevices is related to the mass fraction burned, not the volume fraction burned, to grossly account for the relative size of the side crevices.

To account for side seal leakage, the mass composition of the leaked gas is taken to be equal to the crevice composition. In effect, the model implies that leakage occurs directly from the crevice, to the adjacent chamber, which is probably not true at the apex seal. This is not a large error until the end of combustion when too much unburned gas may start to leak out. However, complete combustion is characterized by a falling chamber pressure and hence a return of crevice mass into the chamber adjacent to the apex seal. It can be reasonably expected, therefore, that the crevice gas which returns, leaves the chamber immediately, via the direct leakage path (Fig.15). Leakage occuring from the crevices allows for the transmission of burned product as well as unburned mixture throughout the cycle.

The performance loss caused by crevice volumes is due to the large amount of heat transfered to the engine components and the removal of charge from the combustion chamber. Leakage reduces power by decreasing volumetric efficiency (real and effective), and by allowing unburned fuel energy and sensible enthalpy to escape. Real volumetric efficiency is decreased by burned product entering the induction chamber from the adjacent combustion and exhaust chambers. Effective volumetric efficiency is decreased as charge escapes from the compression chamber to the exhaust and intake chambers prior to combustion. The assumptions made by the leakage and crevice volume model are listed below.

a) Constant leakage area at apex seals. Side leakage effects are modelled implicitly.

b) Quasi one-dimensional isentropic leakage flow.

c) Leakage composition and temperature is equal to the crevice composition and temperature.

d) Crevices modeled at apex seals only. Side crevice effects are lumped into apex crevice volumes.

e) A crevice has constant volume and gas temperature.

f) Crevice gas pressure is equal to chamber pressure.

g) Only one crevice exists per apex seal. The crevice is associated with the chamber at higher pressure and assumes that pressure.

h) The composition of gas entering the crevice is assumed to equal the mass fraction burned in order to account for burned gas that enters side crevices.

i) For computational simplicity burned and unburned gas are perfectly mixed in the crevice but return to their respective zones when they re-enter the chamber.

As there is only one crevice per apex seal the program must be capable of deciding which of the two adjacent chambers contains the crevice. In this model, it is postulated that the crevice is located behind the apex seal and that the crevice is associated with the chamber at higher pressure. If the pressure difference across the apex seal reverses, the seal moves across its seat and the crevice is again associated with the chamber at higher pressure (Fig. 16). A table of chamber pressure versus crank angle is stored within the program, enabling evaluation of the pressure difference across each apex seal to determine crevice location and leakage direction. Since the pressure history is not constructed until the first cycle is completed the leakage and crevice volume models are not activated until the second iteration begins.

At crank angles where pressure is low gas, leaks into the system from the leading and trailing chambers. To determine the composition of this flow the crevice composition is stored in the same manner as chamber pressure, and is used to assign composition to the leakage flows entering the system in the next iteration. Over the first cycle iteration this information is not available so initial values are assumed at the start of the second iteration.

It should be noted that the program sets the leakage composition equal to the mass fraction unburned , which allows the program to operate if the crevice volume is set equal to zero. A variable was added to account for the fuel energy that escapes unburned to the exhausting chamber.

3.3 THERMODYNAMIC EQUATIONS OF CREVICE VOLUME AND LEAKAGE MODEL

The final thermodynamic equations of Chapter 2 (Eqs. 2.18 and 2.19) assumed that all mass flows are independent of changes in system pressure. This is clearly not the case when crevice volumes are present. The driving force for mass flow into or out of the crevice is a change in chamber pressure. Figure 17 shows the thermodynamic system boundary superimposed on the crevice and leakage model schematic. It should be noted that the system only contains the chamber and not the crevice volumes themselves. Positive direction flows are as shown for each mass flux. The perfect gas equation applied to a crevice volume holds that:

$$m_{crevice} = \left(\frac{pV}{RT} \right)_{crevice} = p \left(\frac{V}{RT} \right)_{crevice} \qquad (3.1)$$

Since crevice volume and temperature are constant, differentiating both sides of equation 3.1 yields:

$$\left(\frac{\dot{m}}{m} \right) = \frac{\dot{p}}{p} - \left(\frac{\dot{R}}{R} \right)_{crevice} \qquad (3.2)$$

If the rate of change of the gas constant is assumed to be negligible Eq. 3.2 reduces to:

$$\dot{m}_{crevice} = \frac{\dot{p}}{p} m_{crevice} \tag{3.3}$$

The total mass flow into the chamber is then defined as:

$$\dot{m} = \sum \dot{m}_j = \dot{m}_{intake} - \dot{m}_{exhaust} - (\dot{m}^{lead} + \dot{m}^{lag})_{leakage} - (\dot{m}^{lead} + \dot{m}^{lag})_{crevice} \tag{3.4}$$

Substituting equation 3.3 in for the crevice flow terms of the last equation yield:

$$\dot{m} = \dot{m}_{in} - \dot{m}_{ex} - (\dot{m}^{lead} + \dot{m}^{lag})_{leak} - \frac{\dot{p}}{p}(m^{lead} + m^{lag})_{crev} \tag{3.5}$$

An equivalent expression for the mass flow is:

$$\dot{m} = d^* - c^* \dot{p} \tag{3.6}$$

Where:

$$d^* = \dot{m}_{in} - \dot{m}_{ex} - (\dot{m}^{lead} + \dot{m}^{lag})_{leak} \tag{3.7a}$$

$$c^* = \frac{1}{p}(m^{lead} + m^{lag})_{crev} \tag{3.7b}$$

The mass fraction of fresh charge is defined as:

$$x_1 \equiv \frac{m_1}{m} \tag{3.8}$$

Differentiating both sides gives:

$$\frac{\dot{x}_1}{x_1} = \frac{\dot{m}_1}{m_1} - \frac{\dot{m}}{m} = \frac{\dot{m}_1 - \dot{m} x_1}{m x_1} \qquad (3.9)$$

Therefore:

$$\dot{x}_1 = \frac{\dot{m}_1 - \dot{m} x_1}{m} \qquad (3.10)$$

The mass flow of fresh charge entering the system is :

$$\dot{m}_1 = \Sigma\, \dot{m}_j x_{1_j} \qquad (3.11)$$

where :

x_{1j} = Mass fraction of fresh charge in the jth flow.

$$\begin{aligned} m_1 = {} & (mx_1)_{in} - (mx_1)_{ex} - [\, (m_{leak} + m_{crev})\, x_1^{lead} \,] \\ & - [\, (\dot{m}_{leak} + \dot{m}_{crev})\, x_1^{lead} \,] \end{aligned} \qquad (3.12)$$

Recalling that exhaust manifold flow is assumed to be fully burned, the rate of change of mass fraction fresh charge can be expressed as :

$$\begin{aligned} \dot{x}_1 = \frac{1}{m} [\, & \dot{m}_{in}(x_1^{in} - x_1) - \dot{m}_{leak}^{lead}(x_1^{lead} - x_1) - \\ & \dot{m}_{leak}^{lag}(x_1^{lag} - x_1) - \frac{\dot{p}}{p} m_{crev}^{lead}(x_1^{lead} - x_1) \\ & - \frac{\dot{p}}{p} m_{crev}^{lag}(x_1^{lag} - x_1) \end{aligned} \qquad (3.13)$$

Alternatively :

$$\dot{x}_1 = a^* - b^* \dot{p} \qquad (3.14)$$

where :

$$a^* = \frac{1}{m}\left[m_{in}(x_1^{in} - x_1) - \dot{m}_{leak}^{lead}(x_1^{lead} - x_1) - \dot{m}_{leak}^{lag}(x_1^{lag} - x_1)\right] \quad (3.15a)$$

$$b^* = \frac{1}{pm}\left[m_{crev}^{lead}(x_1^{lead} - x_1) + m_{crev}^{lag}(x_1^{lag} - x_1) \right] \quad (3.15b)$$

Eq. 2.18 is rewritten here in order to make the changes due to crevice volumes clear.

$$\dot{P} = \frac{\rho}{(\partial\rho/\partial p)}\left[\left(\frac{R_1 - R_2}{R}\right)\dot{x}_1 + \frac{\dot{m}}{m} - \frac{\dot{V}}{V} - \left(\frac{\partial\rho}{\partial T}\right)\frac{\dot{T}}{\rho} \right] \quad (3.16)$$

We have seen that $\dot{x}_1$ and $\dot{m}$ are dependent on $\dot{p}$, so:

$$\dot{p} = \frac{\rho}{(\partial\rho/\partial p)}\left[\left(\frac{R_1 - R_2}{R}\right)(a^* - b^*\dot{p}) + \left(\frac{d^* - c^*\dot{p}}{m}\right) - \frac{\dot{V}}{V} - \frac{\dot{T}}{\rho}\frac{\partial\rho}{\partial T} \right] \quad (3.17)$$

Factoring all the p terms to the left hand side gives:

$$p = \left[\frac{1}{\dfrac{(\partial\rho/\partial\rho)}{\rho} + b^*\dfrac{R_1 - R_2}{R} + \dfrac{c^*}{m}} \right] \left[\left(\frac{R_1 - R_2}{R}\right)a^* - \frac{\dot{V}}{V} - \frac{\dot{T}}{\rho}\frac{\partial\rho}{\partial T} + \frac{d^*}{m} \right] \quad (3.18)$$

Giving the first term a separate variable name shortens the equation:

$$\dot{p} = z^*\left[\left(\frac{R_1 - R_2}{R}\right)a^* - \frac{\dot{V}}{V} - \frac{T}{\rho}\frac{\partial\rho}{\partial T} + \frac{d^*}{m} \right] \quad (3.19)$$

where:

$$z^* = \left[\frac{1}{\dfrac{(\partial\rho/\partial p)}{\rho} + b^*\left(\dfrac{R_1 - R_2}{R}\right) + \dfrac{c^*}{m}} \right] \tag{3.20}$$

The enthalpy flux into the chamber can be written as:

$$\sum \dot{m}_j h_j = (\dot{m}h)_{in} - (\dot{m}h)_{ex} - (\dot{m}_{leak}h)^{lead} - (\dot{m}_{leak}h)^{lag} - (\dot{m}_{crev}h)^{lead} - (\dot{m}_{crev}h)^{lag} \tag{3.21a}$$

$$= (\dot{m}h)_{in} - (\dot{m}h)_{ex} - (\dot{m}_{leak}h)^{lead} - (\dot{m}_{leak}h)^{lag} - \frac{\dot{p}}{p}\left[(m_{crev}h)^{lead} + (m_{crev}h)^{lag} \right] \tag{3.21b}$$

$$= e^* - f^*\dot{p} \tag{3.21c}$$

where:

$$e^* = (\dot{m}h)_{in} - (\dot{m}h)_{ex} - (\dot{m}_{leak}h)^{lead} - (\dot{m}_{leak}h)^{lag} \tag{3.22a}$$

$$f^* = \frac{1}{p}\left[(m_{crev}h)^{lead} + (m_{crev}h)^{lag} \right]$$

Recalling the First Law expression of Eq. 2.3 rewritten here:

$$m\dot{h} = -\dot{Q}_w - h\sum \dot{m}_j + \sum \dot{m}_j h_j + V\dot{p} \tag{3.23}$$

Using the definitions of the dummy variables defined in Eqs. (3.15a), (3.15b), (3.20), (3.22a), and (3.22b) the energy balance is:

$$m\{ (h_1 - h_2)a^* + [c_T - b^*(h_1 - h_2)]\dot{p} + c_p\dot{T} \} = -Q_w - h(d^* - c^*p) + e^* - f^*p + Vp \tag{3.24}$$

An expression for the rate of change of temperature is found to be:

$$\dot{T} = \frac{1}{mc_p}\{ \dot{p} [V - f^* + hc^* + mb^*(h_1 - h_2) - c_T m] - ma^*(h_1 - h_2) - hd^* + e^* - \dot{Q}_w \qquad (3.25)$$

Substituting Eq. 3.19, derived from the perfect gas equation of state, into the last equation yields:

$$T = \frac{1}{mc_p}\{ z^* [(\frac{R_1 - R_2}{R})a^* - \frac{\dot{V}}{V} - \frac{\dot{T}}{\rho}\frac{\partial \rho}{\partial T} + \frac{d^*}{m}] [V - f^* + hc^* + mb^*(h_1 - h_2) - cT_m] - ma^*(h_1 - h_2) - hd^* + e^* - \dot{Q}_w \} \qquad (3.26a)$$

$$T = [\frac{1}{mc_p + (\frac{w^*z^*}{\rho})(\partial \rho/\partial T)}] \{ w^*z^* [(\frac{R_1 - R_2}{R})a^* - \frac{\dot{V}}{V} + \frac{d^*}{m}] - ma^*(h_1 - h_2) - hd^* + e^* - \dot{Q}_w \} \qquad (3.26b)$$

where:

$$w^* = V - f^* + hc^* + mb^*(h_1 - h_2) - c_T m \qquad (3.27)$$

Equation 3.26b is valid for intake, compression and exhaust. During the combustion-expansion phase two separate zones are hypothesized and each has an individual gas temperature. The First Law for a system with no compositional variation shows:

$$m\dot{h} = mc_p\dot{T} + mc_T\dot{p} = -\dot{Q}_w - h\sum\dot{m}_j + \sum(\dot{m}_j h_j) + V\dot{p} \qquad (3.28)$$

Since only ideal gases are considered, the specific heat at constant temperature term is zero. The unburned and burned zone temperatures may be written as:

$$\dot{T}_u = \frac{1}{m_u c_{p_u}} \left[\sum(\dot{m}_j h_j)_u - h_u \sum(\dot{m}_j)_u + V_u \dot{p} - \dot{Q}_u \right] \tag{3.29a}$$

$$\dot{T}_b = \frac{1}{m_b c_{p_b}} \left[\sum(\dot{m}_j h_j)_b - h_b \sum(\dot{m}_j)_b + V_b \dot{p} - \dot{Q}_b \right] \tag{3.29b}$$

From the definition of density:

$$V = \frac{m}{\rho} \tag{3.30}$$

We have:

$$\frac{\dot{V}}{V} = \frac{\dot{m}}{m} - \frac{\dot{\rho}}{\rho} = \frac{\dot{m}}{m} - \frac{1}{\rho} \left[\left(\frac{\partial \rho}{\partial T}\right) \dot{T} + \left(\frac{\partial \rho}{\partial p}\right) \dot{p} \right] \tag{3.31}$$

So for each zone we have:

$$\frac{V_u}{V_u} = \frac{m_u}{m_u} - \frac{1}{\rho} \left[\left(\frac{\partial \rho}{\partial T}\right)_u \dot{T}_u + \left(\frac{\partial \rho}{\partial p}\right)_u \dot{p} \right] \tag{3.32a}$$

$$\frac{\dot{V}_b}{V_b} = \frac{\dot{m}_b}{m_b} - \frac{1}{\rho} \left[\left(\frac{\partial \rho}{\partial T}\right)_b \dot{T}_b + \left(\frac{\partial \rho}{\partial p}\right)_b \dot{p} \right] \tag{3.32b}$$

Also, since the rate of change of chamber volume is known:

$$\frac{\dot{V}_b}{V_b} = \frac{\dot{V} - \dot{V}_u}{V_b} = \frac{\dot{V}}{V_b} - \frac{\dot{V}_u}{V_u} \frac{V_u}{V_b} \tag{3.33}$$

Combining Eqs. 3.32 and 3.33 and solving for the rate of change of unburned volume yields:

$$\frac{\dot{V}_u}{V_u} = \frac{V_b}{V_u}\left\{\frac{1}{\rho_b}\left[(\partial\rho/\partial T)_b\dot{T}_b + (\partial\rho/\partial p)_b\dot{p}\right] - \frac{\dot{m}_b}{m_b} + \frac{\dot{V}}{V_b}\right\} \quad (3.34)$$

Equating Eqs. 3.34 and 3.32a and using the expressions for temperature from Eqs. 3.29a and 3.29b provides:

$$\frac{\dot{m}_u}{m_u} - \frac{1}{\rho_u}\left\{\left(\frac{\partial\rho}{\partial T}\right)_u \frac{1}{m_u c_{p_u}}\left[\sum(\dot{m}_j h_j)_u - h_u\sum(\dot{m}_j)_u + V_u\dot{p} - \dot{Q}_u\right] + \left(\frac{\partial\rho}{\partial p}\right)_u\dot{p}\right\}$$

$$= \frac{V_b}{V_u}\left\{\frac{\dot{V}}{V_b} - \frac{\dot{m}}{m_b} + \frac{1}{\rho_b}\left[\left(\frac{\partial\rho}{\partial T}\right)_b \frac{1}{m_b c_{p_b}}\left[\sum(\dot{m}_j h_j)_b - h_b\sum(\dot{m}_j)_b + V_b\dot{p} - \dot{Q}_b\right] + \left(\frac{\partial\rho}{\partial p}\right)_b\dot{p}\right\} \quad (3.35)$$

Again, the mass flows and enthalpy fluxes are pressure change dependent so let:

$$\sum(\dot{m}_j h_j)_u = \left(-\dot{m}_{leak}^{lead} - \dot{m}_{leak}^{lag} - \frac{m_{crev}^{lead}}{p}\dot{p} - \frac{m_{crev}^{lag}}{p}\dot{p}\right)_u - \dot{m}_{comb} \quad (3.36a)$$

$$= d^*{}_u - c^*{}_u\dot{p} \quad (3.36b)$$

$$\sum(\dot{m}_j h_j)_b = \left(-\dot{m}_{leak}^{lead} - \dot{m}_{leak}^{lag} - \frac{m_{crev}^{lead}}{p}\dot{p} - \frac{m_{crev}^{lag}}{p}\dot{p}\right)_b + \dot{m}_{comb} \quad (3.36c)$$

$$= d^*{}_b - c^*{}_b\dot{p} \quad (3.36d)$$

$$\sum(\dot{m}_j h_j)_u = \{ - (\dot{m}_{leak}h)^{lead} - (\dot{m}_{leak}h)^{lag} - \frac{\dot{p}}{p} [(m_{crev}h)^{lead} + m_{crev}h)^{lag}]_u - \dot{m}_{comb}h_u \} \quad (3.36e)$$

$$= e^*_u - f^*_u\dot{p} \quad (3.36f)$$

$$\sum(\dot{m}_j h_j)_b = \{ - (\dot{m}_{leak}h)^{lead} - (\dot{m}_{leak}h)^{lag} - \frac{\dot{p}}{p} [(m_{crev}h)^{lead} + (m_{crev}h)^{lag}]_b + \dot{m}_{comb}h_b \} \quad (3.36g)$$

$$= e^*b - f^*b\dot{p} \quad (3.36h)$$

Substituting Eqs. 3.36 into Eq. 3.35 and solving for the rate of pressure change gives:

$$\dot{p} = \frac{\dfrac{d^*_u}{m_u} + \dfrac{(\partial\rho/\partial T)_u}{(\rho m c_p)_u}(d^*_u h_u + \dot{Q}_u - e^*_u) + \dfrac{d^*_b V_b}{m_b V_u}(d^*_b h_b - e^*_b + \dot{Q}_b)\dfrac{V_b}{V} - \dfrac{\dot{V}}{V_u}}{\dfrac{c^*_u}{m_u} + \dfrac{(\partial\rho/\partial T)_u}{(\rho m c_p)_u}(c^*_u h_u + V_u - f^*_u) + \dfrac{(\partial\rho/\partial p)_u}{\rho_u} + \dfrac{V_b}{V_u}\left[\dfrac{(\partial\rho/\partial p)_b}{\rho_b} + \dfrac{c^*_b}{m_b} + \dfrac{(\partial\rho/\partial T)_b}{(\rho m c_p)_b}(c^*_b h_b + V_b - f^*_b) \right]} \quad (3.37)$$

Once the rate of change of pressure is known the rates of change for temperature and volume of each zone can be found from previous equations; they are rewritten here using the dummy variables of Eq. 3.36:

$$\dot{T}_u = \frac{e^*_u - d^*_u h_u - \dot{Q}_u + (c^*_u h_u - f^*_u + V_u)\dot{p}}{(mc_p)_u} \quad (3.38)$$

$$\dot{T}b = \frac{e^*_b - d^*_b h_b - \dot{Q}_b + (c^*_b h_b - f^*_b + V_b)\dot{p}}{(mc_p)_b} \qquad (3.39)$$

$$\dot{V}_u = Vu \left\{ \frac{d^*_u}{m_u} - \frac{(\partial\rho/\partial T)_u}{\rho_u}\dot{T}_u - \left[\frac{(\partial\rho/\partial p)_u}{\rho_u} + \frac{c^*_u}{m_u} \right]\dot{p} \right\} \qquad (3.40)$$

$$\dot{V}_b = \dot{V} - \dot{V}_u \qquad (3.41)$$

3.4 PROGRAMMING CONSIDERATIONS

In order to evaluate the differential equations of Chapter 3, enthalpies must be assigned to each flow. Since the rate of pressure change is not known until later in the calculation it is not possible to determine which direction the combined crevice and leakage flow goes at both the leading and trailing apices. This is resolved by assuming a net direction and checking the assumption when the pressure change has been calculated.

During combustion it is necessary to split the combined crevice and leakage mass flow rates between the burned and unburned zones. When net flow is out of the chamber the fraction of burned gas leaving is equal to the mass fraction burned. For return flow back into the chamber the unburned zone receives only unburned mixture and the burned zone receives only burned products.

$$\alpha = \begin{cases} 1 - x_b & : \text{flow out of chamber} \\ \dfrac{1}{1 - x_{fresh}}\, {x_1}_c & : \text{flow into chamber} \end{cases} \qquad (3.42)$$

where:

α ≡ Mass fraction unburned in flow

x_{1_c} ≡ Mass fraction fresh charge in crevice

x_{fresh}≡ Mass fraction fresh charge in unburned zone (a constant)

It also should be noted that the rate of combustion in an open system is not equal to the rate of increase of burned products characterized by the Wiebe function. The combustion rate also depends on the mass flows to and from the chamber:

$$\dot{m}_b = \dot{x}_b m + x_b \dot{m} = \dot{m}_{comb} - (\dot{m}_{leak}^{lead})_b - (\dot{m}_{leak}^{lag})_b - (\dot{m}_{crev}^{lead})_b - (\dot{m}_{crev}^{lag})_b \quad (3.43)$$

so that:

$$\dot{m}_{comb} = \dot{x}_b m + x_b \dot{m} + (\dot{m}_{leak}^{lead})_b + (\dot{m}_{leak}^{lag})_b + (\dot{m}_{crev}^{lead})_b + (\dot{m}_{crev}^{lag})_b \quad (3.44)$$

Again the crevice mass flow rates are not known until the rate of change of pressure is calculated. However, the combustion rate is needed to evaluate the pressure change. This dilemma is circumvented by approximating the crevice flows by using the last known value.

4.0 MODEL VALIDATION AND CALIBRATION

4.1 INTRODUCTION

To ensure that program output is logical and correct each major change to the program, described in Chapter 1, was separately validated. For this checking process it was often helpful to have the similar reciprocating engine program in order to compare results. This chapter presents the methods used to validate the programming changes and the submodels. A discussion of the procedure used to calibrate the submodels once validation was complete follows.

4.2 GEOMETRY VALIDATION

The alteration of the geometry subroutine and the geometry effects embedded in the rest of the code was the first change made to the program; thus no leakage, crevice volume, or heat transfer models were, as yet, included. The first checks were made by comparing volume and rate of change of volume graphs. A graphical analysis of the slopes and areas under the curve showed that the two variables were consistent. The calculation of compression ratio made by the program was also found to be correct proving that the chamber volume equations were behaving as expected. After the geometry switch had been accomplished a motoring run was made to allow comparison of this pressure trace to the pressure trace of a motoring run on a reciprocating engine with no heat transfer. The traces were similar enough for engines with somewhat different compression ratios and no obvious errors were apparent. The constant for a polytropic compression in the Wankel engine simulation was found to be 1.33 which is within the expected range of :

$1.3 < \gamma < 1.35$

The program itself has several built in error checks that are useful for the end user. The fact that the program converges to a solution is a good indication , in itself, that the program is running smoothly. Calculations made at the end of each cycle also provide consistency checks. For instance, a motoring run with no heat transfer, leakage, or crevice volume energy loss models activated should have a gross indicated mean effective pressure (gross IMEP) of exactly zero. The program also performs a global energy balance and prints out the net energy gain over a complete cycle divided by the enthalpy of the charge inducted. Errors of less than one percent can be expected for motoring runs.

Specified burn rate firing runs were made on both the reciprocating and rotating engine simulations, and the outputs checked against each other. Again, the pressure traces were similar and no obvious discontinuities existed. Cycle outputs such as volumetric efficiency, indicated mean effective pressure, and exhaust energy were also cross-checked and found to be comparable. For the firing case the code again provides a useful check on the program operation. The global energy gain as a percentage of the fuel energy inducted should be on the order of one percent for a converged cycle.

4.3 CREVICE AND LEAKAGE MODEL VALIDATION

To gain more detailed information about the crevice and leakage model behaviour a separate output file was created for this subprogram. In order to check this model a crevice volume of 2 cm^3 per apex seal and a leakage area of 1 mm^2 per apex seal were used. These values were taken from experimental data and previous computer simulations of the Wankel engine.

One good quantitative check of the model is that over the entire cycle the algebraic addition of leakage mass past each apex seal is zero (by mass conservation). A second quantitative check is that the crevice mass, and composition should be the same for both chambers at the crank angle where a crevice transfers from one chamber to the other. It must be remembered that the lead crevice which transfers out of the chamber at approximately +500° is, as far as the program is concerned, the same as the lag crevice that switches into the chamber at -220°. Also, at any crank angle that a crevice transfers into or out of the chamber the pressure difference across the appropriate apex seal and the leakage flow rate are zero. Qualitatively the crevice volumes flatten out (vertically compress) the pressure trace and leakage reduces peak pressure and advances the crank angle for peak pressure.

4.4 HEAT TRANSFER VALIDATION

The total heat loss from a spark ignition engine is about one third of the fuel energy input. Once the heat transfer subroutine had been debugged the model predicted roughly this amount of heat loss. An additional check was made by comparing output from the original reciprocating engine simulation to ensure that heat transfer rates were correct at least to an order of magnitude.

4.5 MODEL CALIBRATION

Once all the program code had been debugged and each new subprogram validated the submodel parameters required calibration so that the model would accurately predict the engine operating characteristics at different loads and speeds. These parameters requiring calibration were leakage area, crevice volume, and heat transfer velocity. Finding appropriate values for each of these input variables required matching computer output with data supplied by N.A.S.A. .

N.A.S.A. has provided us with sufficient motoring engine data useful for a preliminary calibration. However, a lack of data from a firing engine makes the results discussed in the next chapter limited in scope.

Motoring data allows the matching of three engine operating characteristics :

volumetric efficiency	(m_{in})
peak pressure	(p_{max})
crank angle at peak pressure	(Θ_{peak})

The calibration strategy was to select nine motoring runs made at three engine speeds (1000, 2000, and 3,000 RPM) and three throttle settings (33%, 66% , and 100% open) and construct a test matrix, (Table 4). The model was then calibrated to match as closely as possible the data from the median engine speed and throttle position. Computer runs were then made at different speeds or throttle settings (four separate points) while the model calibration parameters were held constant to check that the model adequately matched engine data. A first attempt to match the data provided good agreement with peak pressure, and volumetric efficiency at parameter values of :

$V_{crevice} = 1.0\ cm^3$ per apex

$A_{leak} = 0.004\ cm^3$ per apex

$Vel_{non-fire} = 0.5\ V_{rotor}$

However, the pressure at the end of intake was appreciably in error and an effort was made to correct this problem.

4.5.1 INTAKE PORT OPEN AREA

Table 5 shows the basic engine geometric information supplied by N.A.S.A. for the Mazda test engine . The N.A.S.A. engine has been modified by enlarging one of the two side ports. By comparing engine data and model output that uses the intake port timings supplied, it can be seen that the modelled port opens approximately 10 degrees later in the model,than in the engine, as shown by the shift in the pressure drop that occurs as the port opens (Fig. 18). Also the port closing time appears to be significantly late. The intake port timings were advanced 10 crank angle degrees in the model to match the port opening pressure trace but intake port close pressure was still significantly low.

All attempts to match the intake port closing pressure while also matching the other operating characteristics by varying the submodel parameters failed. The only method that allowed a good match for all four characteristics was by variation of the intake port closing profile. Initially the intake port was assumed to open and close at a constant rate. Once the experimental modification to the intake port became known the closing profile was adjusted (Fig 19). To match p_{IPC} a set of exponential profiles were used to close the extended portion of the port. The profile which gave the best data fit is shown on the last figure. There appears to be a discrepency between the intake port timing data provided, and the input data that matches the pressure trace. This is a problem which should be fairly easy to resolve by accurately measuring the intake port open area profile on the engine. By using the exponential port closing profile the intake port is effectively closed at -210°, some 40° advanced from the reported value.

Because the port area was reduced during the last stages of induction, the reverse flow out of the chamber was minimized and the volumetric efficiency increased to a level significantly higher than measured. To decrease the volumetric efficiency the intake manifold pressure was decreased by 2% and the leakage area and heat transfer velocity were increased (Fig. 20).

4.5.2 FINAL MOTORING CALIBRATION

Because heat transfer and leakage had been increased from the values reported above, in order to decrease volumetric efficiency, the crevice volume was reduced in order to match peak chamber pressure.

Vcrevice = 0.875 cm^3 per apex seal

Aleak = 0.010 cm^2 per apex seal

$Vel_{non-fire} = 0.75$

Table 6 shows the computer output for the variables matched and the relative error between predicted and measured values. No attempt was made to match the crank angle at peak pressure for two reasons. First, at low speeds the measured Θ_{peak} was consistently after top dead center (TDC). This is not reasonable since it would require a net energy influx. The second reason for not attempting to match Θ_{peak} was the trend of the measured values with RPM. For motored conditions Θ_{peak} is strongly affected by leakage and heat transfer, which are both time dependent energy loss mechanisms. The time dependence of both of these phenomena suggests that at slower speeds θ_{peak} becomes further advanced as more energy is lost due to leakage and/or heat transfer.

This predicted trend is opposite from the observed trend of lower energy loss (even a net gain) with reduced engine speed. The reason for this behaviour of the data is not immediately obvious, although it could be explained by a speed dependent leakage area or experimental errors. The fact that Θ_{peak} occured at + 0.5° and + 1.5° consistently for engine speeds of 1000 and 1500 RPM respectively, is an indication of at least some experimental error. The variable leakage area problem is currently being evaluated by the N.A.S.A. researchers in a dynamic study of apex seal motion. Leakage area may be increased at points in the cycle where the apex seal possibly lifts off from the housing surface due to dynamic forces. In the future, a variable leakage area may be included in the model.

A comparison between predicted and measured pressure traces during compression and expansion is shown in Fig. 21. Agreement is good except through top dead center. During expansion, predicted pressures are significantly below measured values. To check compression and expansion pressures a normalized logarithmic plot of chamber pressure versus volume was made (Fig. 22). The graph clearly shows that for all three engine speeds the polytropic expansion exponent is not constant for the engine data; in fact the measured chamber pressures at +180° are greater than or equal to the chamber pressures at -180° (nominal intake port close). During compression the measured polytropic constant also appears to change appreciably. This behaviour may be due to pressure transducer calibration problems, phasing difficulties with the angle indicator, or possibly very high heat transfer or leakage rates in the engine.

To check the calibrated model four other motoring runs were made, selecting a different speed or throttle position than the run used for calibration. The model was in good agreement with experimental data for each of these runs except the low speed case. Two other runs were made at 1000 RPM to see if the model problems were speed dependent only. For each run at 1000 RPM the volumetric efficiency agreement was good to excellent, however, the predicted maximum pressure was significantly higher than the measured value. This leads one to expect that the crevice volumes may be somewhat larger than the calibrated value as this would decrease peak pressure without significantly affecting the volumetric efficiency or θ_{peak}.

4.5.3 FIRING CASE CALIBRATION

Only one cycle of firing data was available from N.A.S.A., which made firing case calibration preliminary. The engine operating condition was extremely throttled (11% open) at 2000 RPM. The equivalence ratio was assumed to be 1.2 which is typical of throttled conditions for reciprocating engines . While the calibration was necessarily limited by the lack of engine data, matching the light load engine data may provide some useful insights into an operating regime where the Wankel engine has been criticized for poor fuel economy and high HC emissions. A parametric study on the effects of reducing either crevice volume, heat transfer, or leakage will identify the major causes of poor engine performance at light load.

By varying the mass fraction burned equation (Eq. 2.25) variables, a fair agreement between predicted and measured pressure traces was found (Fig 23). There was no need to alter the leakage area for firing conditions which both Danieli, and Eberle & Klomp had reported. This is possibly a result of using a constant gas temperature for the leakage gas. The pressures during expansion were somewhat low presumably the consequence of the transducer calibration error discussed above. The timing of peak pressure was again advanced compared to the engine data, similar to the motored pressure traces.

4.5.4 COMMENTS ON CALIBRATION

Calibration of the model indicates the importance of various aspects of the test engine geometry and experimental data. These are:

a) Intake port timing and open area profile.

b) Chamber pressure rise above intake manifold pressure before bottom center of the intake stroke

c) Timing of peak pressure.

Once further information is available it will be possible to recalibrate the model parameters.

5.0 MODEL RESULTS

Once the simulation had been calibrated by using the experimental data a parametric study was conducted on the effects of changes in heat transfer rates, crevice volume, or leakage area on engine performance. Motoring computer runs for this parametric study were all made at a baseline operating point used to calibrate the model (2000 RPM, and 66% open throttle setting). The firing case runs were made at the light load setting available from N.A.S.A.. Since this firing case is extremely throttled, the chamber pressures and temperatures are low, so crevice volume effects can be expected to be minimal in comparison to the performance effects due to leakage and heat transfer. The results of this study are presented in this chapter.

5.1 MOTORING

Motored engine data is used in research activities to determine, approximately, the friction power of a given engine. Indicated power losses are generally not included in the calculation. However, for motored Wankel engines gas leakage between adjacent chambers is an appreciable power sink. The program's calculations may, therefore, be useful for experimental research into the actual friction power loss of the engine.

5.1.1 MOTORING VOLUMETRIC EFFICIENCY

Figure 24 shows the effect of changing the submodel parameters on the motored engine's volumetric efficiency. It can be seen that both heat transfer and crevice volumes have little effect on volumetric efficiency; in fact the calibrated values for these parameters are near the point where they have the largest negative effect upon the engine's breathing. Increasing heat transfer rates or crevice volumes to values larger than calibrated, results in compression and expansion pressures being somewhat lowered. Consequently, a net reduction in leakage results in increased volumetric efficiency. Decreasing heat transfer causes the residual gases at the end of the cycle to be hotter, and therefore less dense. Therefore, during intake the smaller mass of residual gas is cooled to a lower temperature by the incoming charge. This results in a somewhat higher volumetric efficiency and a lower residual fraction. The leakage area has the greatest influence on volumetric efficiency.

5.1.2 MOTORING GROSS INDICATED MEAN EFFECTIVE PRESSURE

The significant effect of leakage on motoring engine power is shown in Fig. 25 where the effect on motoring gross IMEP by varying the three simulation parameters is shown. A reduction of 50% of motoring indicated power is predicted by the model if leakage could be eliminated. Reducing heat transfer would also have a significant effect on the motored engine's power consumption. The crevice volume effect is negligible because the working gas pressures and temperatures are too low for significant amounts of heat transfer to occur within the crevice.

5.1.3 MAXIMUM PRESSURE AND θ_{PEAK}

The compression expansion pressure traces for each variation in a parameter value are shown in figures 26-28. The effects of the submodel variables on maximum pressure and the angle where maximum chamber pressure is attained are shown in figures 29 and 30. Changing the crevice volume size does not affect θ_{peak} but does have a significant effect on maximum pressure without altering gross IMEP. During motoring the crevice volume effect is quite symmetrical about top dead center. It appears that for the parameter values chosen crevice volumes have a greater effect on peak pressure than heat transfer, because energy is lost during compression while gas is pushed into the small volume; whereas convection heat transfer to the chamber walls is concentrated over the period before and after top dead center when gas temperatures are highest. Again, leakage is shown to be the dominant loss mechanism during motoring. Leakage out of the chamber occurs during compression and expansion so it has a large effect upon peak pressure and advances it significantly.

5.2 FIRING

The parametric study for a firing engine was made at the throttled operating condition for which experimental data was available. The chamber pressures and temperatures for this load point are low so heat transfer and, especially crevice volume losses are expected to be lower than for a high load operating condition. Also, at faster engine speeds the crevice volume losses will become a greater fraction of the total loss because of the time dependence of heat transfer and leakage. Additionally, the calibrated size of the crevice volume may be conservative as noted in Chapter 4.

5.2.1 FIRING VOLUMETRIC EFFICIENCY

The effects of parametric variation on volumetric efficiency show the same trends as for the motored engine with the exception of the zero heat transfer case (Fig. 31). This result may be amplified as wall temperature increases for high load conditions. In a fired adiabatic engine the residual gases at the end of exhaust are hotter than in a conventional engine (Fig. 32) . The incoming fresh charge is heated by the residual gases and the intake chamber walls provide no cooling so less fresh charge is inducted. Crevice volumes have a negligible effect on volumetric efficiency for this case.

5.2.2 FIRING GROSS INDICATED MEAN EFFECTIVE PRESSURE

Figure 33 shows the dominance of leakage as the primary performance loss mechanism at light load. While power output is not a critical issue at light load it is instructive to note that a 36% gain in gross indicated power could be realized by eliminating leakage from the engine. Reducing the heat transfer coefficient has little effect on gross IMEP because any gain due to reduced energy losses is offset by a reduction in volumetric efficiency. The crevice volumes have negligible effect on engine power at such light load because of the low peak pressures and gas temperatures.

5.2.3 UNBURNED FUEL ENERGY EXHAUSTED

The model predicts that at the light load condition tested, 3.75% of the inducted fuel escapes to the exhaust chamber (Fig. 34). By reducing the leakage area to zero the escaping fuel energy can be reduced as no leakage path would exist for mass transfer between the high pressure expansion chamber and the exhaust chamber. Some fuel is left unburned because the crevice volumes withhold a significant amount of charge from the combustion process. The figure shows the effect of reducing leakage area or crevice volume on the fraction of charge that escapes. A 50% reduction is predicted by the model if the crevice volumes are eliminated.

While complete elimination of leakage or crevice volume is impossible an effort to reduce the size of the engine's crevice volumes should result in large decreases of fuel energy loss and quite possibly a significant reduction in HC emissions.

As the crevice volume model is designed to predict performance loss only, its predictions cannot be strictly used to infer HC emissions data. This is because unburned fuel that returns to the expansion or exhaust chamber will partially burn in the engine. This burn up phenomenon and the other variables that influence HC emissions are not included in the simulation. However, the predicted data does provide insight into the reduction of HC emission possible by reducing crevice volumes.

The model also predicts that reduced heat transfer will result in an increased percentage of fuel energy leaving through the exhaust port. There are two major causes for this, both relating to the induction phase. First, the residual gas fraction is lower, so the charge that enters the crevice volumes before escaping from the chamber is less dilute. Secondly, the volumetric efficiency is lower but chamber pressures during compression and early combustion are equivalent to the baseline case because of an increased thermal efficiency . Therefore, comparable amounts of gas escape but a larger fraction of the trapped mass leaves the chamber. Since the exhaust gases are hotter in an adiabatic engine, more partially burned charge will oxidize in the exhaust chamber and manifold. A turbocharger or compound device would recover this 'lost' energy.

5.2.4 RESIDUAL FRACTION

The effect of varying the submodel parameters on residual fraction is shown in Figure 35. It can be seen that leakage area strongly affects the light load residual fraction. Burned product leaks past the apex seal from the exhaust chamber to the intake chamber and also flows past the side seals during combustion which reaches the intake chamber as previously explained. Reducing residual fraction in the Wankel could therefore result in increased combustion stability which has been a problem for the engine at light load (23).

Reduced heat transfer also affects the residual fraction, due to the lower density of the chamber contents at the end of exhaust. So less mass remains in the chamber at the beginning of the induction phase. Conversely, reduced crevice volume lowers the exhaust chamber temperatures allowing more mass to reside in the clearance volume.

5.3 DISCUSSION

As was predicted, the major energy loss mechanism for motoring and light load is the gas leakage problem which confirms the results of previous work (5,19,20). Heat transfer was also found to have significant influence on the engine's thermal and volumetric efficiency. These two effects offset each other in an adiabatic engine (at light load) and no change in gross IMEP is predicted. Crevice volumes have little effect on engine performance or efficiency for motoring and light load conditions. However, at higher speed and higher load conditions, crevice effects may become important.

6.0 SUMMARY AND CONCLUSIONS

6.1 SUMMARY

The purpose of this modelling study has been to construct a computer simulation of a spark ignited, pre-mixed charge Wankel rotary engine. Since the model is to be used for preliminary studies on engine performance characteristics and size requirements a zero-dimensional model using a specified combustion rate was used. The model can also be used to predict the performance changes brought about by advances in engine design and technology, such as the use of improved seal materials and/or insulative ceramic components. An evaluation of crevice volumes in the Wankel engine was undertaken which determined that their size and location are a possible source of performance loss. A crevice volume model was included in the simulation, for the first time in a model of the Wankel , to evaluate the relative importance of the crevice volumes on the engine's performance.

Previous research has shown that Wankel engine performance and efficiency is severely degraded by gas leakage between adjacent chambers. Most earlier models have ignored side seal leakage as a mode of mass loss, although side seal leakage has been documented to be one third of the total leakage of gas from the engine. The program implicitly includes the effect of side seal leakage by using the crevice gas compositions as the leakage gas composition. This enables the model to leak burned and unburned gas throughout the engine cycle as occurs in the real engine.

Engine motoring data collected by N.A.S.A. researchers from a Mazda two rotor Wankel engine was used to calibrate the submodel parameters. At the present time only one, low load, data point for a firing cycle is available. Comparison of engine data and model predictions have shown some significant discrepencies, especially during intake and expansion. Some of these differences were reduced by changing the intake port timing and open area profile. It is believed that the calibration of the expansion chamber pressure transducer may be the cause of the discrepencies in the expansion chamber pressure between engine data and model calculations. It should be realized that running experimental and theoretical programs concurrently, commonly results in a more thorough understanding of the results from both efforts.

A clear need exists to resolve questions concerning the intake port timing. The possible errors in engine pressure data have made the parameter calibration values somewhat suspect and new data should be used to recalibrate the model. A lack of firing data at high load and speed points make any predictions about these operating regimes impossible at the present time. A light load engine data point was used to study the effects of crevice volumes, heat transfer, and leakage on engine performance at this operating condition.

The calibration of the model for motoring data produced simulation parameter values of:

A_{leak} = 1.0 mm^2 per apex

$V_{crevice}$ = 0.875 cm^3 per apex

$Vel_{non-fire}$ = 0.75 (V_{rotor})

There was generally good agreement between model and engine data at various engine speeds and throttle settings. There was, however, a significant error in the predicted value of peak pressure at low engine speeds (1000 RPM). It is believed that this last problem is due to a conservative estimate of crevice volume.

A sensitivity study of the effects of changing leakage areas, crevice volumes, and heat transfer rates was done for motoring. At the mid speed and throttle setting tested the leakage area has the strongest effect on volumetric efficiency, gross indicated mean effective pressure, and maximum pressure. The crevice volumes had negligible effect on engine performance but strongly affected maximum chamber pressure. Reducing heat transfer had a negligible effect on volumetric efficiency but increased the mean effective pressure by virtue of an increased thermal efficiency.

The same parametric study was performed on the light load firing case. At light load the relative (to leakage) performance effects of heat transfer and crevice volume are small. The model shows that gas leakage is the primary source of performance loss at very light load, low volumetric efficiency and a large amount of unburned fuel energy that escapes to the exhaust results in a low IMEP. Burned product leaking into the induction chamber results in a higher residual fraction that could possibly cause combustion stability problems.

Crevice volume effects had little impact on engine performance at this light load. However, the crevice did strongly influence the amount of unburned fuel energy that escapes to the exhaust. This is due to the crevices storing unburned charge that eventually leaks out of the chamber.

The model's predictions for an adiabatic engine at light load are a reduced volumetric efficiency, a reduced residual fraction, an increase in thermal efficiency, an increase in the fuel energy that escapes to the exhaust, and a large increase in the temperature of the exhaust gases.

6.2 CONCLUSIONS

It may be concluded that:

a) The cycle simulation is behaving well and although some discrepancies exist between predicted and measured data, the problems can be resolved quickly.

b) The calibration, although preliminary, yielded some useful information relative to the experimental data.

c) The sensitivity study on the performance effects of the heat transfer crevice volume and leakage models, showed that at light loads and motoring conditions leakage has the greatest effect upon engine performance.

REFERENCES

1. Willis, E.A. , "Development Potential of Intermittent Combustion (I.C.) Aircraft Engines For Commuter Transport Applications, " N.A.S.A. T.M.-82869, 1982.

2. Zmroczek, L.A. , "Advanced General Aviation Comparative Engine/Airframe Integration Study, " N.A.S.A. C.R.-165565, 1982.

3. Huggins, J.L. and Ellis, D.R. , "Advanced General Aviation Comparative Engine/ Airframe Integration Study, " N.A.S.A. C.R.- 165564, 1981.

4. Jones, C. , "An Update of Applicable Automotive Engine Rotary Stratified Charge Developments, " SAE paper 820347, 1982.

5. Burley, H.A., Melogeny, M.R., and Stark, T.L. , "Sources of Hydrocarbon Emissions in Rotary Engines, " SAE paper 780419, 1978.

6. Yamamoto, K., Muroki, T. , "Development on Exhaust Emissions and Fuel Economy of the Rotary Engine at Toyo Kogyo, " SAE paper 780417,1978.

7. Jones, C., Lamping, H.D., Myers,D.M., and Loyd, R.W. , "An Update of the Direct Injected Stratified Charge Rotary Combustion Engine Developments at Curtiss-Wright, " SAE paper 770044, 1977.

8. Poulos, S.G. , "The Effect of Combustion Chamber Geometry On S.I. Engine Combustion Rates- A Modeling Study, " M.I.T. Department of Mechanical Engineering, SM Thesis, 1982.

9. Shampine, L.F., and Gordon, M.K. , "Computer Solutions of Ordinary Differential Equations: The Initial Value Problem, " Freeman, 1974.

10. Ansdale, R.F. , The Wankel RC Engine, Iliffe Books Ltd., London, 1968.

11. Yamamoto, K. , Rotary Engine, Toyo Kogyo Co. Ltd, Hiroshima, 1969.

12. Heywood, J.B. , "Engine Combustion Modeling - An Overview, " From Combustion Modeling Reciprocating Engines. Ed. by Mattavi and Amann, Plenum Corp., New York, 1980.

13. Annand, W.J.D. and Roe, G.E. , Gas Flow in the Internal Combustion Engine, Haessner Publishing, Inc. , 1974.

14. Wiebe, J.J. , "Das Wiebe - Brenngesitz ein Fortschnitt in der Kreigspozesse von Verbrennungsmotoren, " Trans. by Prof A. Joute and T.H. Dresen, Kraftadrzeugtechnik, Vol. 9 (1960).

15. Heywood, J.B., Higgins, J.M., Watts, P.A., and Tabaczynski, R.J. , "Devlopment and Use of a Cycle Simulation to Predict SI Engine Efficiency and NO_x Emissions, " SAE paper, 1979.

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

17. Woshni, G. , "A Universally Applicable Equation for the Instantaneous Heat Transfer Coefficient in the Internal Combustion Engine, " SAE Transactions, Vol. 76, paper 670931, (1968).

18. Danieli, G.A., Ferguson, C.R., Heywood, J.B. and Keck, J.C. , "Predicting the Emissions and Performance Characteristics of a Wankel Engine, " SAE Transactions, Vol. 83, paper 740186, (1974)

19. Eberle, M.K., and Klomp, E.D. , "An Evaluation of the Potential Performance Gain From Leakage Reduction in Rotary Engines, " SAE paper 730117, 1973.

20. Danielli, G.A., Keck, J.C., and Heywood, J.B. , "Experimental and Theoretical Analysis of Wankel Engine Performance, " SAE paper 780416, 1978.

21. McCuiston, F.D. , "Analytical Evaluation of the Effect of Leakage on no Emissions From a Rotary Engine, " SAE paper 750023, 1975.

22. Namazian, M. and Heywood, J.B. , "Flow in the Piston-Cylinder-Ring Crevices of a Spark Ignition Engine: Effect of Hydrocarbon Emissions, Efficiency and Power, " SAE paper 820088, 1982.

23. Kohno, T., Ito, R., Morita, M., and Mizuno, N. , "Analysis of Light-Load Performance in Rotary Engines, " SAE paper 790435, 1979.

Solid-State Ignition Trigger Vs Mechanical Trigger

Plasma Jet Ignition System

Eliminating Pilot Injector

High Temperature Aluminum Castings

Turbocharger

Thin Wall (Iron) Rotor

Exhaust Port Thermal Liner (Metallic)

Improved Lubricants

Multiple Power Source for Ignition

Induction Air Intercooler

Variable Displacement Pressure Oil Pump

Provision for Counter-Rotating Propellers

Total Diagnostics

Electronic Ignition Schedule

Computer Vs Mechanical Timing

Fiber Optics Data Bus

Low Pressure Drop Heat Exchangers

NASVYTIS Traction Speed Reducer (Prop)

Alternate Cooling Fluid

Composite Rotor Housing (Wear Resistant Liner)

Wing Leading Edge with Integral Coolant Cooler

Alternate Materials Seals

Retracting Apex Seals

Thermostatically Controlled Rotor Oil Cooling

Turbocharger with Variable Area Turbine

Spark Ignition Start/Auto-Ignition Run

Aluminum Rotor (Reinforced Lands)

Insulated Rotor - Thermal Barrier Coating

Independent Dual Ignition

Variable Compression Ratio

Insulated Rotor - Inserts on Metallic Pad Insulator

Adiabatic Engine Ceramic End Walls

Composite Rotor (Reinforced Apex Seal Land)

Electronic Injection (Fuel)

Adiabatic Engine Ceramic Rotor Inserts

Turbocompound

Adiabatic Engine - Ceramic Rotor Housing Liner

Pilot Nozzle Trigger for Ignition System

High Speed Propeller (No Reduction Gear)

NASVYTIS Traction Speed Reducer (Turbocompound Drive - If Used)

Adiabatic Engine - Ceramic Rolling Element Bearings

Table 1. Advanced rotary engine technologies.

ENGINE	RN_{SINGLE}	RN_{TWIN}	RN_{TOTAL}
BASELINE	100	100	200
ADVANCED TECHNOLOGY SPARK IGNITION	121	126	247
HIGHLY ADVANCED TECHNOLOGY SPARK IGNITION	139	143	282
HIGHLY ADVANCED TECHNOLOGY DIESEL	140	145	285
ADVANCED ROTARY	137	141	278
HIGHLY ADVANCED ROTARY	144	149	293
GATE TURBINE (REVISED)	124 (131)	131 (138)	255 (269)

Table 2. Final engine/airframe rankings for different engine concepts relative to a base general aviation engine.

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

Table 3 location and size of crevice volumes in a model 12B Mazda Wankel engine.

Throttle Setting	1029 RPM	2052 RPM	2925 RPM
30-33%	$m_{in} = 0.393$ g $P_{max} = 14.02$ atm $\theta_{peak} = +0.5^\circ$	$m_{in} = 0.406$ $P_{max} = 14.91$ atm $\theta_{peak} = -1.1^\circ$	$m_{in} = 0.353$ g $P_{max} = 13.27$ atm $\theta_{peak} = -3.2^\circ$
60-66%	$m_{in} = 0.448$ g $P_{max} = 14.44$ atm $\theta_{peak} = +0.5^\circ$	$m_{in} = 0.469$ g $P_{max} = 16.37$ atm $\theta_{peak} = -1.1^\circ$	$m_{in} = 0.460$ g $P_{max} = 16.38$ atm $\theta_{peak} = -2.6^\circ$
100%	$m_{in} = 0.436$ g $P_{max} = 13.75$ atm $\theta_{peak} = +0.5^\circ$	$m_{in} = 0.476$ g $P_{max} = 16.56$ atm $\theta_{peak} = -1.1^\circ$	$m_{in} = 0.475$ g $P_{max} = 16.59$ atm $\theta_{peak} = -2.6^\circ$

Table 4. Motored engine test matrix with experimental data.

ENGINE GEOMETRY

Rotor radius	10.5 cm
Eccentricity	1.5 cm
Housing depth	7.0 cm
Compression ratio	9.4 : 1
Displacement	573 cm^3 x 2 rotors

INTAKE PORT DATA

Number of intake ports	2 per rotor
Total area	13.8 cm^2 per rotor
Ports open at	- 520 (deg ATDC)
Larger port closes at	- 170 (deg ATDC)
smaller port closes at	- 230 (deg ATDC)

Table 5. Basic engine geometry as supplied by N.A.S.A. .

Throttle Setting	1029 RPM	2052 RPM	2925 RPM
30-33%	m_{in} = 0.412 g relative error = +4.8% P_{max} = 14.94 atm relative error = +6.5% θ_{peak} = -4.5°	m_{in} = 0.419 g relative error = +3.2% P_{max} = 15.10 atm relative error = +1.3% θ_{peak} = -2.7°	
60-66%	m_{in} = 0.445 g relative error = -0.7% P_{max} = 15.36 atm relative error = +9.3% θ_{peak} = -4.5°	m_{in} = 0.476 g relative error = +1.4% P_{max} = 16.54 atm relative error = +1.0% θ_{peak} = -2.7°	m_{in} = 0.480 g relative error = +4.3% P_{max} = 16.50 atm relative error = +0.7% θ_{peak} = -2.1°
100%	m_{in} = 0.434 g relative error = -0.4% P_{max} = 15.26 atm relative error = +10.9% θ_{peak} = -4.5°	m_{in} = 0.488 g relative error = +2.5% P_{max} = 16.64 atm relative error = +0.5% θ_{peak} = -2.7°	

Table 6. Motored engine test matrix with computer results and, relative to measured engine data, error.

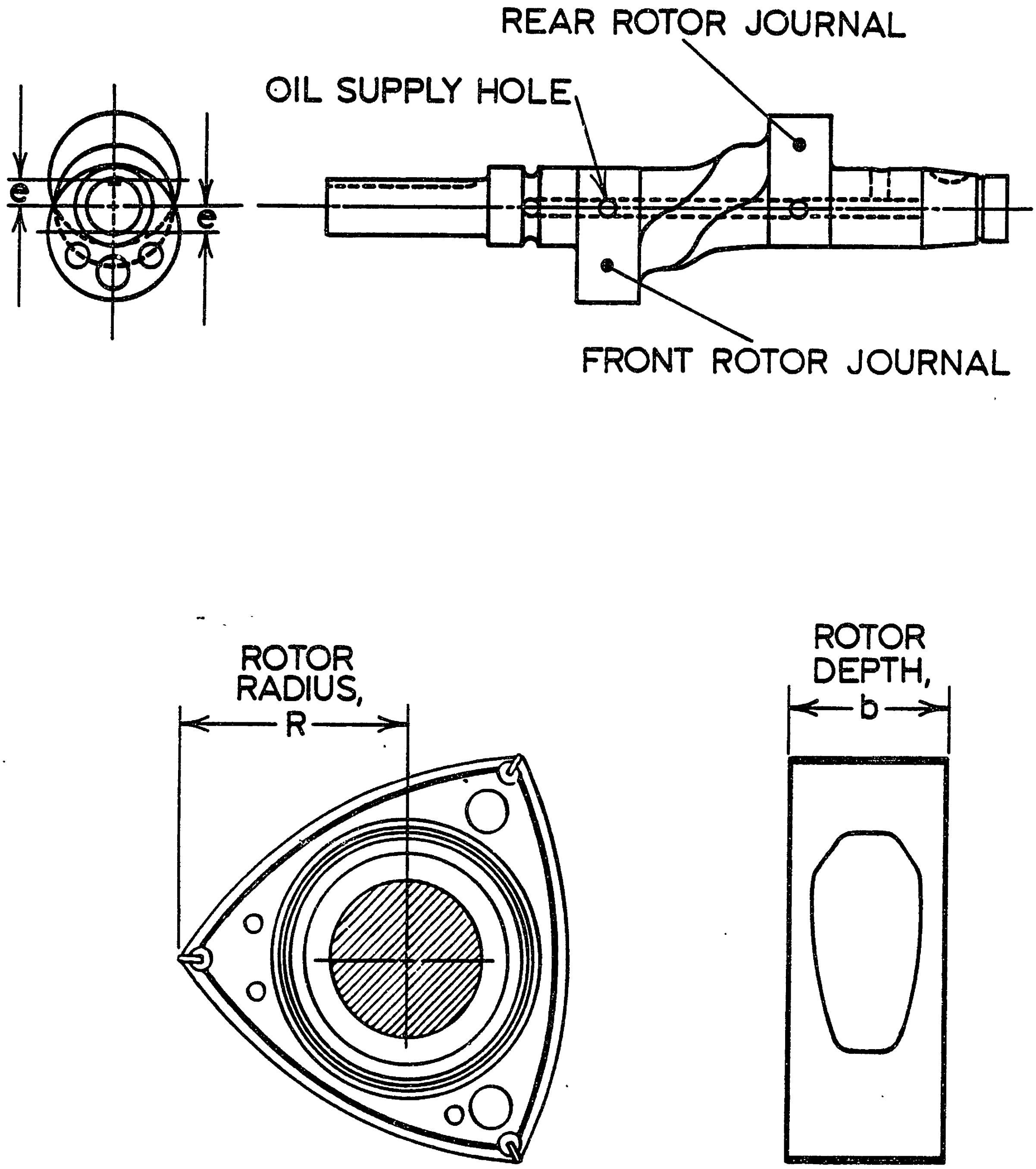

Figure 1. Side and end views of shaft and rotor showing basic engine dimensions.

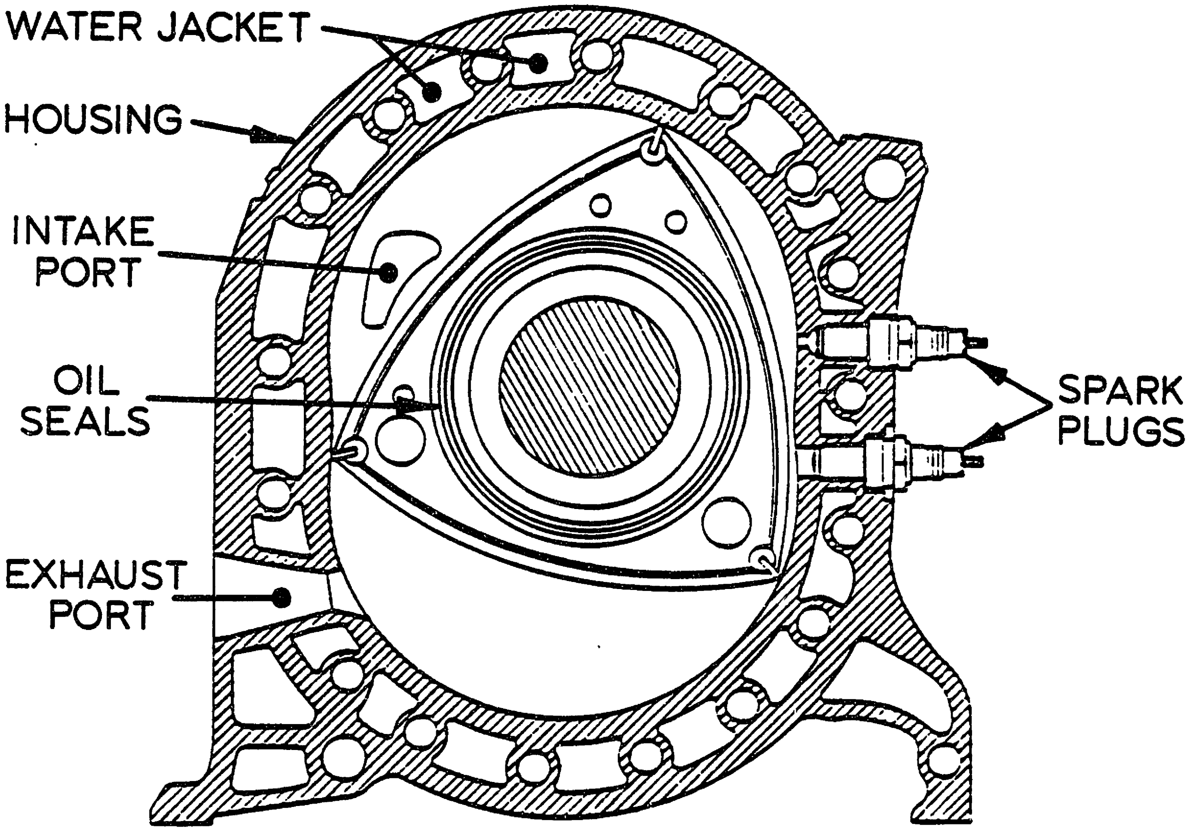

Figure 2. Side view of rotor and housing detailing engine geometry.

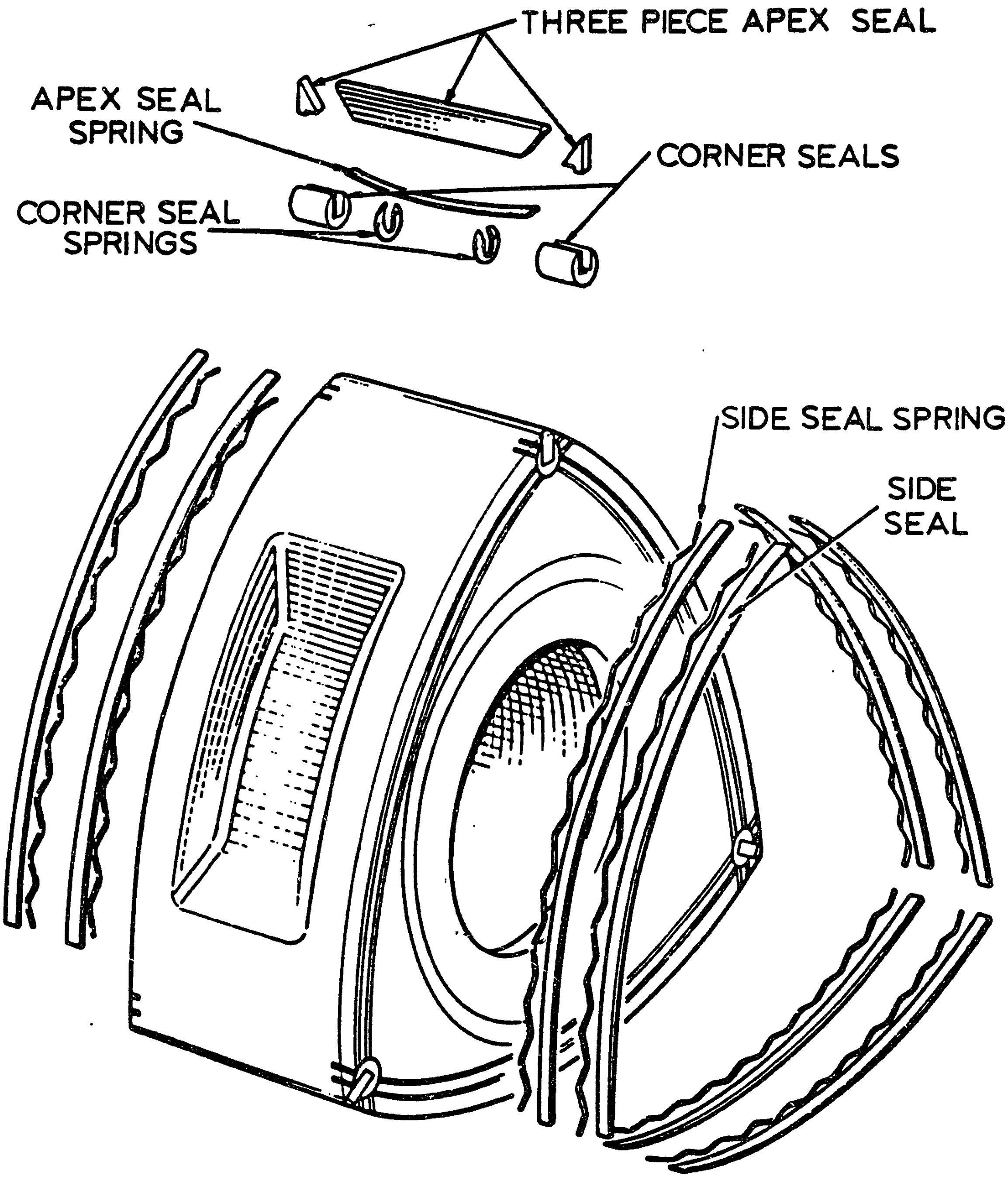

Figure 3. Exploded view of typical engine gas seals.

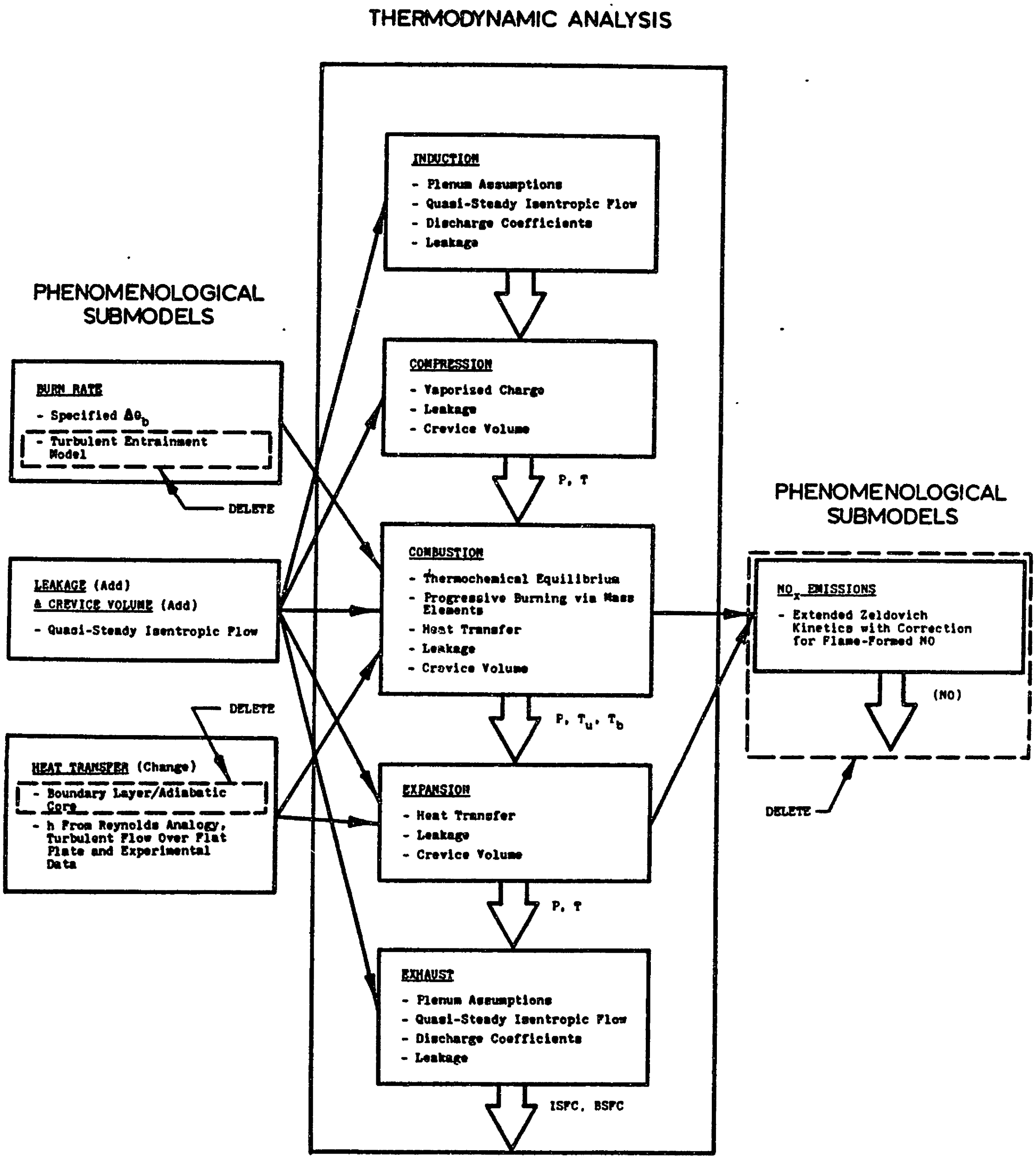

Figure 4. Flow chart of reciprocating engine program indicating deletions, additions, and alterations required for transformation to a Wankel engine simulation.

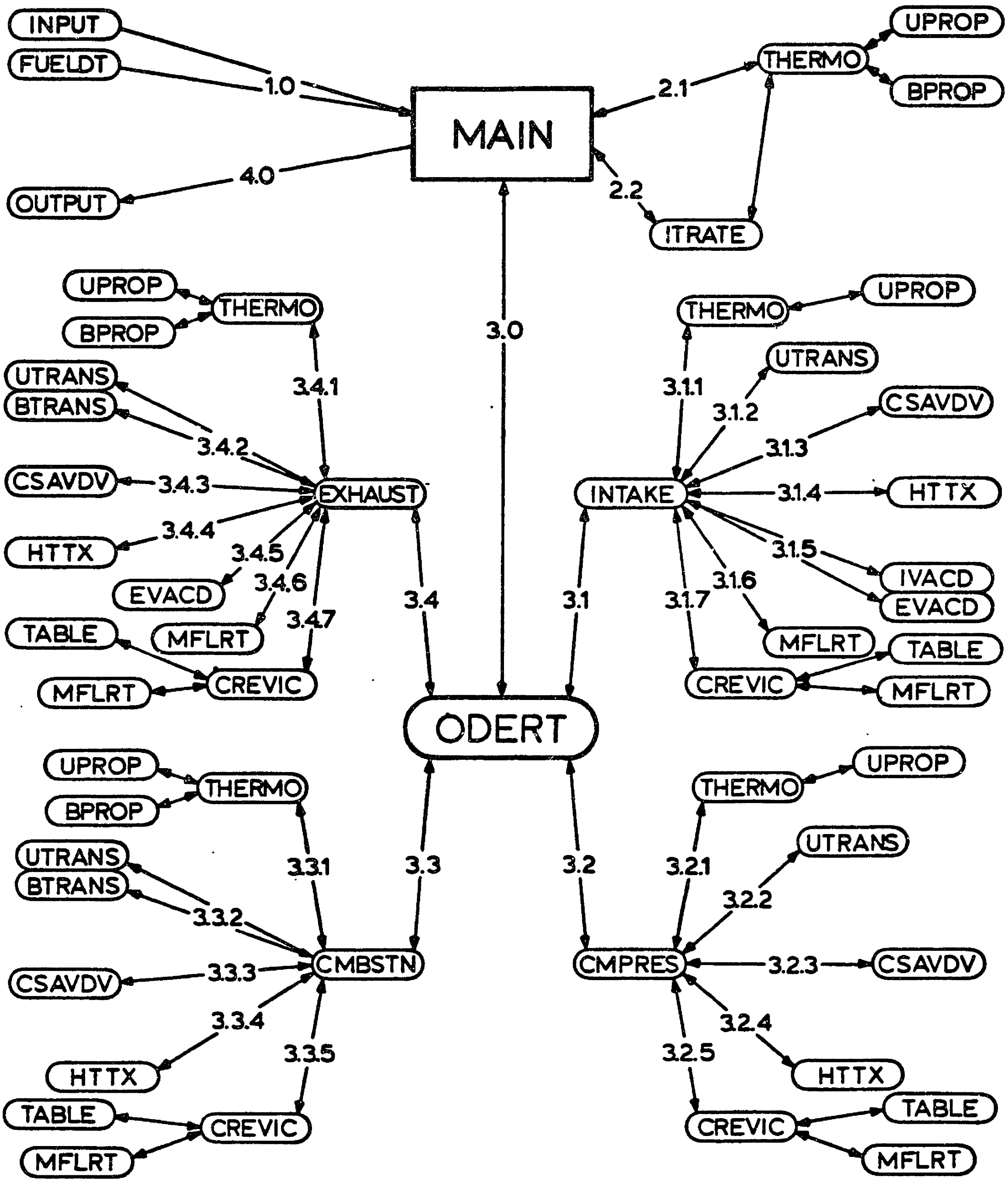

Figure 5. Detailed flow chart of Wankel simulation showing the order of subroutine calls.

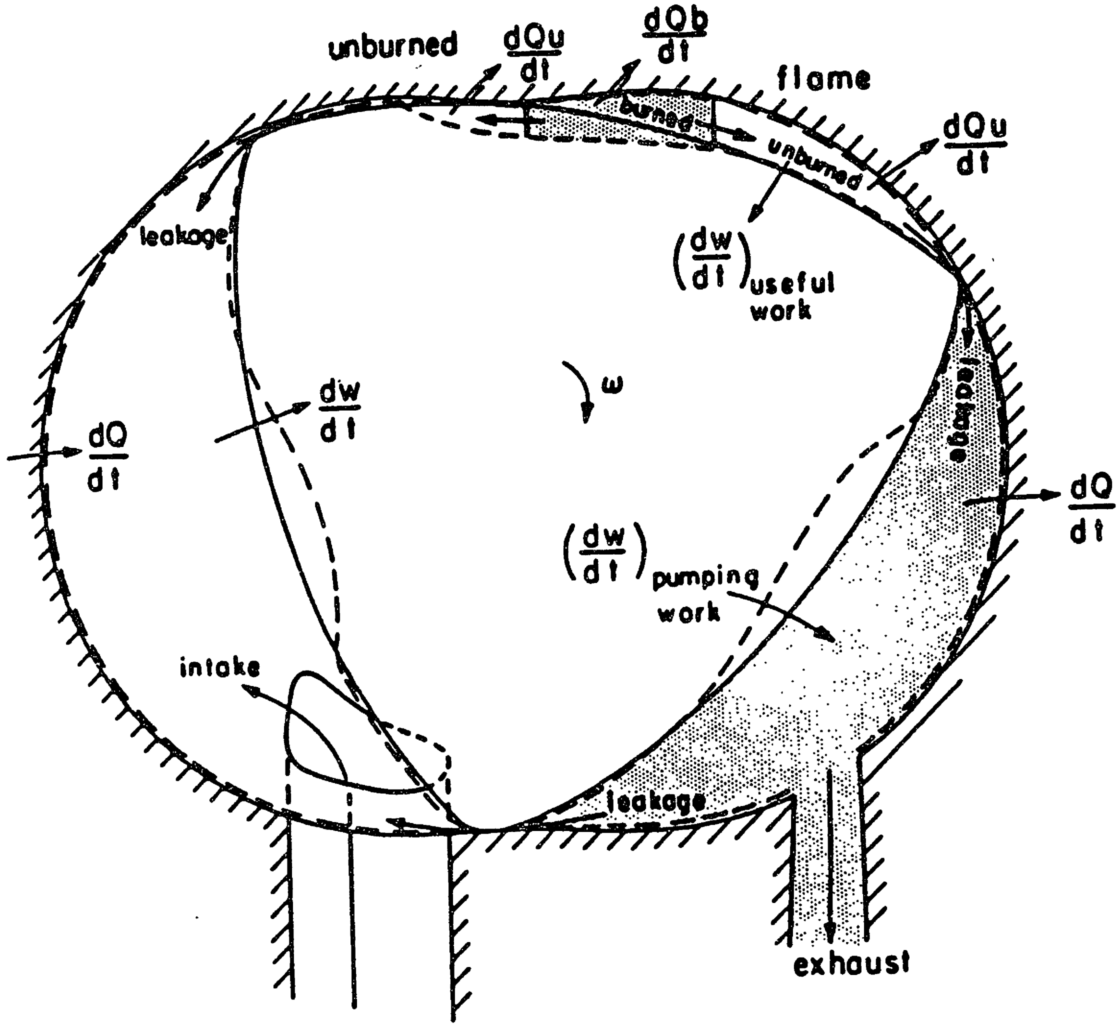

Figure 6. Schematic diagram depicting the coupling of three engine chambers by leakage past the apex seals and the two zone combustion model.

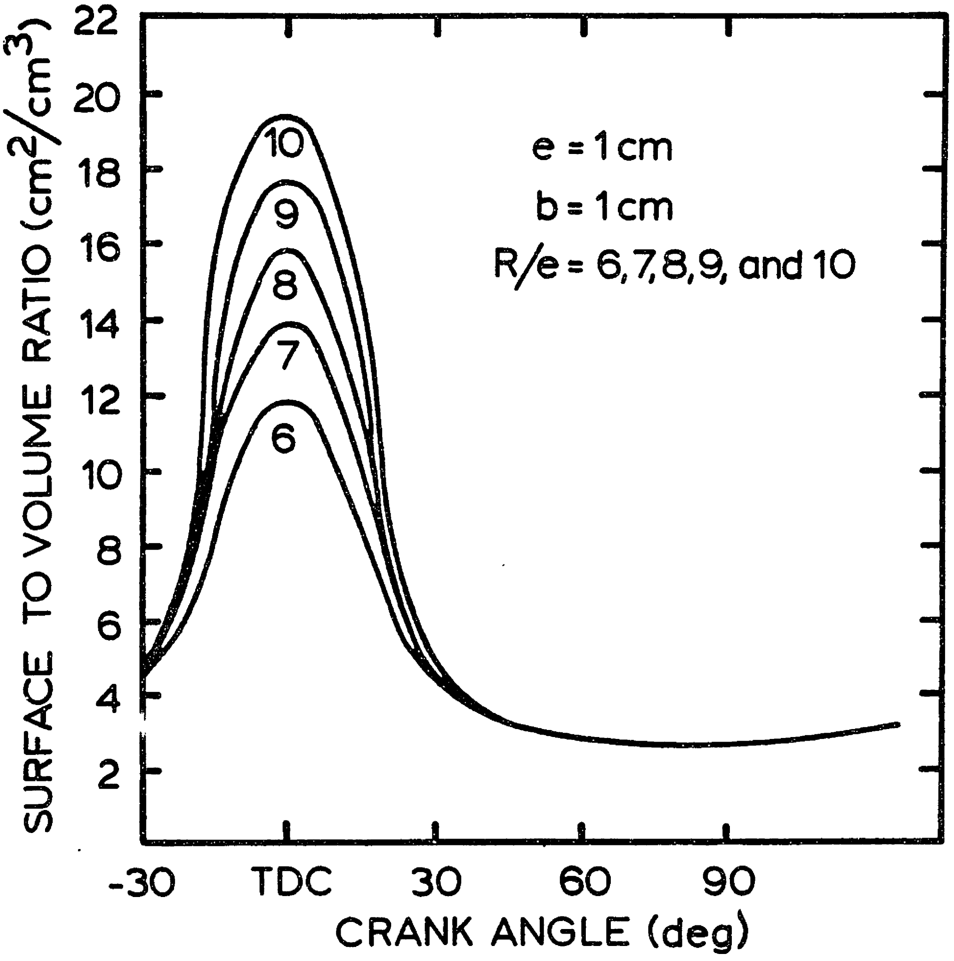

Figure 7. Wankel engine surface to volume ratio versus crank angle for several engine geometries.

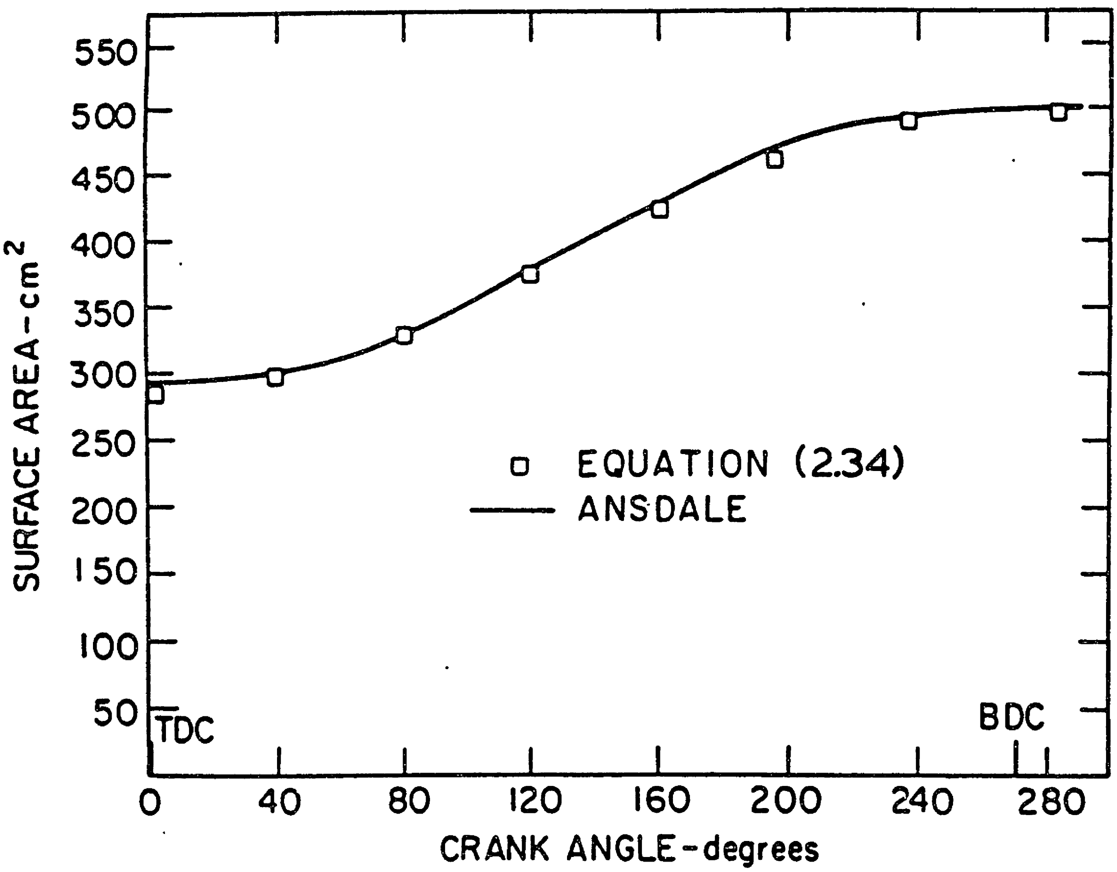

Figure 8. Comparison of true and approximate Wankel engine surface area calculations.

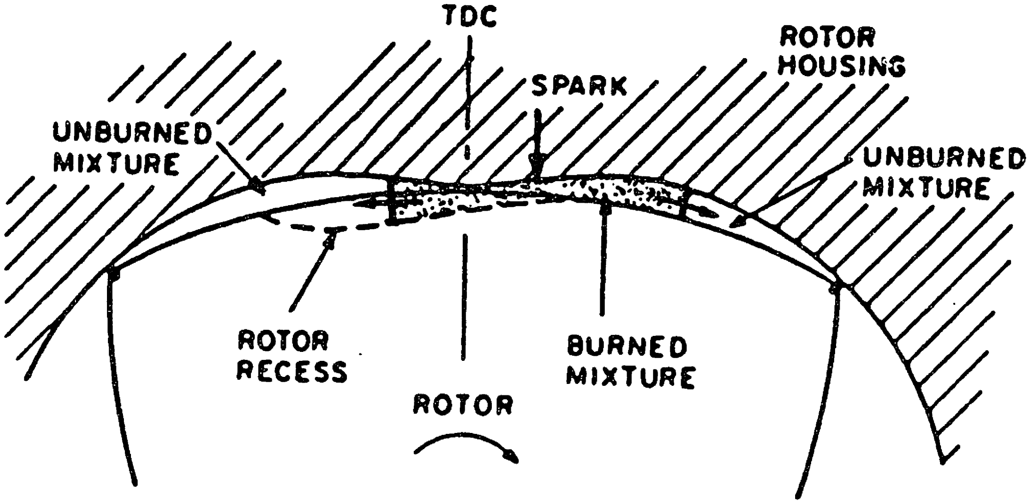

Figure 9. Diagram of the assumed flame front propagation.

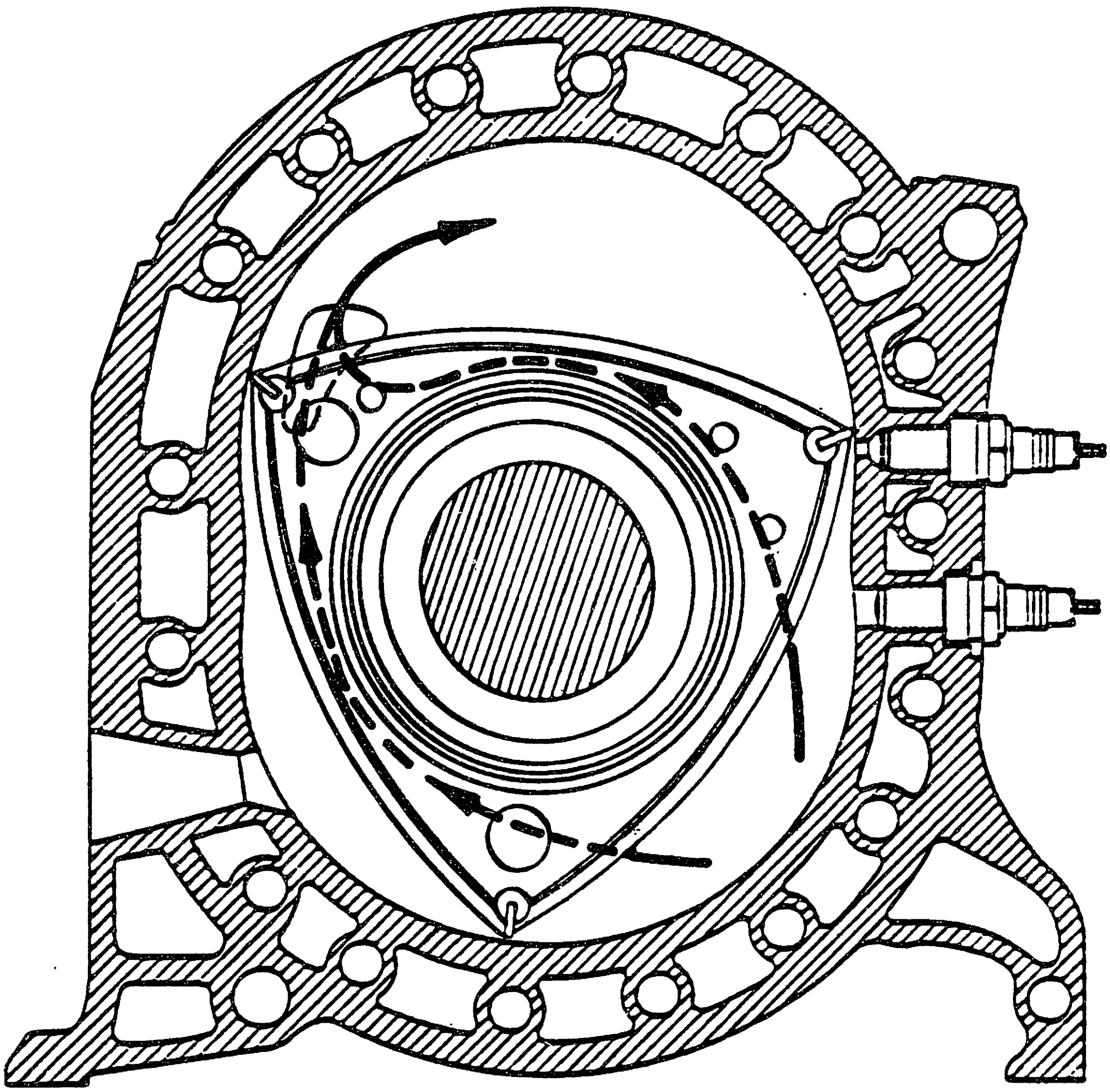

Figure 10. Schematic diagram of side seal leakage path.

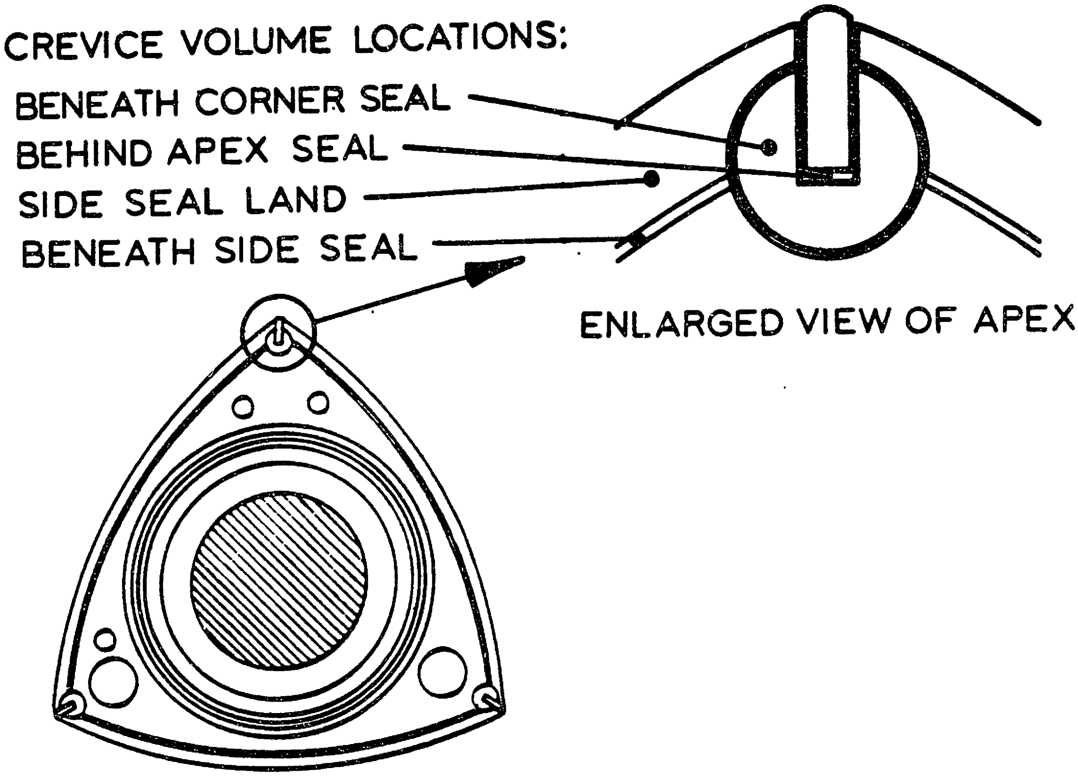

Figure 11. Diagram of crevice volume locations in the Wankel engine.

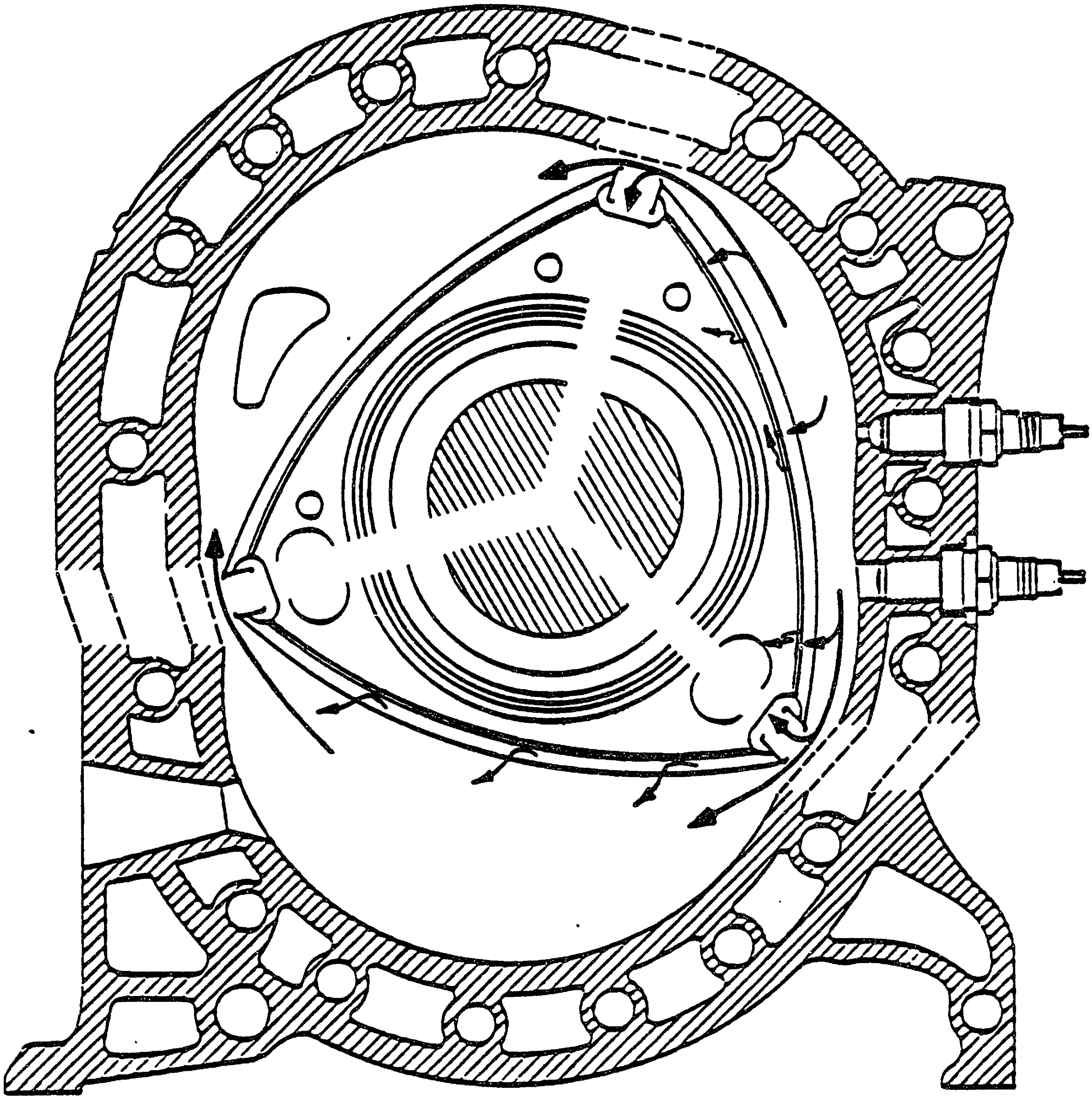

Figure 12. A pictorial schematic of crevice volumes and leakage gas flows.

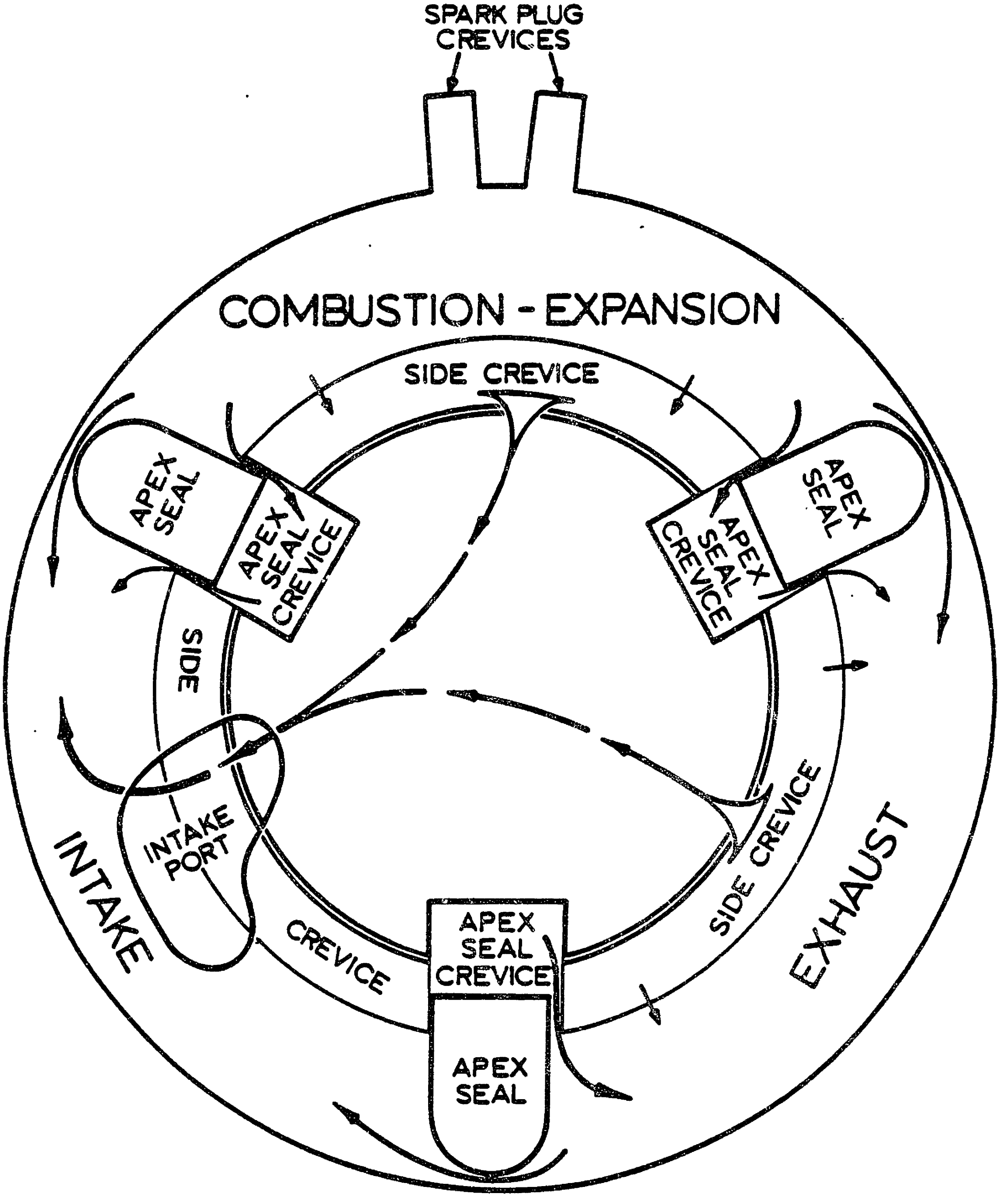

Figure 13. Schematic diagram of a simulation that explicitly models all leakage paths and crevice volumes.

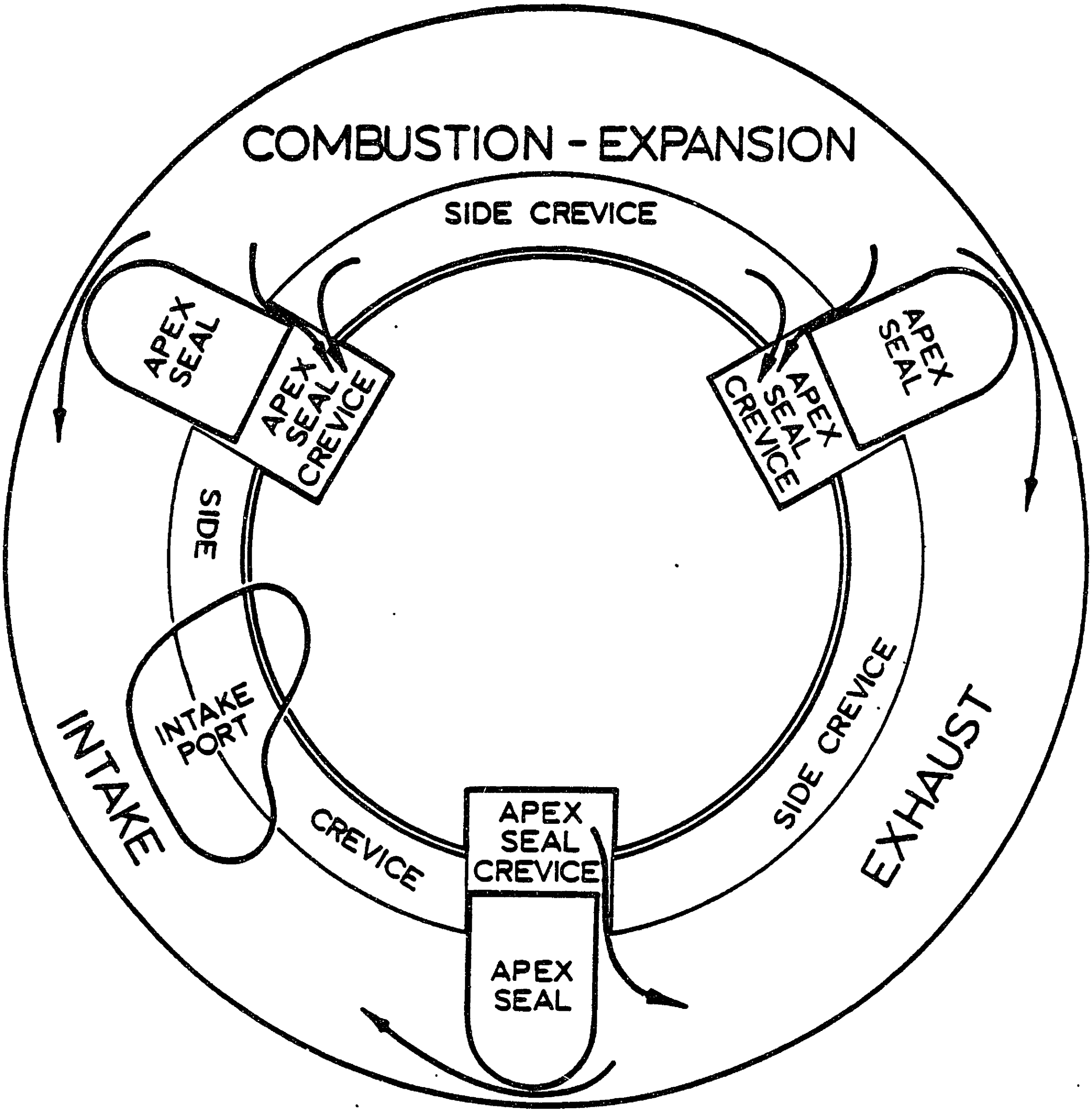

Figure 14. Schematic diagram of the crevice volume and leakage model as used in the program.

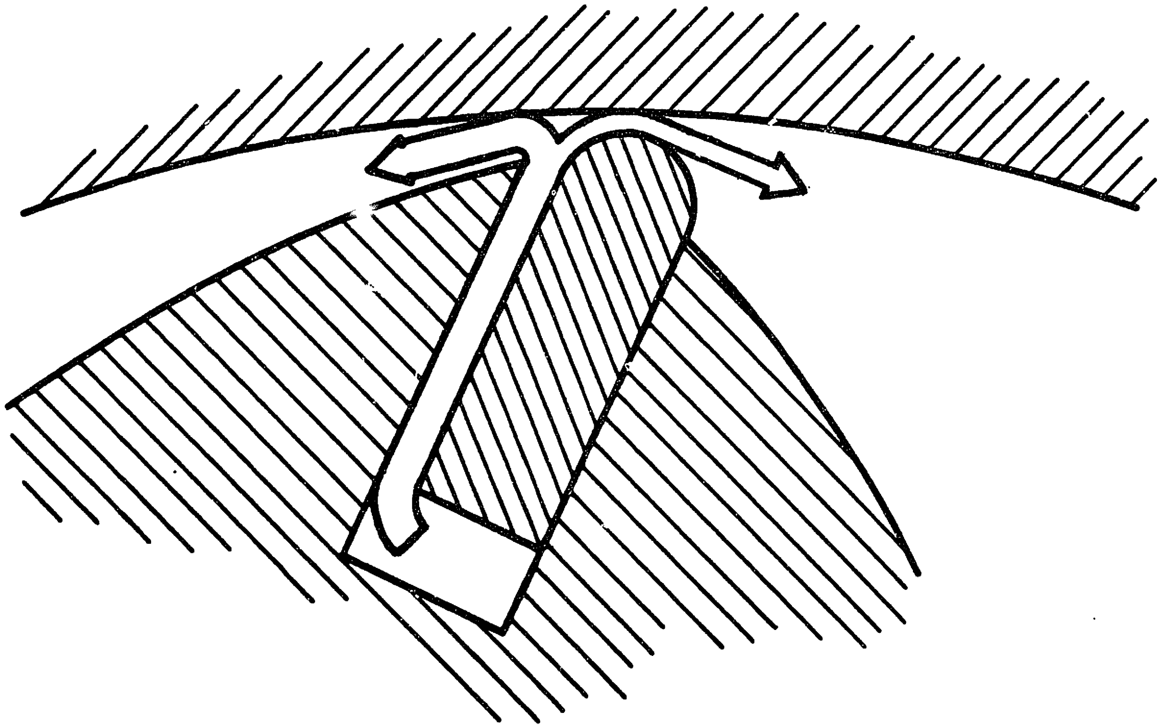

Figure 15. Diagram of crevice gas returning to chamber and being diverted into leakage flow.

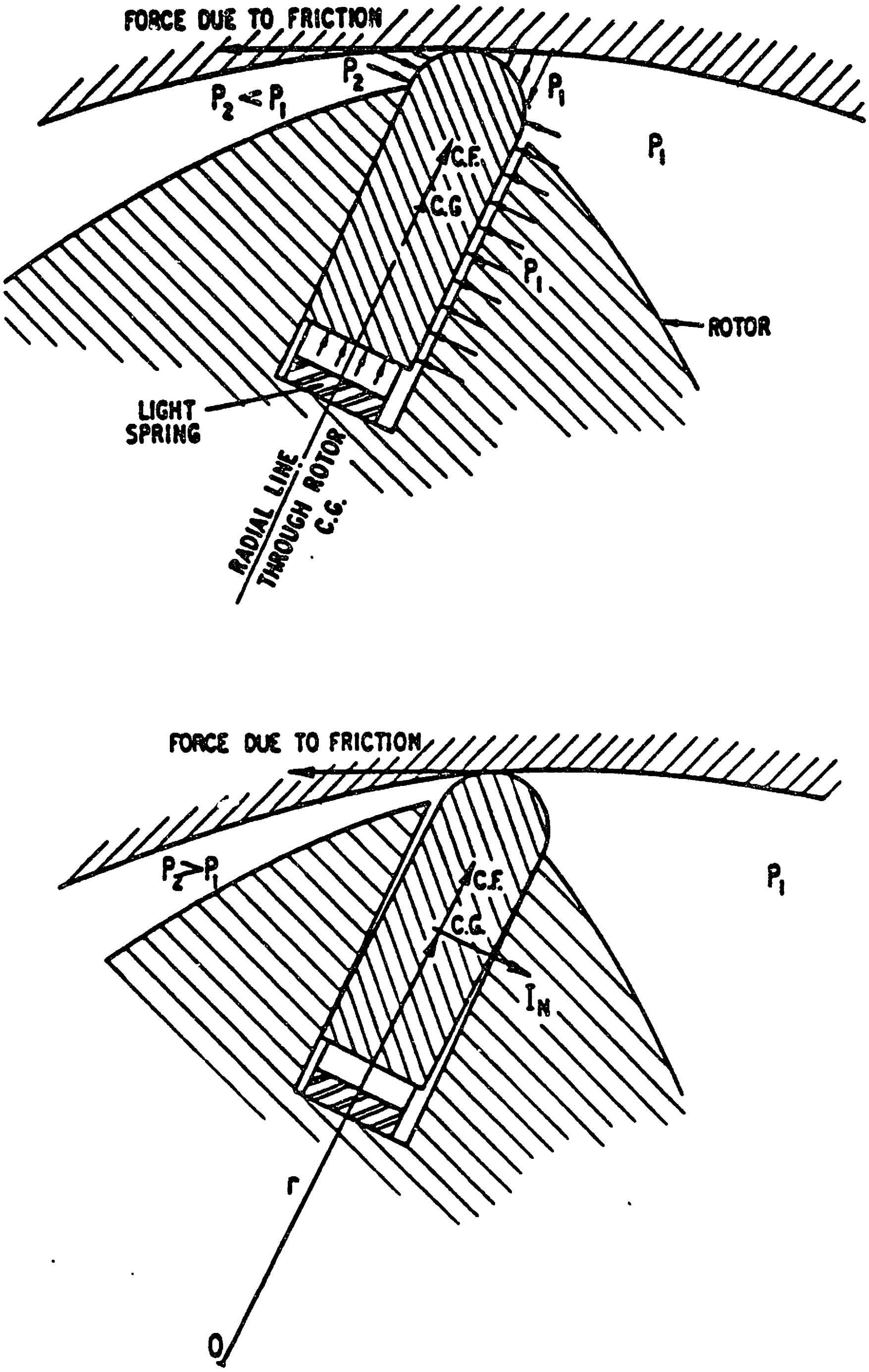

Figure 16. Motion of Apex seal as resultant pressure forces reverse direction.

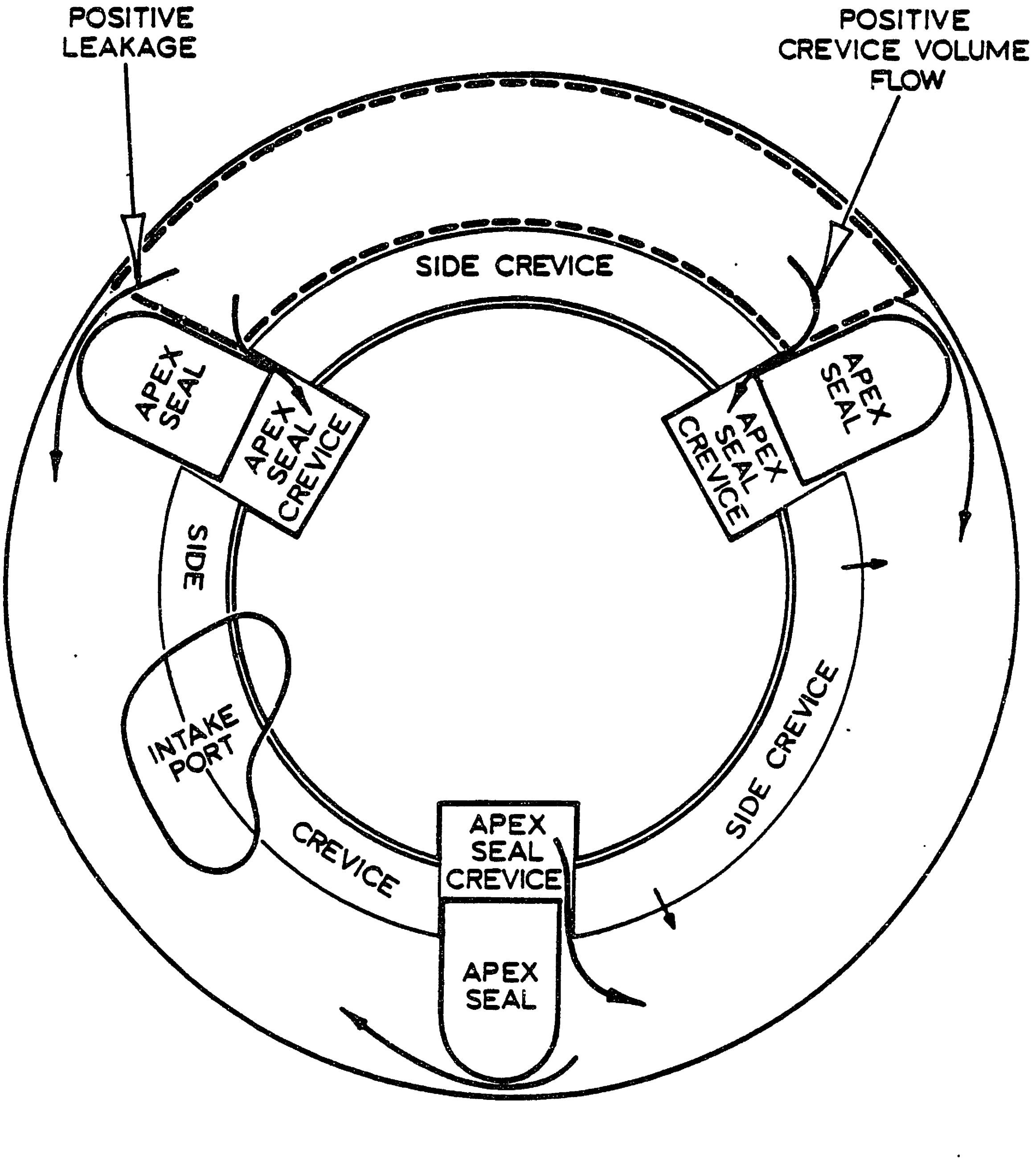

Figure 17. Schematic diagram of crevice volume and leakage model with a thermodynamic system imposed and positive mass flows shown.

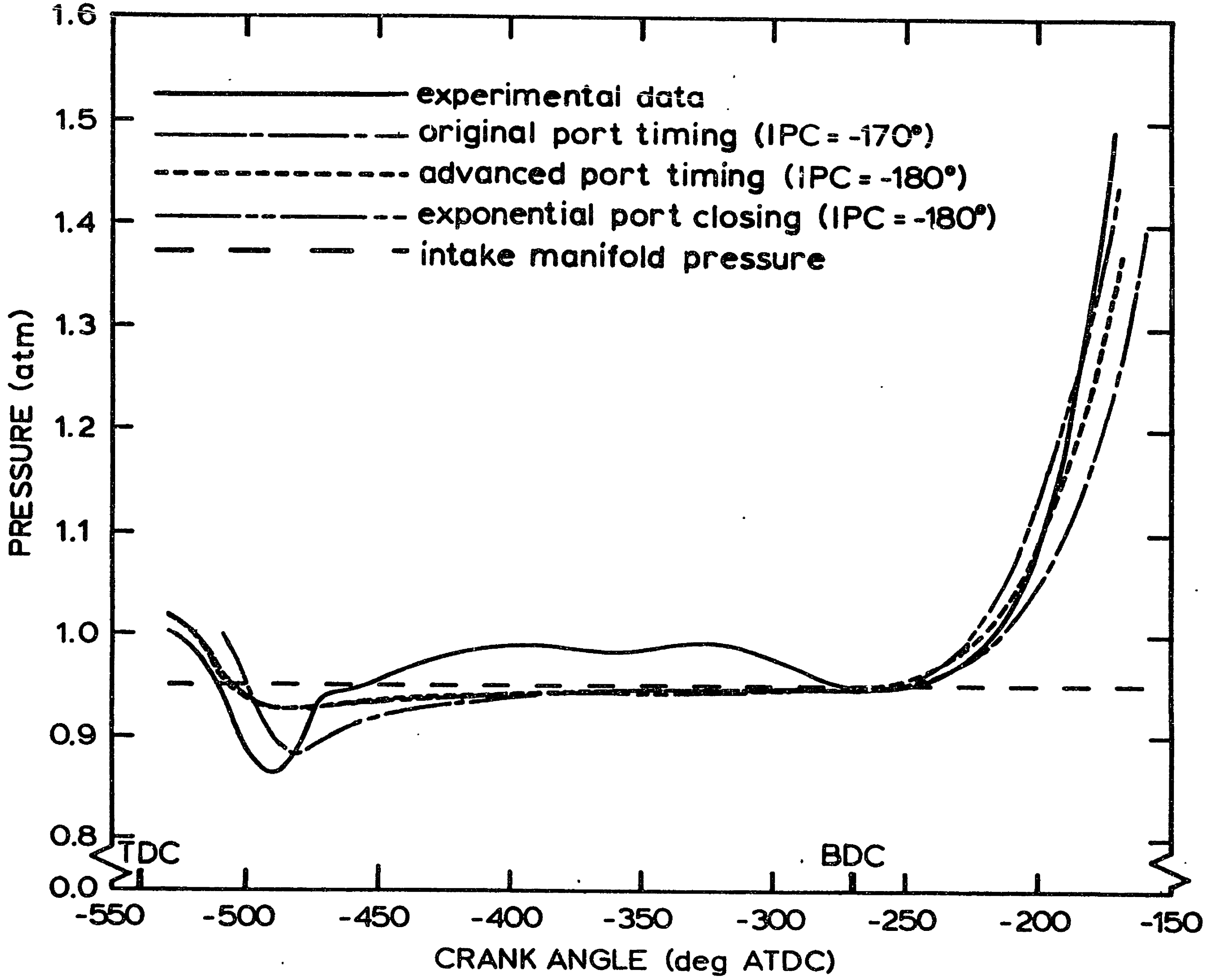

Figure 18. Comparison of intake chamber pressure for different intake port area profiles and experimental data.

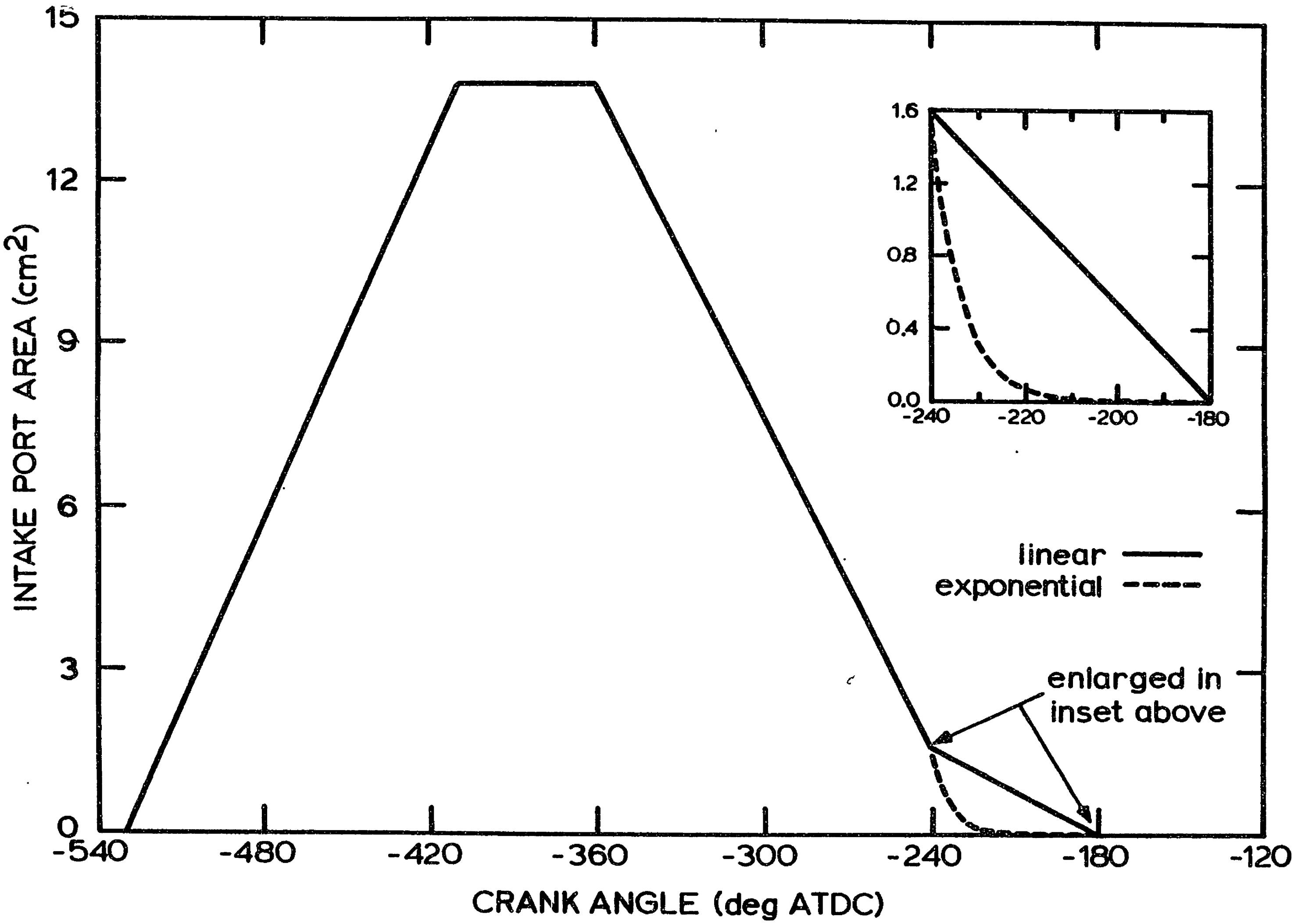

Figure 19. Comparison plot of intake port area profiles used during model calibration.

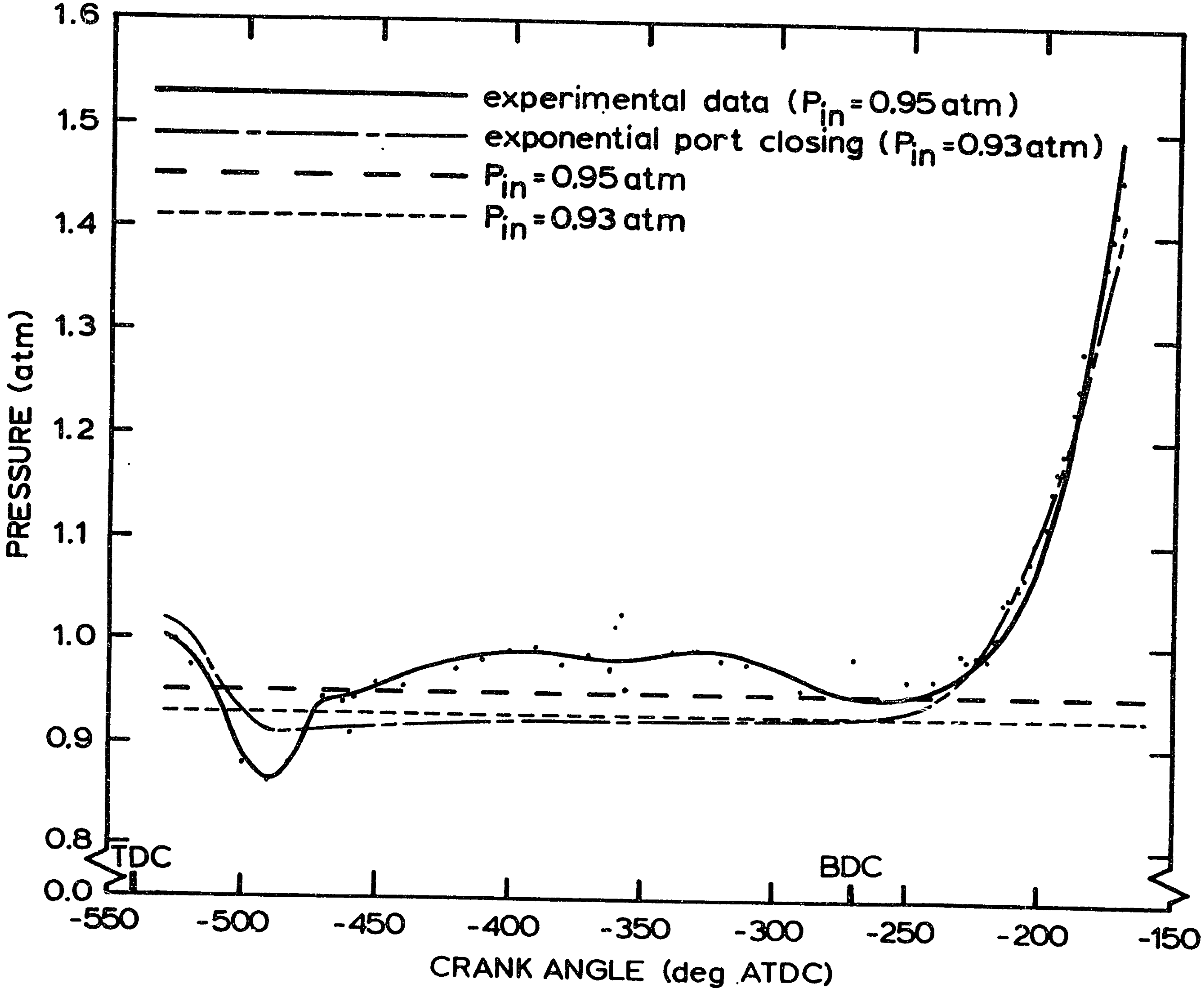

Figure 20. Comparison of intake chamber pressure between calibrated model and experimental data.

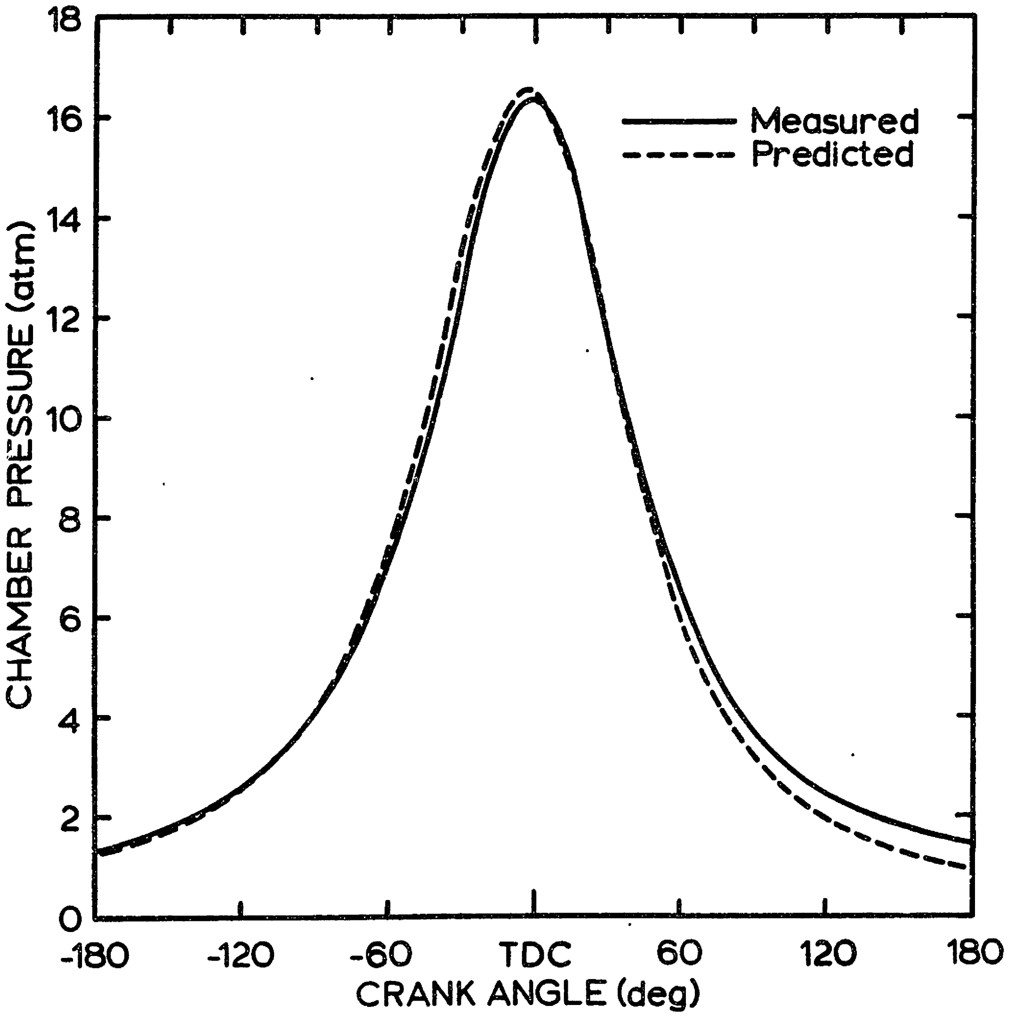

Figure 21. Comparison of measured and calibrated compression-expansion pressure trace for median engine speed and throttle setting.

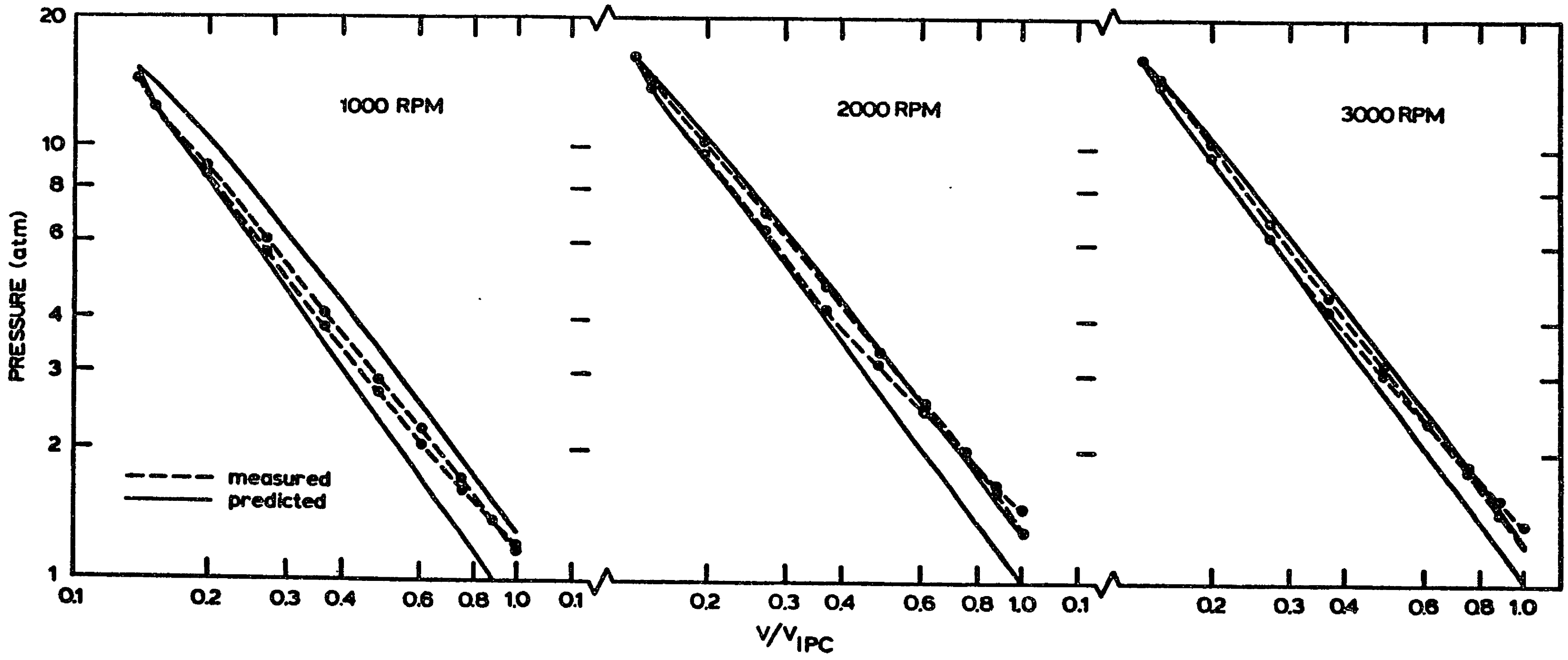

Figure 22. Log P versus normalized log V for motoring runs at three engine speeds: measured and predicted.

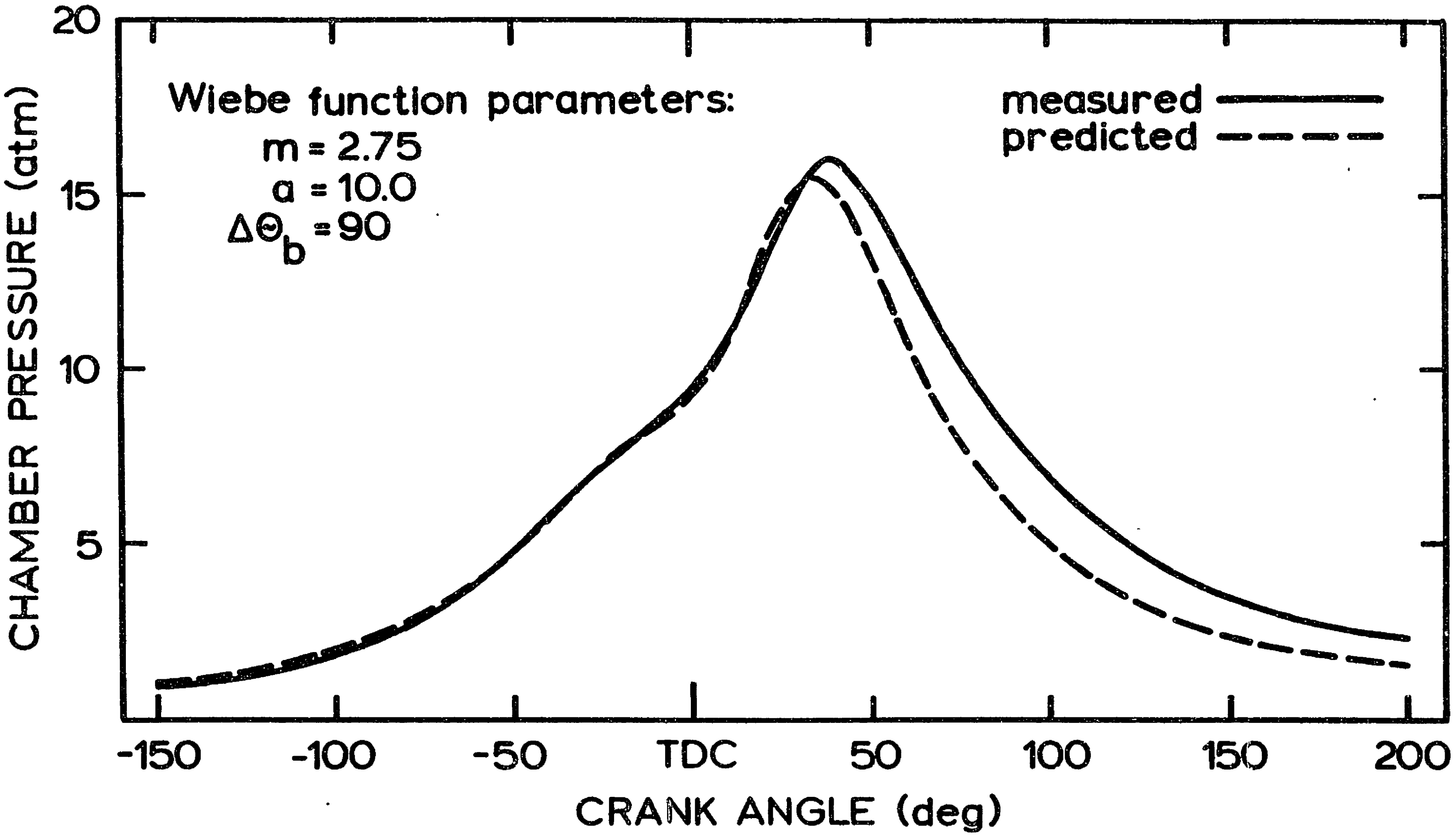

Figure 23. Comparison of predicted and measured pressure versus crank angle for low engine load and speed.

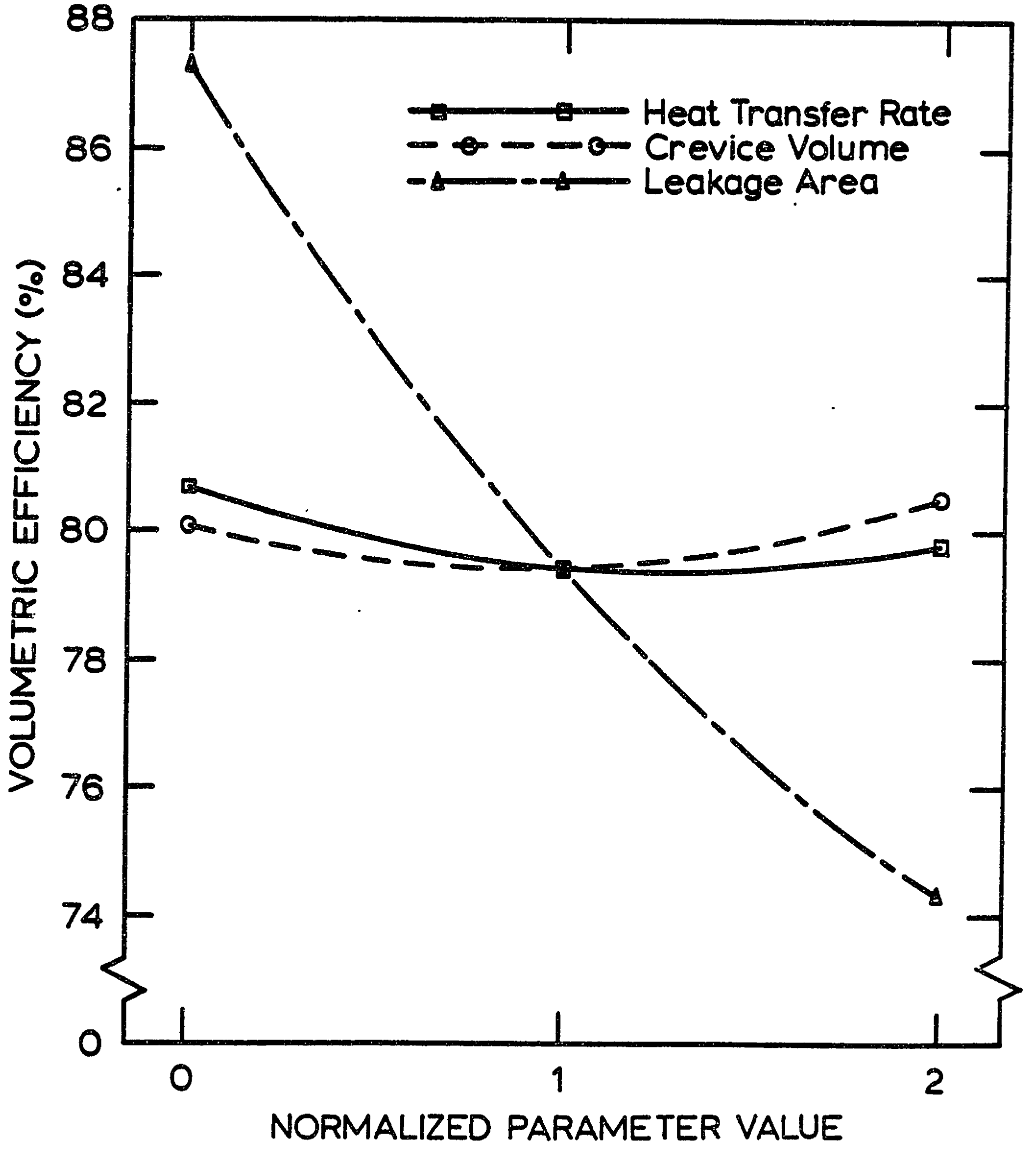

Figure 24. Effect of parametric variation on motoring volumetric efficiency.

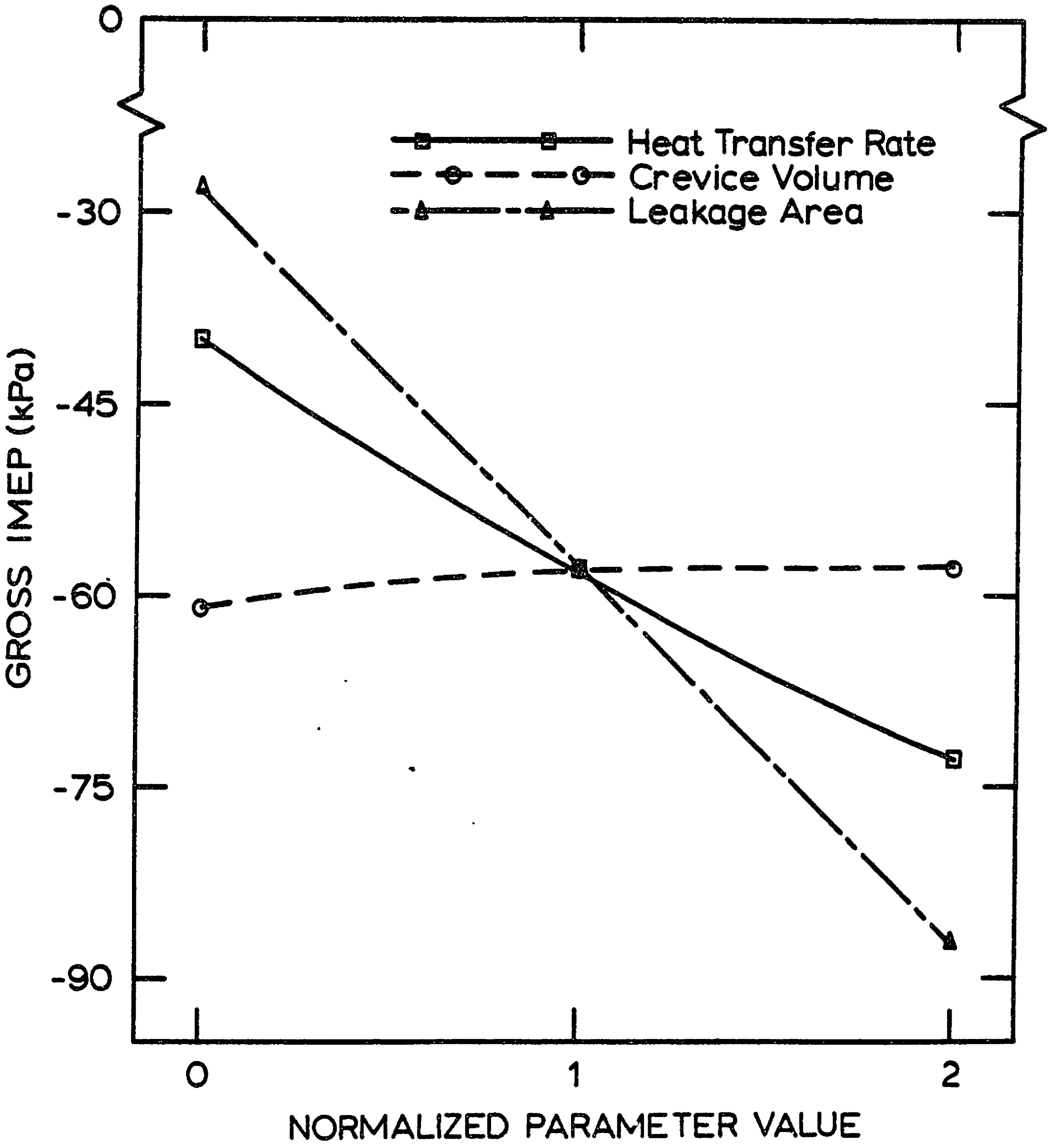

Figure 25. Effect of parametric variation on motoring gross IMEP.

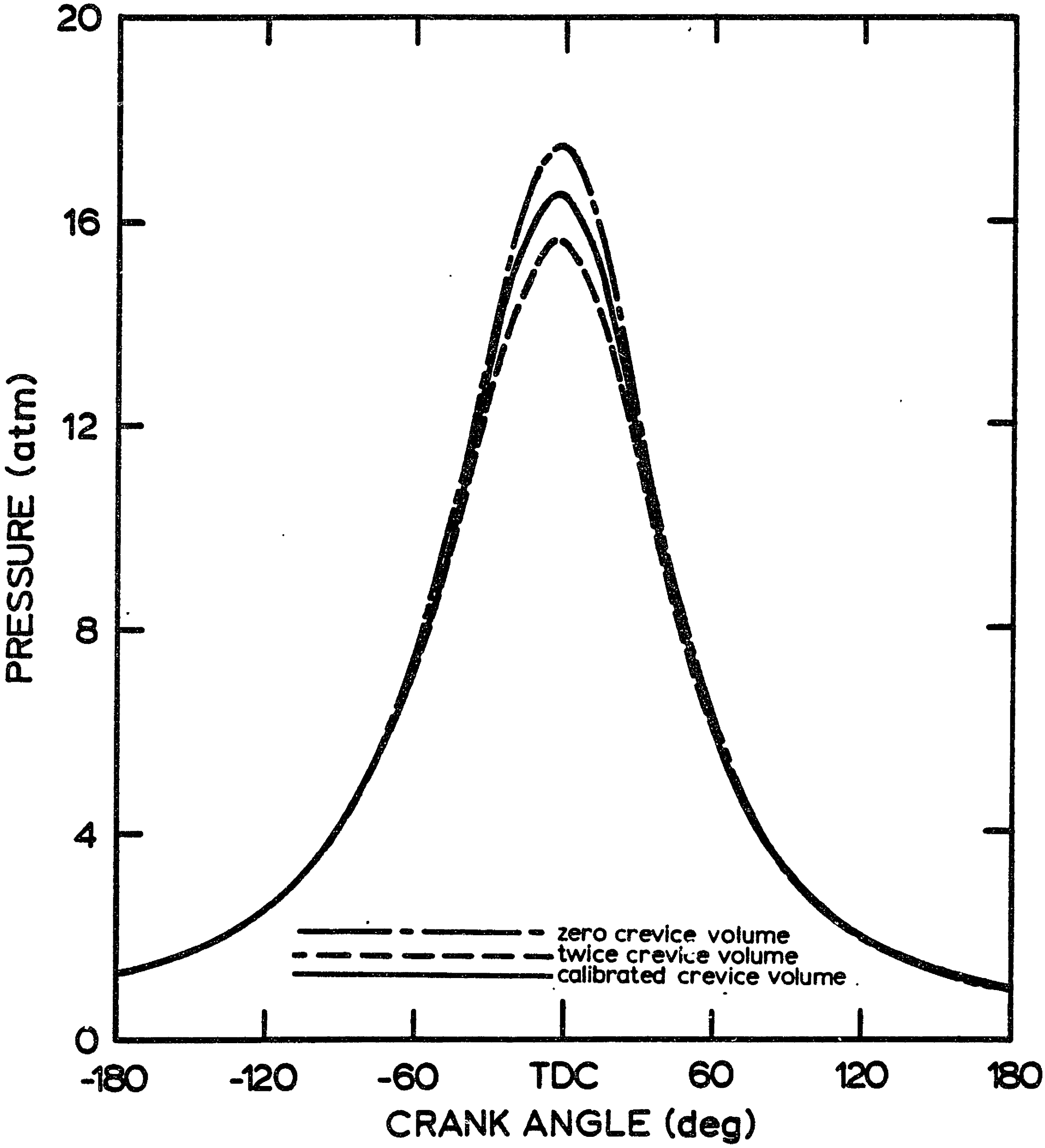

Figure 26. Effect of reducing crevice volumes on compression - expansion pressure trace (motoring).

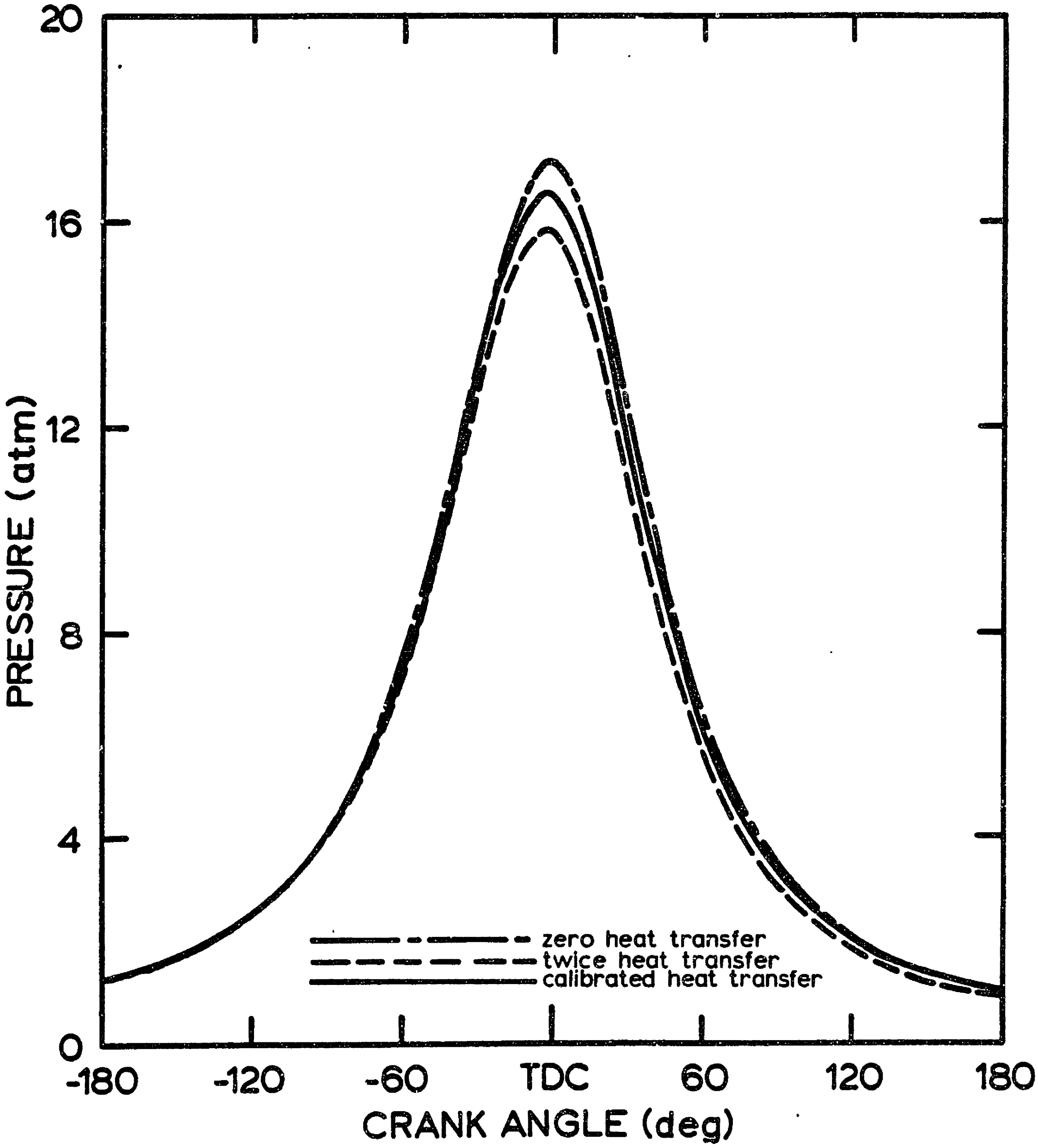

Figure 27. Effect of reducing leakage area on compression - expansion pressure trace (motoring).

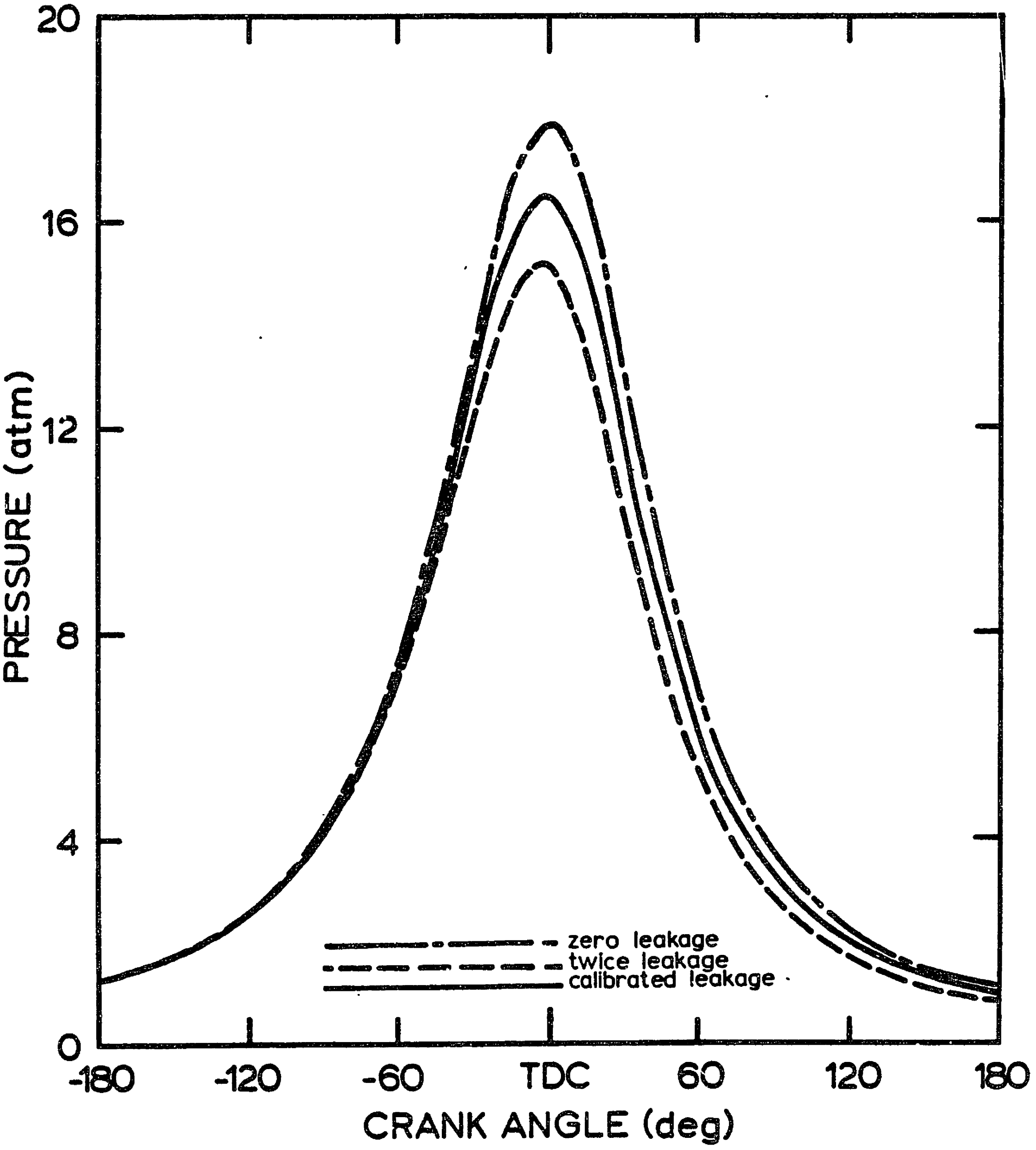

Figure 28. Effect of reducing leakage area on compression - expansion pressure trace (motoring).

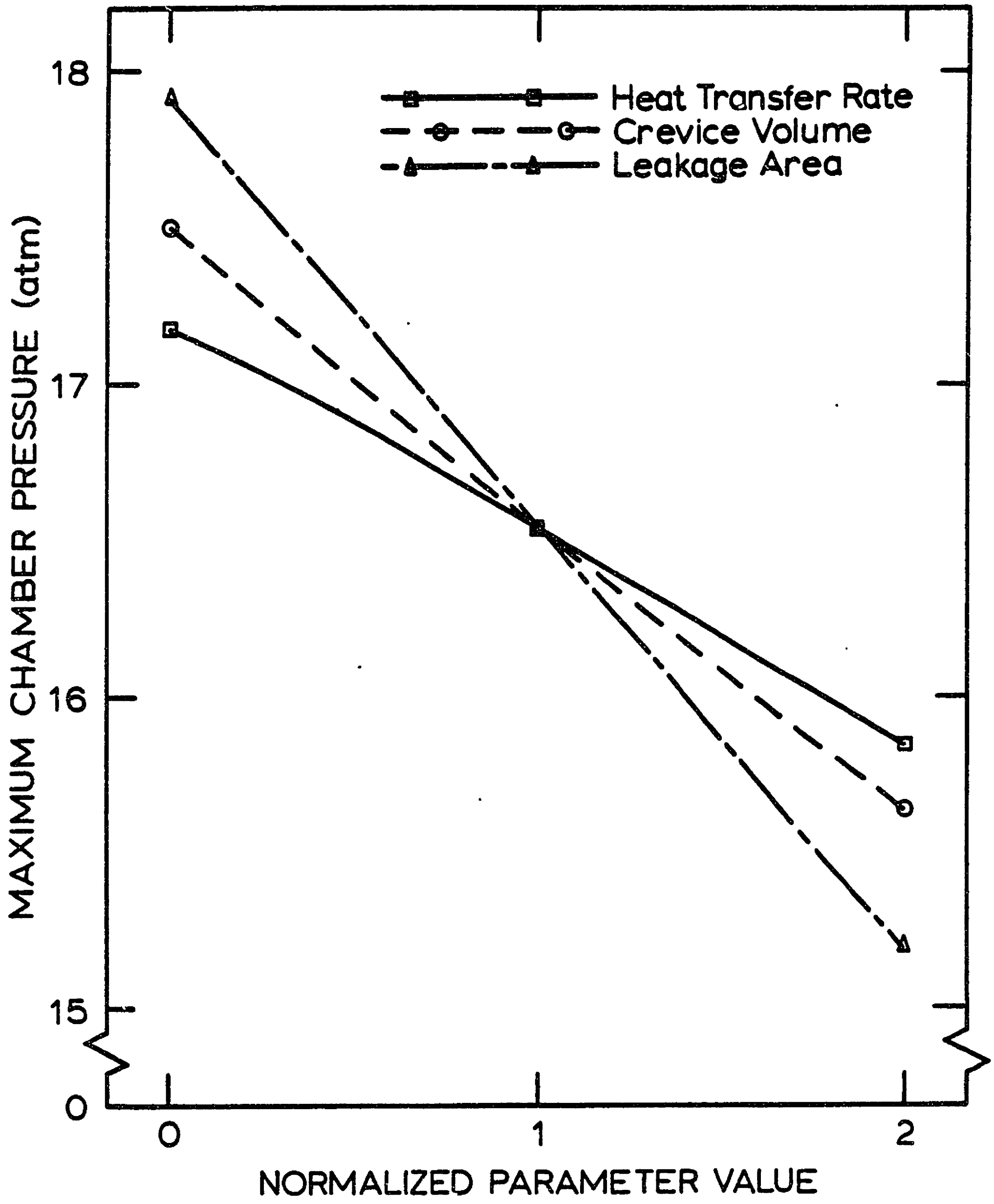

Figure 29. Effect of parametric variation on maximum motoring pressure.

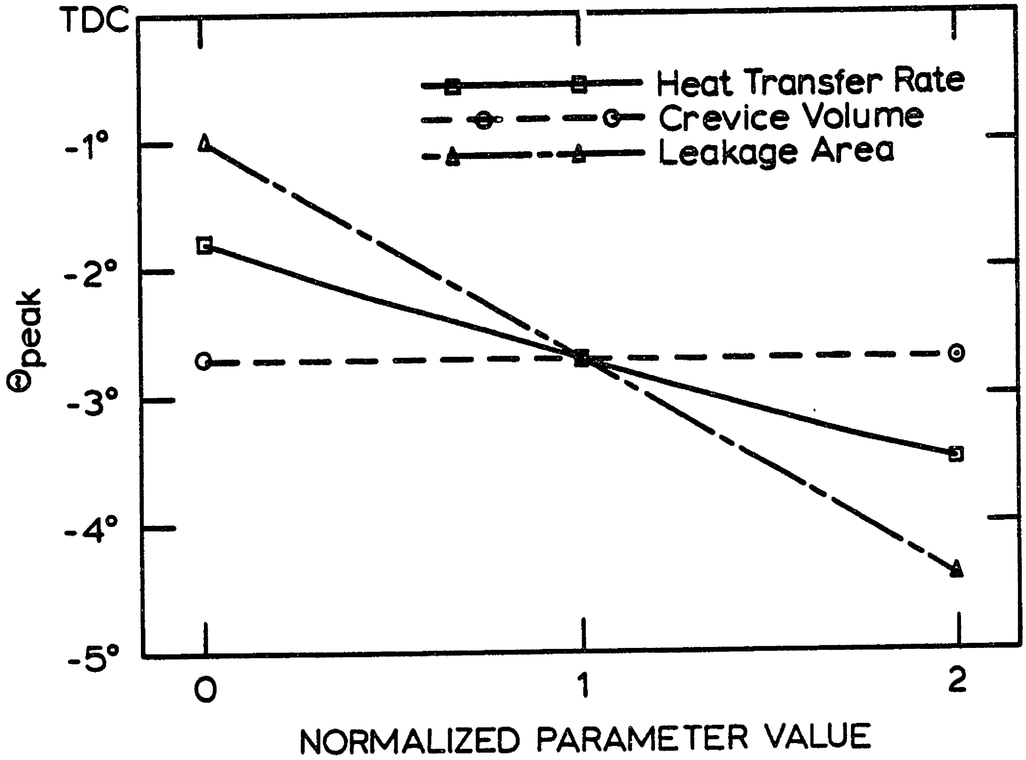

Figure 30. Effect of parametric variation on motoring θ_{peak}.

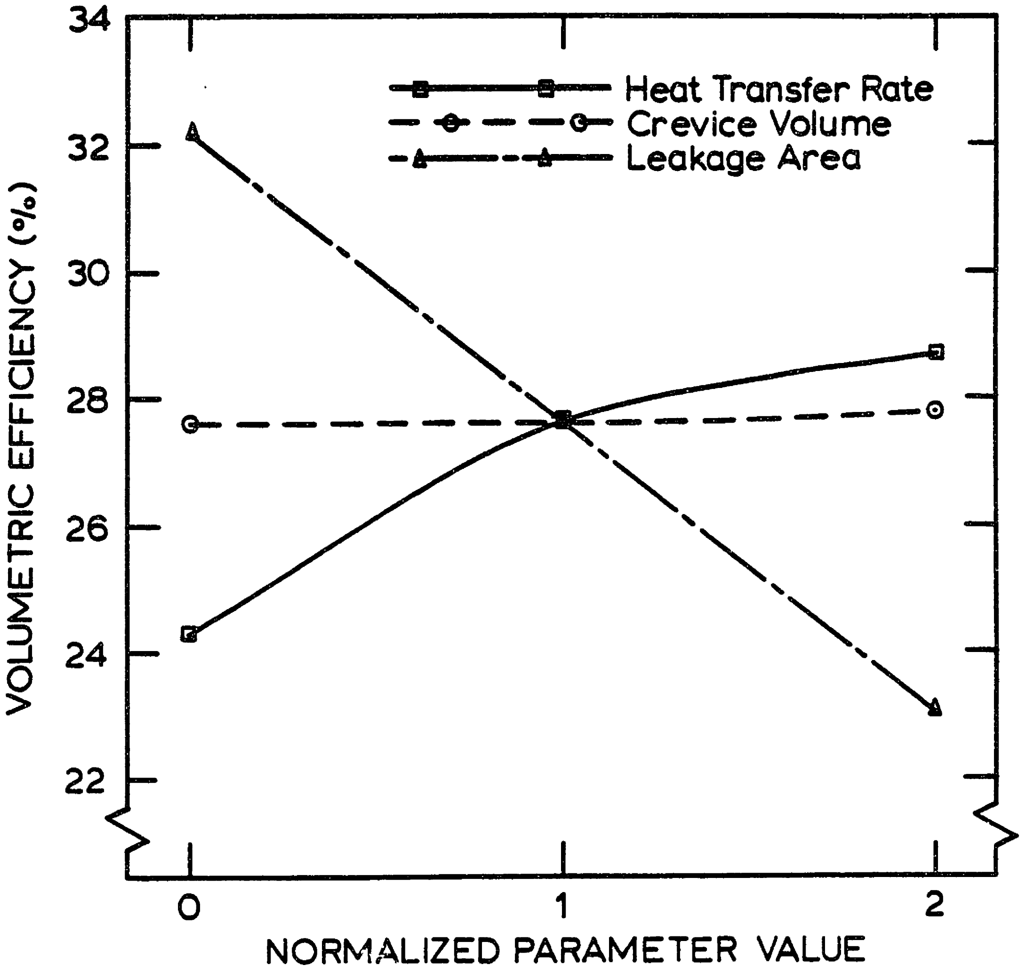

Figure 31. Effect of parametric variation on firing volumetric efficiency.

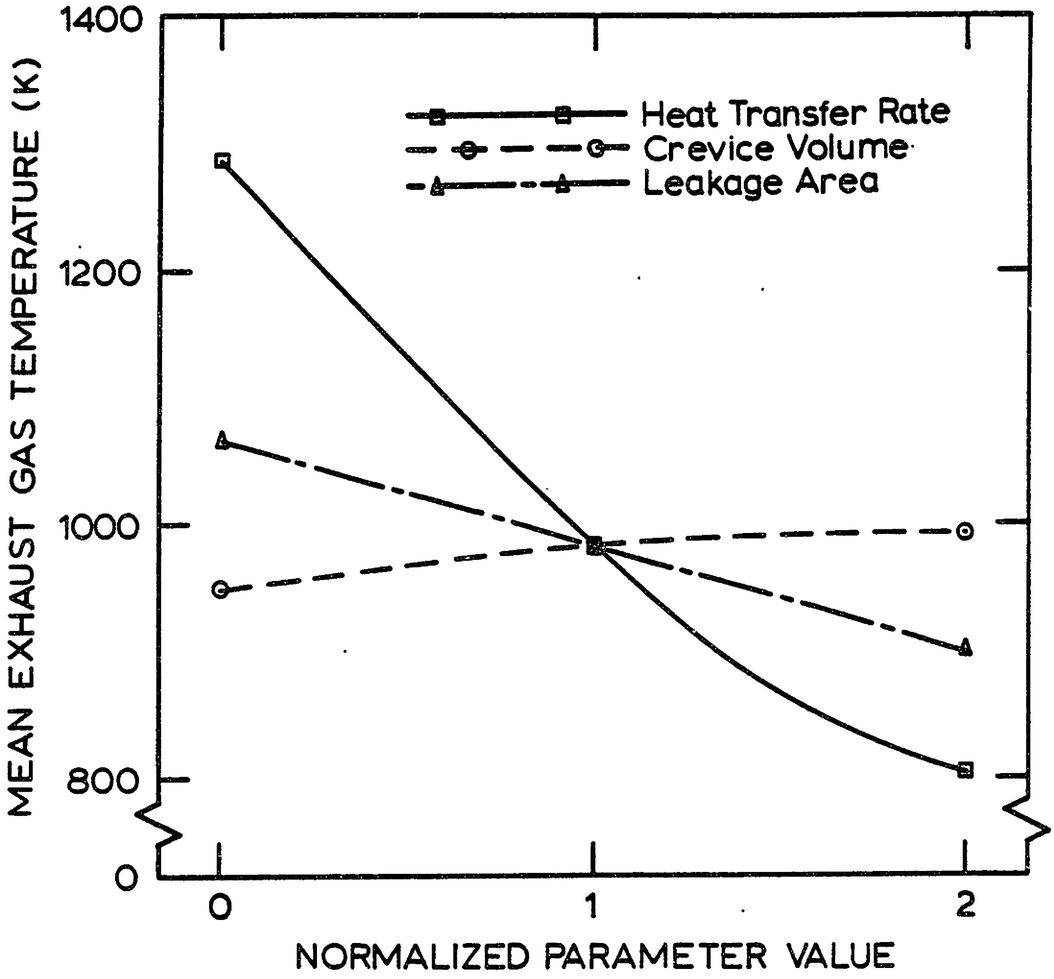

Figure 32. Effect of parametric variation on mean exhaust gas temperature at light load.

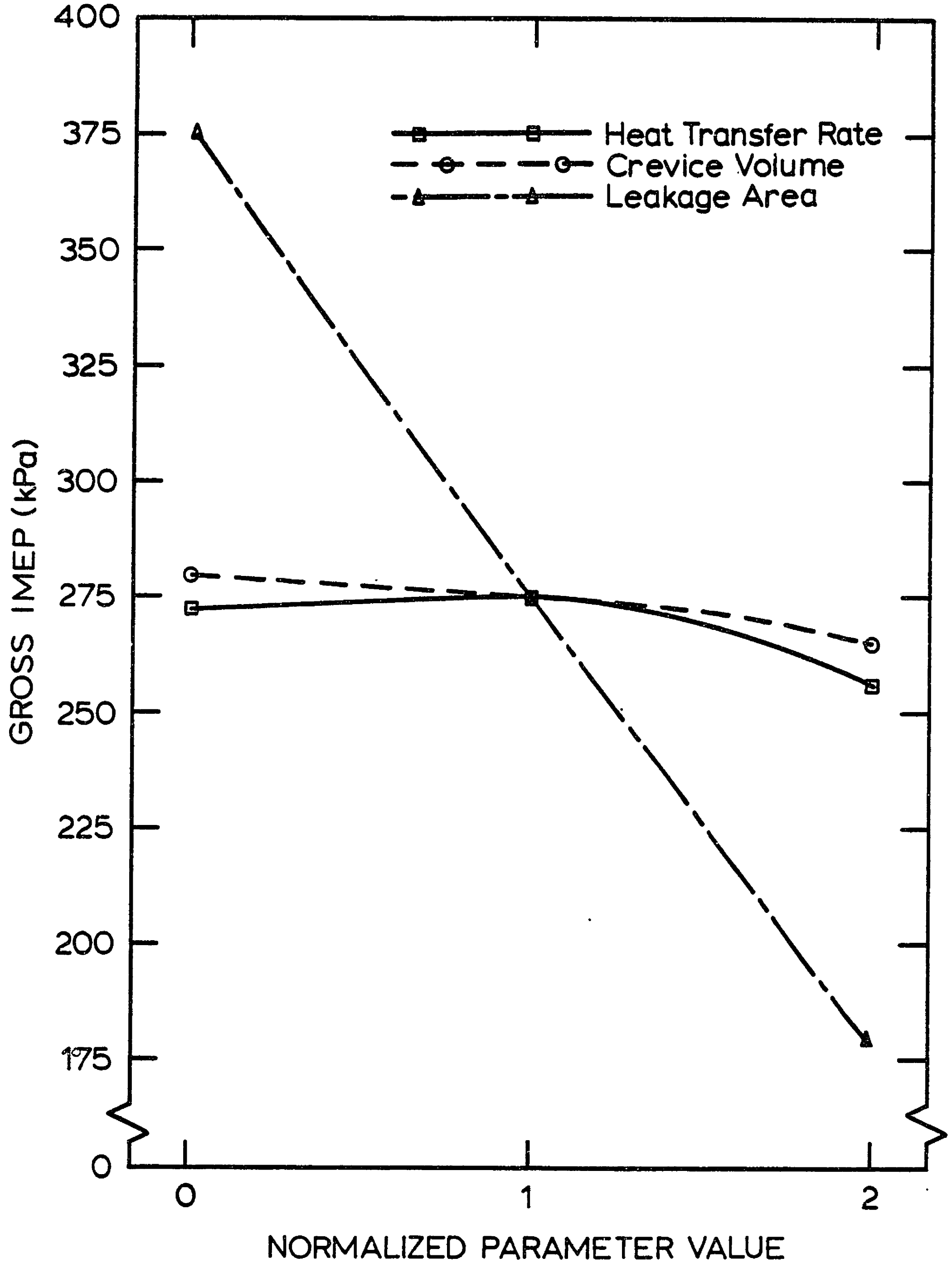

Figure 33. Effect of parametric variation on light load gross mean effective pressure.

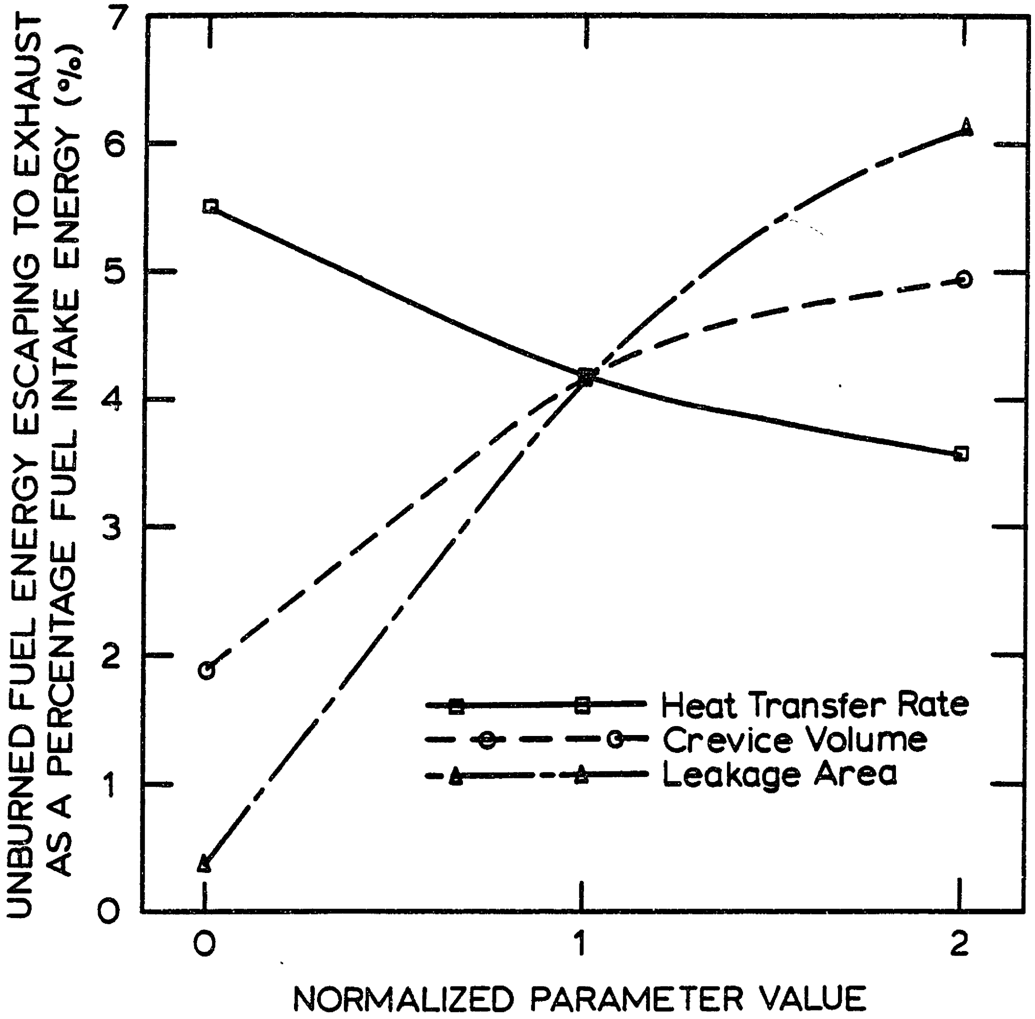

Figure 34. Effect of parametric variation on unburned fuel energy escaping to exhaust at light load.

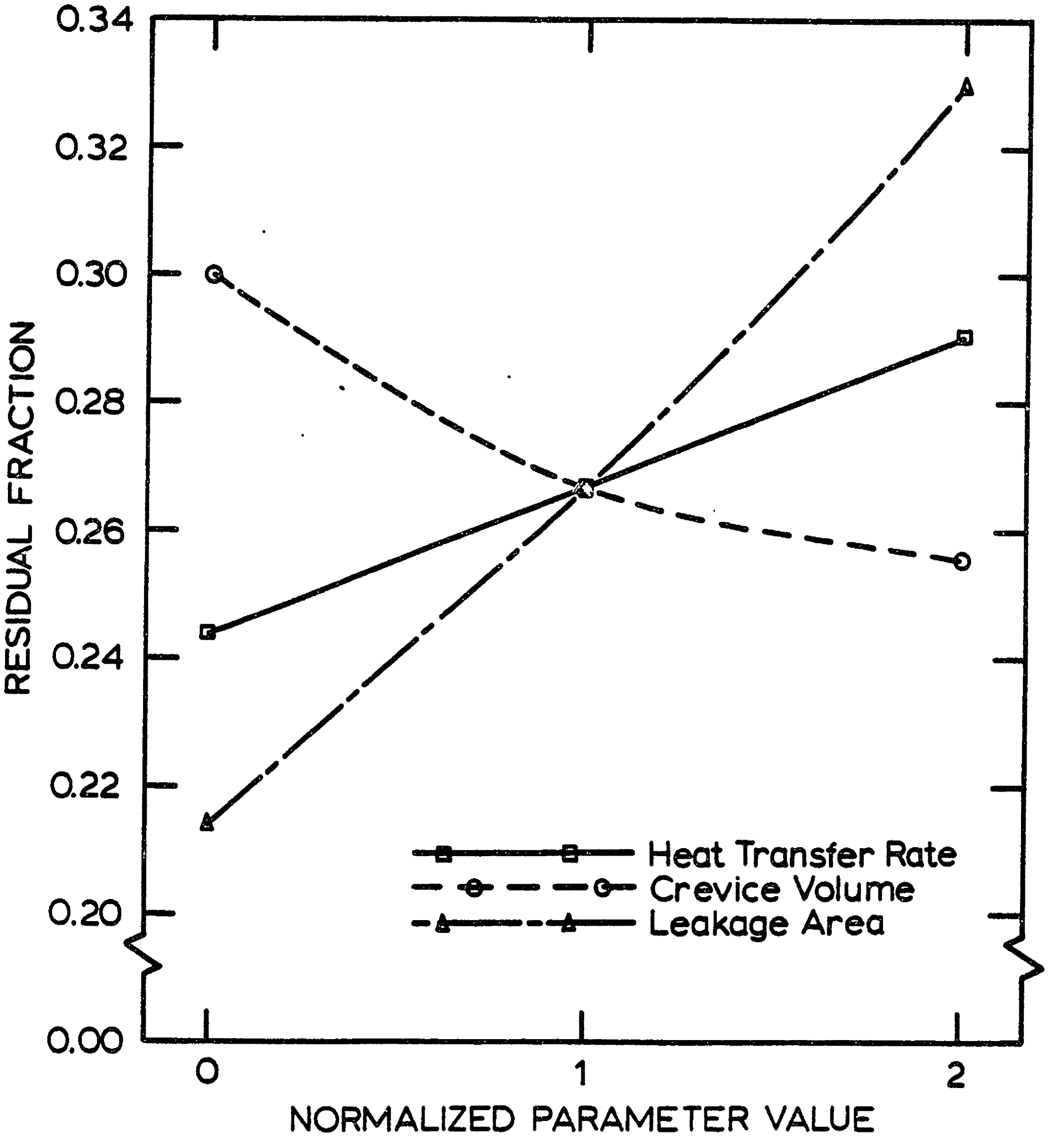

Figure 35. Effect of parametric variation on residual gas fraction at light load.

A PERFORMANCE MODEL OF A SPARK IGNITION WANKEL ENGINE: INCLUDING THE EFFECTS OF CREVICE VOLUMES, GAS LEAKAGE, AND HEAT TRANSFER

by

TIMOTHY JOHN NORMAN

B.S.M.E. University of Massachusetts, Amherst
(1981)

Submitted to the Department of
Mechanical Engineering
in Partial Fulfillment of the
Requirments of the Degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 1983

© Massachusetts Institute of Technology

VOLUME 2

Archives
MASSACHUSETTS INSTITUTE
OF TECHNOLOGY
JUN 23 1983
LIBRARIES

WANKEL CYCLE SIMULATION CODE

```
C
C
C
C                 ZERO-DIMENSIONAL SIMULATION OF THE
C
C
C                 SPARK-IGNITION WANKEL ENGINE CYCLE:
C
C
C                      A PERFORMANCE PREDICTIVE MODEL
C
C
C
C
C
C
C                                   BY
C
C
C
C
C                           TIMOTHY J. NORMAN
C
C                           JOHN B. HEYWOOD
C
C                           STEPHEN G. POULOS
C
C                           S. HOSSEIN MANSOURI
C
C
C
C
C                      SLOAN AUTOMOTIVE LABORATORY
C
C
C                 MASSACHUSETTS INSTITUTE OF TECHNOLOGY
C
C
C
C
C
C
C                             FEBRUARY 1983
C
C
C
C
C
C
C
C     ADDRESS: TIMOTHY J. NORMAN
C              ROOM 3-339, 77 MASS. AVE.
C              MASSACHUSETTS INSTITUTE OF TECHNOLOGY
C              CAMBRIDGE, MASS  02139
C
```

```
C
C
C
C
C     PURPOSE
C
C        THE PROGRAM IS A ZERO-DIMENSIONAL SIMULATION OF THE
C
C        WANKEL ROTARY SPARK-IGNITION ENGINE OPERATING CYCLE.
C
C        THE PROGRAM CALCULATES TEMPERATURE AND PRESSURE IN THE
C
C        CHAMBER AND PREDICTS ENGINE PERFORMANCE AS A FUNCTION
C
C        OF ENGINE DESIGN AND OPERATING CONDITIONS.
C
C
C     DESCRIPTION OF PARAMETERS:
C
C        PARAMETER  INPUT  OUTPUT   DESCRIPTION
C
C
C     1  GEOMETRICAL AND DESIGN PARAMETERS
C
C        ECCEN       YES     NO       ECCENTRICITY OF ROTOR (CM)
C        ROTRAD      YES     NO       RADIUS OF ROTOR (CM)
C        DEPTH       YES     NO       HEIGHT OF CHAMBER (CM)
C        VFLANK      YES     NO       VOLUME OF ROTOR POCKET (CM**3)
C        TIPO        YES     NO       INTAKE PORT OPENS (DEG)
C        TIPC        YES     NO       INTAKE PORT CLOSES (DEG)
C        TEPO        YES     NO       EXHAUST PORT OPENS (DEG)
C        TEPC        YES     NO       EXHAUST PORT CLOSES (DEG)
C        THIPO       YES     NO       INTAKE PORT OPENING TIME (DEG)
C        THEPO       YES     NO       EXHAUST PORT OPENING TIME (DEG)
C        IPA         YES     NO       INTAKE PORT OPEN AREA (CM**2)
C        EPA         YES     NO       EXHAUST PORT OPEN AREA (CM**2)
C
C
C     2  OPERATING PARAMETERS
C
C        PATM        YES     NO       ATMOSPHERIC PRESSURE (ATM)
C        TATM        YES     NO       ATMOSPHERIC TEMPERATURE (K)
C        PIM         YES     NO       INTAKE PRESSURE (ATM)
C        PEM         YES     NO       EXHAUST PRESSURE (ATM)
C        TFRESH      YES     NO       FRESH CHARGE TEMPERATURE (K)
C        TEGR        YES     NO       EGR TEMPERATURE (K)
C        EGR         YES     NO       EXHAUST GAS RECIRCULATION (%)
C        TSPARK      YES     NO       IGNITION TIMING (DEG)
C        RPM         YES     NO       ENGINE SPEED (RPM)
C
C
C     3  LEAKAGE AND CREVICE VOLUME SUB-MODEL CONSTANTS
C
C        AREALK      YES     NO       LEAK AREA PER APEX SEAL (CM**2)
C        CREVOL      YES     NO       CREVICE VOLUME PER APEX SEAL (CM**2)
```

```
C         TPRINT     YES     NO       PRINTING INTERVAL DURING INTAKE,
C         ------     ---     --       COMPRESSION, AND EXHAUST (DEG)
C         TPRINX     YES     NO       PRINTING INTERVAL DURING COMBUSTION
C         ------     ---     --       AND EXPANSION(DEG)
C
C
C      9  OPERATING CASE
C
C         FIRE       YES     NO       = .TRUE.  FOR FIRING CASE
C         ----       ---     --       = .FALSE. FOR MOTORING CASE
C         SPBURN     YES     NO       = .TRUE.  FOR SPECIFIED BURN RATE
C         ----       ---     --       = .FALSE. NOT USED IN THIS PROGRAM
C
C
C     10  COMBUSTION MODEL INPUTS
C
C         XBZERO     YES     NO       INITIAL MASS FRACTION BURNED
C         ------     ---     --       (INITIALIZES COMBUSTION MODEL)
C         XBSTOP     YES     NO       MASS FRACTION BURNED AT END OF
C         ------     ---     --       COMBUSTION.
C         DTBRN      YES     NO       BURN DURATION FOR WIEBE
C         -----      ---     --       FUNCTION (DEG)
C         CONSPB     YES     NO       WIEBE FUNCTION CONSTANT
C         EXSPB      YES     NO       WIEBE FUNCTION EXPONENT
C
C
C
C      REMARKS
C         NONE
C
C
C      SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED:
C
C      1  WORKING SUBROUTINES
C
C         INTAKE     CMPRES     CMBSTN     EXAUST    CREVIC
C         GINT1      GINT2      GCMP       GEXH
C
C
C      2  SPECIAL UTILITY SUBROUTINES
C
C         IPACD      EPACD      CSAVDV     TABLE     BUILD
C
C
C      3  GENERAL UTILITY SUBROUTINES
C
C         UPROP      HPROD      CLDPRD     HELPHT
C         UTRANS     BTRANS     MFLRT      THERMO     PTCHEM
C         FUELDT     WRITE      ERRCHK     INTRP      ITRATE
C         ODERT      DERT1      ROOT       STEP1
C
C
C      METHOD
C         SEE REPORT
C
```

```
C        TCREV       YES     NO        CREVICE VOLUME GAS TEMPERATURE (K)
C
C
C     4  HEAT TRANSFER CONSTANTS: NU = CONS'T * (REYNOLDS NO.)**EXP'NT
C
C        CONHT       YES     NO        CONS'T
C        EXPHT       YES     NO        EXP'NT
C        CON1        YES     NO        CONSTANT FOR NON-FIRE CHARACTERISTIC
C                    ---     --        VELOCITY
C        CON2        YES     NO        CONSTANT FOR COMBUSTION
C                    ---     --        CHARACTERISTIC VELOCITY
C        TROTOR      YES     NO        ROTOR SURFACE TEMPERATURE (K)
C        TSIDE       YES     NO        SIDE PLATE SURFACE TEMPERATURE (K)
C        THOUS       YES     NO        HOUSING SURFACE TEMPERATURE (K)
C
C
C
C     5  FUEL AND AIR SPECIFICATIONS
C
C        FUELTP      YES     NO        = 1   :   ISOOCTANE
C        ------      ---     --        = 2   :   PROPANE
C        ------      ---     --                  (SEE SUBROUTINE FUELDT)
C        PHI         YES     NO        EQUIVALENCE RATIO
C        CX          NO      NO        NUMBER OF CARBON ATOMS IN THE
C        -----       --      --        FUEL (8.0 FOR C8H18)
C        DEL         NO      NO        MOLAR C:H RATIO OF THE FUEL
C        PSI         NO      NO        MOLAR N:O RATIO OF AIR
C        QLOWER      NO      NO        LOWER HEATING VALUE OF FUEL (MJ/KG)
C
C
C     6  ERROR TOLERANCES
C
C        AREROT      YES     NO        ERROR TOLERANCE FOR CALCULATING
C        ------      ---     --        ROOTS (SEE SUBROUTINE ODERT).
C        CIINTG      YES     NO        ERROR TOLERANCE FOR INTEGRATION
C        ------      ---     --        DURING INTAKE PROCESS (SEE
C        ------      ---     --        SUBROUTINE ODERT).
C        CCINTG      YES     NO        SAME, DURING COMPRESSION PROCESS
C        CBINTG      YES     NO        SAME, DURING COMBUSTION PROCESS
C        CEINTG      YES     NO        SAME, DURING EXHAUST PROCESS
C        REL         YES     NO        RELATIVE ERROR TOLERANCE FOR
C        ---         ---     --        CONTINUING INTEGRATION TO TOUT
C        ---         ---     --        (SEE MAIN PROGRAM).
C        MAXITS      YES     NO        MAXIMUM NUMBER OF ITERATIONS TO
C        ------      ---     --        COMPLETE CYCLE SIMULATION
C
C
C     7  INITIAL GUESSES AT THE START OF INTAKE PROCESS
C
C        PSTART      NO      NO        INITIAL PRESSURE IN CYLINDER (ATM)
C        TSTART      NO      NO        INITIAL TEMPERATURE IN CYLINDER (K)
C
C
C     8  TIME INCREMENTS
C
```

```
C     WRITTEN BY  S. G. POULOS, S. H. MANSOURI, AND T. J. NORMAN
C     EDITED BY T. J. NORMAN
C
      LOGICAL FIRE, SPBURN
      INTEGER FUELTP
      REAL*8 DT, DY(25), TOUT, RELERR, ABSERR, WORK, REROOT, AEROOT
      REAL MW, MWIM, MSTART, MASS, MAXERR, IPA
      DIMENSION Y(25), YP(25), WORK(625), IWORK(5)
      COMMON/EPARAM/ ECCEN, ROTRAD, DEPTH, VFLANK
      COMMON/TEMPS/TROTOR,TSIDE,THOUS
      COMMON/MANFP/ PIM, TIM, EGR, PEM, MSTART
      COMMON/BURN/ SPBURN, FIRE, FIREFL
      COMMON/DTDTH/ ESPDI, RPM
      COMMON/TIMES/ TIPO, TIPC, TEPO, TEPC, THIPO, THEPO, TSPARK
      COMMON/PORTS/ IPA, EPA
      COMMON/IMTHP/ HIM, MWIM, GIM, RHOIM
      COMMON/FUEL/ FUELTP, ENW, CX, HY, OZ, DEL, PSI, PHICON, PHI,
     &             QLOWER, FASTO
      COMMON/FIXX/ INFLAG
      COMMON/HEATS/VELHTX, HTRCOE, HTPARO, HTPASI, HTPAHO, HTXRO,
     &             HTXSI, HTXHO,  QFRRO, QFRSI, QFRHO
      COMMON/HTRAN/THTRAN
      COMMON/UBHEAT/ UHTRCO, BHTRCO
      COMMON/YYYY1/ VIP, VEP
      COMMON/ITRLIM/ MAXTRY, MAXERR
      COMMON/RHMAS/ RHO, MASS, VOLUME, H, GAMMA, GAMAB
      COMMON/SPECB/ DTBRN, CONSPB, EXSPB
      COMMON/XSTOP/ XBSTOP
C
C
      COMMON/CREV/DRHODP,CSUBT,MW,ITERAS,DVDT,CSUBP,DRHODT,HIMM,RESIDL,
     &            RESFIM
      COMMON/CREVIN/AREALK,CREVOL,TCREV,X1LDIN,X1LGIN
      COMMON/CREVQ/CRMASD,CRMASG,X1LDC,X1LAGC,ZMAST,ZMASS,ZLEAKD,ZLEAKG,
     &             ZCRCOD,ZCRCOG
      COMMON/TABLES/ PRES(1080), X1LD(1080), X1LG(1080)
      COMMON/HEATXG/AROTOR,ASIDE,AHOUS,ROTVEL,DCHAR
      COMMON/HTTXIN/CONHT,EXPHT,CON1,CON2
C
      NAMELIST/INPUT/ FIRE, SPBURN, FUELTP, PHI, ECCEN, ROTRAD, DEPTH,
     &          VFLANK, RPM, TIPO, TIPC, TEPO, TEPC, TSPARK, THIPO,
     & THEPO, IPA, EPA, XBZERO, XBSTOP, DTBRN, CONSPB, EXSPB,
     & PATM, TATM, PIM, TFRESH, TEGR, EGR, PEM, TROTOR, TSIDE, THOUS,
     & CONHT, EXPHT, TPRINT, TPRINX, AREROT, CIINTG,
     & CCINTG, CBINTG, CEINTG, MXTRY, REL, MAXITS, MAXERR,
     & MAXTRY, AREALK, CREVOL, TCREV,  CON1, CON2
C
      EXTERNAL INTAKE, CMPRES, CMBSTN, EXAUST, GINT1, GINT2, GCMP,
     &          GCMB, GEXH
C
C@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
C
C        STANDARD DATA SET -- OVERRIDE BY USING NAMELIST INPUT
C
C-------------------
```

```
      FIRE   = .TRUE.
      SPBURN = .TRUE.
      FUELTP =  1
      PHI    =  1.00
C-------------------
      ECCEN  =  1.50
      ROTRAD = 10.5
      DEPTH  =  7.00
      VFLANK = 25.00
      RPM    = 3000.
C-------------------
      TIPO   = -500.0
      TIPC   = -220.0
      TEPO   = 190.0
      TEPC   = 580.0
      TSPARK = 0.00
      THIPO  = 67.0
      THEPO  = 30.0
      IPA    = 12.2
      EPA    = 6.5
C-------------------
      XBZERO = 0.005
      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-------------------
      TROTOR = 462.
      TSIDE  = 462.
      THOUS  = 462.
      CONHT  = 0.377
      EXPHT  = 0.8
      CON1   = 0.75
      CON2   = 0.324
C-------------------
      TPRINT = 10.0
      TPRINX = 1.0
C-------------------
      AREROT = .0002
      CIINTG = 0.0001
      CCINTG = 0.0001
      CBINTG = 0.00005
      CEINTG = 0.0001
      MXTRY  = 1
      REL    = .0002
      MAXITS = 2
      MAXERR = 0.03
```

```
      MAXTRY = 5
C--------------------
      AREALK = .01
      CREVOL = 2.00
      TCREV  = 300
C--------------------
C
C          READ NAMELIST INPUT
C
      READ (8,INPUT)
C
      ESPDI  = 1./(6. * RPM)
C
C
C           TO ALLOW A NORMALIZED OUTPUT INTO DUMMY1 DATA FILE GIVE
C           ZMAST (MASS AT TIPC) A VALUE OF UNITY UNTIL INTAKE PORT CLOSES
C
      ZMAST = 1.
C
C           CALCULATE COMPRESSION RATIO
C
      PI=3.1415926539
      ROOT3 = SQRT(3.0)
      DVOLUM = 3. * ROOT3 * ECCEN * ROTRAD * DEPTH
      ALEAN  = ASIN( 3.*ECCEN/ROTRAD)
      FH     = 1.5 * ROOT3 * ECCEN * ROTRAD
      FC     = 2. * ECCEN * ROTRAD * COS( ALEAN ) +
     &           ( 2/9.*ROTRAD*ROTRAD + 4.*ECCEN*ECCEN ) * ALEAN +
     &           PI/3. * ECCEN*ECCEN
      CMRTIO = (( FH + FC )*DEPTH + VFLANK)/(( FC- FH )*DEPTH + VFLANK)
C
C          CALCULATE ALL FUEL-RELATED PARAMETERS
C
C
C
      IF ((.NOT. FIRE) .OR. (PHI .LE. 0.0)) PHI = 0.00001
      CALL FUELDT
C
C
C          FIND THERMODYNAMIC STATE OF INTAKE CHARGE
C
      CALL THERMO (TIPO, TFRESH, PIM, 0.0, HFRESH, XXA, XXB, XXC,
     &             XXD, XXE, XXF, XXG, XXH, XXI, XXJ, XXK)
      CALL THERMO (TIPO, 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 (TIPO, 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
      PSTART = 1.1
```

```
      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 (TIPO, TSTART, PSTART, RESFRK, ENTHLP, CSUBP, CSUBT,
     &       RHO, DRHODT, DRHODP, GAMMA, MW, ADUMY, BDUMY, GDUMY, HDUMY)
      CALL CSAVDV (TIPO, VOLUME, DVDT)
      MSTART = RHO * VOLUME
C
C        PREPARE ALL OUTPUT FILES FOR OUTPUT FROM THIS ITERATION
C
CJ  5 REWIND  6
CJ    REWIND  9
CJ    REWIND 10
CJ  5 REWIND 11
CJ    REWIND 12
CJ    REWIND 13
CJ    REWIND 14
CJ    REWIND 15
CJ    REWIND 16
C
C        WRITE MAIN HEADINGS AND ECHO INPUT PARAMETERS
C
    5 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, TROTOR, TSIDE, THOUS
      WRITE  (6,3333)
      WRITE  (6,2918)
      WRITE  (6,2919) ECCEN, ROTRAD, DEPTH, CMRTIO, DVOLUM,
     &                VFLANK, TIPO, TIPC, TEPO, TEPC
      WRITE  (6,3333)
      WRITE  (6,2940)
      WRITE  (6,2941) AREALK, CREVOL, TCREV
      WRITE  (6,3333)
      WRITE  (6,2920)
      WRITE  (6,2921) MAXITS, ITERAS, TPRINT, TPRINX, XBZERO, XESTOP,
     &                XBSTOP, CIINTG, CCINTG, CBINTG, CEINTG, AREROT,
     &                REL, ERMAX, MAXERR, MAXTRY
      WRITE  (6,3333)
      WRITE  (6,3333)
      WRITE  (6,2225)
      WRITE (10,2225)
      WRITE (13,2225)
C
      WRITE  (6,4595)
      WRITE  (6,4596)
      WRITE  (6,3333)
      WRITE (10,8111)
      WRITE (10,9900)
      WRITE (10,3333)
      WRITE (13,7111)
      WRITE (13,4592)
      WRITE (13,3333)
C
C        INITIALIZE PARAMETERS FOR CALL TO SUBROUTINE ODERT
C
      Y(1)  = 0.0
      Y(2)  = 0.0
      Y(3)  = 0.0
      Y(4)  = 0.0
      Y(5)  = 1.0
      IF (FIRE) Y(5) = 0.0
CJ    Y(6) REMOVED
CJ    Y(7) REMOVED
      Y(8)  = 0.0
      Y(9)  = 0.0
      Y(10) = 0.0
      Y(11) = TSTART
      Y(12) = PSTART
      Y(13) = 0.0
```

```
      Y(14) = 0.0
      Y(15) = 0.0
      Y(16) = 0.0
      Y(17) = 0.0
      Y(18) = 0.0
      Y(19) = 0.0
      Y(20) = 0.0
      Y(21) = X1LDIN
      Y(22) = X1LGIN
      Y(23) = MSTART
      Y(24) = 0.0
      Y(25) = 0.0
C
      HEATI = 0.0
      WORKI = 0.0
      VIP = 0.0
C
      DO 10 I = 1, 25
           DY(I) = Y(I)
   10 CONTINUE
      WRITE (6,1277) TIPO, DY(12), DY(11), DY(1), DY(2), VIP,
     &               DY(5), DY(16)
      AEROOT = AREROT
      REROOT = AREROT
C
C#######################################################################
C
C         START OF INTAKE PROCESS (TIPO - TIPC)
C
C#######################################################################
C
   20 I = 0
      NEQN = 25
      IFLAG = 1
      T = TIPO
      TEND = -270.
      DT = T
C
C         CHECK WHICH WAY INTAKE FLOWS AT CYCLE START
C
   30 I = I + 1
      IFLAG = 1
      IF (DY(12) .GT. PIM) GO TO 90
C
C         INTAKE FLOW INTO CHAMBER OF NEW CHARGE
C         ( FRESH AIR/FUEL MIXTURE + EGR ); SET INFLAG = 1
C
   40 INFLAG = 1
C
C
      NCALL = IFIX( ABS(TEND - T) )
      IF (NCALL .LE. 0) GO TO 70
C
C         NCALL:  NO. OF TIMES INTEGRATING SUBROUTINE IS CALLED
C
```

```
      DO 60 NC = 1, NCALL
           TOUT = INT (T + 1.)
   50      ABSERR = CIINTG
           RELERR = CIINTG
C
           CALL ODERT (INTAKE, NEQN, DY, DT, TOUT, RELERR, ABSERR,
     &                 IFLAG, WORK, IWORK, GINT1, REROOT, AEROOT)
           CALL HELPHT (DT, DY, 1)
C
           T = DT
C
C          SUBROUTINE BUILD CONSTRUCTS THE PRESSURE HISTORY OF
C          THE CHAMBER AND STORES THE CREVICE GAS COMPOSITIONS
C          WHEN AVAILABLE.
C
           CALL BUILD (DT,DY)
C
       TWRITE = T/TPRINT
C
C           IFLAG IS THE RETURN CODE FROM ODERT. IFLAG NOT EQUAL
C           TO 2 OR 8 IS ABNORMAL AND SHOULD BE CHECKED (REFER
C           TO SUBROUTINE ODERT).
C
       IF ( IFLAG .NE. 2 ) GO TO 55
       IF ( TWRITE .NE. INT(TWRITE) ) GO TO 56
C
   55      WRITE  (7,881)  DT, DY(12), INFLAG, IFLAG
           WRITE  (6,1210) DT, DY(12), DY(11), DY(1), DY(2), VIP,
     &                     VEP, DY(5), THTRAN, DY(16), INFLAG, IFLAG
           WRITE (10,9210) DT,DY(23),CRMASD,CRMASG,DY(18),DY(19),
     &                     ZCRCOD,ZCRCOG
           WRITE (13,4210) DT, VELHTX, HTPARO, HTPASI, HTPAHO,
     &                     QFRRO, QFRSI, QFRHO
C
   56 CONTINUE
           IF (ABS(T/TEND - 1.0) .LE. REL) GO TO 190
           IF (IFLAG .EQ. 8) GO TO 90
C
C             I.E. REVERSE FLOW ACROSS INTAKE PORT.
C
           IF (IFLAG .NE. 2) GO TO 50
   60 CONTINUE
C
C        NO ROOT FOR GINT1; COMPLETE INTAKE PROCESS.
C
   70 TOUT = TEND
   80 ABSERR = CIINTG
      RELERR = CIINTG
C
      CALL ODERT (INTAKE, NEQN, DY, DT, TOUT, RELERR, ABSERR,
     &            IFLAG, WORK, IWORK, GINT1, REROOT, AEROOT)
      CALL HELPHT (DT, DY, 1)
C
           T = DT
           CALL BUILD (DT,DY)
```

```
C
       TWRITE = T/TPRINT
       IF ( IFLAG .NE. 2 ) GO TO 85
       IF ( TWRITE .NE. INT(TWRITE) ) GO TO 86
C
   85 WRITE  (7,881)  DT, DY(12), INFLAG, IFLAG
      WRITE  (6,1210) DT, DY(12), DY(11), DY(1), DY(2), VIP,
     &                VEP, DY(5), THTRAN, DY(16), INFLAG, IFLAG
      WRITE (10,9210) DT,DY(23),CRMASD,CRMASG,DY(18),DY(19),
     &                ZCRCOD,ZCRCOG
      WRITE (13,4210) DT, VELHTX, HTPARO, HTPASI, HTPAHO,
     &                QFRRO, QFRSI, QFRHO
C
   86 CONTINUE
      IF (ABS(T/TEND - 1.0) .LE. REL) GO TO 190
      IF (IFLAG .EQ. 8) GO TO 90
      IF (IFLAG .NE. 2) GO TO 80
C
C        ROOT FOUND FOR GINT1; FLOW ACROSS INTAKE PORT
C        REVERSES AND FLOWS INTO INTAKE MANIFOLD.  FIND
C        ROOT WHEN FLOW ONCE AGAIN REVERSES DIRECTION.
C
   90 INFLAG = 0
      NCALL = IFIX( ABS(TEND - T) )
      IF (NCALL .LE. 0) GO TO 120
      DO 110 NC = 1, NCALL
           TOUT = INT(T + 1.)
  100      ABSERR = CIINTG
           RELERR = CIINTG
C
           CALL ODERT (INTAKE, NEQN, DY, DT, TOUT, RELERR, ABSERR,
     &                  IFLAG, WORK, IWORK, GINT1, REROOT, AEROOT)
           CALL HELPHT (DT, DY, 1)
C
           T = DT
           CALL BUILD (DT,DY)
       TWRITE = T/TPRINT
       IF ( IFLAG .NE. 2 ) GO TO 105
       IF ( TWRITE .NE. INT(TWRITE) ) GO TO 106
  105      WRITE  (7,881)  DT, DY(12), INFLAG, IFLAG
           WRITE  (6,1210) DT, DY(12), DY(11), DY(1), DY(2), VIP,
     &                     VEP, DY(5), THTRAN, DY(16), INFLAG, IFLAG
           WRITE (10,9210) DT,DY(23),CRMASD,CRMASG,DY(18),DY(19),
     &                     ZCRCOD,ZCRCOG
           WRITE (13,4210) DT, VELHTX, HTPARO, HTPASI, HTPAHO,
     &                     QFRRO, QFRSI, QFRHO
C
  106   CONTINUE
           IF (ABS(T/TEND - 1.0) .LE. REL) GO TO 190
           IF (IFLAG .EQ. 8) GO TO 140
           IF (IFLAG .NE. 2) GO TO 100
  110 CONTINUE
  120 TOUT = TEND
  130 ABSERR = CIINTG
      RELERR = CIINTG
```

```
C
      CALL ODERT (INTAKE, NEQN, DY, DT, TOUT, RELERR, ABSERR,
     &            IFLAG, WORK, IWORK, GINT1, REROOT, AEROOT)
      CALL HELPHT (DT, DY, 1)
C
           T = DT
           CALL BUILD (DT,DY)
       TWRITE = T/TPRINT
       IF ( IFLAG .NE. 2 ) GO TO 135
       IF ( TWRITE .NE. INT(TWRITE) ) GO TO 136
  135 WRITE  (7,881)  DT, DY(12), INFLAG, IFLAG
      WRITE  (6,1210) DT, DY(12), DY(11), DY(1), DY(2), VIP,
     &                VEP, DY(5), THTRAN, DY(16), INFLAG, IFLAG
      WRITE (10,9210) DT,DY(23),CRMASD,CRMASG,DY(18),DY(19),
     &                ZCRCOD,ZCRCOG
      WRITE (13,4210) DT, VELHTX, HTPARO, HTPASI, HTPAHO,
     &                QFRRO, QFRSI, QFRHO
C
  136 IF (ABS(T/TEND - 1.0) .LE. REL) GO TO 190
      IF (IFLAG .EQ. 8) GO TO 140
      IF (IFLAG .NE. 2) GO TO 130
C
C        ROOT FOUND FOR GINT1; FLOW ACROSS INTAKE PORT HAS
C        REVERSED DIRECTION.  FIND ROOT WHEN ALL MASS THAT HAS
C        FLOWN INTO INTAKE MANIFOLD FLOWS BACK INTO CYLINDER.
C
  140 INFLAG = 0
      NCALL = IFIX( ABS(TEND - T) )
      IF (NCALL .LE. 0) GO TO 170
      DO 160 NC = 1, NCALL
           TOUT = INT( T + 1.)
  150      ABSERR = CIINTG
           RELERR = CIINTG
C
           CALL ODERT (INTAKE, NEQN, DY, DT, TOUT, RELERR, ABSERR,
     &                 IFLAG, WORK, IWORK, GINT2, REROOT, AEROOT)
           CALL HELPHT (DT, DY, 1)
C
           CALL BUILD (DT, DY)
           T = DT
       TWRITE = T/TPRINT
       IF ( IFLAG .NE. 2 ) GO TO 155
       IF ( TWRITE .NE. INT(TWRITE) ) GO TO 156
  155      WRITE  (7,881)  DT, DY(12), INFLAG, IFLAG
           WRITE  (6,1210) DT, DY(12), DY(11), DY(1), DY(2), VIP,
     &                     VEP, DY(5), THTRAN, DY(16), INFLAG, IFLAG
           WRITE (10,9210) DT,DY(23),CRMASD,CRMASG,DY(18),DY(19),
     &                     ZCRCOD,ZCRCOG
           WRITE (13,4210) DT, VELHTX, HTPARO, HTPASI, HTPAHO,
     &                     QFRRO, QFRSI, QFRHO
C
  156      IF (ABS(T/TEND - 1.0) .LE. REL) GO TO 190
           IF (IFLAG .EQ. 8) GO TO 40
           IF (IFLAG .NE. 2) GO TO 150
  160 CONTINUE
```

```
  170 TOUT = TEND
  180 ABSERR = CIINTG
      RELERR = CIINTG
C
      CALL ODERT (INTAKE, NEQN, DY, DT, TOUT, RELERR, ABSERR,
     &            IFLAG, WORK, IWORK, GINT2, REROOT, AEROOT)
      CALL HELPHT (DT, DY, 1)
C
      CALL BUILD (DT, DY)
      T = DT
       TWRITE = T/TPRINT
       IF ( IFLAG .NE. 2 ) GO TO 185
       IF ( TWRITE .NE. INT(TWRITE) ) GO TO 186
  185 WRITE  (7,881)  DT, DY(12), INFLAG, IFLAG
      WRITE  (6,1210) DT, DY(12), DY(11), DY(1), DY(2), VIP,
     &                VEP, DY(5), THTRAN, DY(16), INFLAG, IFLAG
      WRITE (10,9210) DT,DY(23),CRMASD,CRMASG,DY(18),DY(19),
     &                ZCRCOD,ZCRCOG
      WRITE (13,4210) DT, VELHTX, HTPARO, HTPASI, HTPAHO,
     &                QFRRO, QFRSI, QFRHO
C
  186 IF (ABS(T/TEND - 1.0) .LE. REL) GO TO 190
      IF (IFLAG .EQ. 8) GO TO 40
      IF (IFLAG .NE. 2) GO TO 180
C
C######################################################################
C
C       END OF INTAKE PROCESS
C
C######################################################################
C
  190 IF (I .EQ. 2) GO TO 200
      HEATI = DY(8) + DY(9) + DY(10)

      WORKI = DY(16)
      TEND = TIPC
      GO TO 30
C
C       CALCULATE VOLUMETRIC EFFICIENCY (VOLEFI)
C
  200 VOLEFI = 100. * DY(1)/( DVOLUM * RHOIM * (1. + PHI*FASTO) )
      VOLEFA = VOLEFI * (PIM/PATM) * (TATM/TIM)
      WRITE (7,1281) VOLEFI
      WRITE  (6,1210) TIPC, DY(12), DY(11), DY(1), DY(2), VIP,
     &                    VEP, DY(5), THTRAN, DY(16), INFLAG, IFLAG
      WRITE (6,3333)
      WRITE (6,2225)
      WRITE (6,1110)
      WRITE (6,4597)
      WRITE (6,3333)
      WRITE (6,1211) TIPC, DY(12), DY(11), THTRAN,
     &               DY(16), IFLAG
C
C       CALCULATE TOTAL MASS OF FUEL INDUCTED IN THIS CYCLE (FMIN)
C
```

```
      ZMAST = DY(23)
      FMIN = DY(1) * (1. - EGR/100.) * PHI * FASTO/(PHI*FASTO + 1.)
      IF (.NOT. FIRE) FMIN = 0.0
C
C        CALCULATE RESIDUAL FRACTION AT TIPC
C
      RESIDL = 1. - DY(5)
C
C########################################################################
C
C        START OF COMPRESSION PROCESS (FIRING CASE) (TIPC - TSPARK)
C        START OF COMPRESSION AND EXPANSION PROCESSES
C        (MOTORING CASE) (TIPC - TEPO)
C
C########################################################################
C
      TID = TSPARK
      TBD = TSPARK
      NEQN = 25
      IFLAG = 1
      T = TIPC
      TEND = TEPO
      IF (FIRE) TEND = TSPARK
      DT = T
      NCALL = IFIX( ABS(TEND - T) )
      IF (NCALL .LE. 0) GO TO 230
      DO 220 NC = 1, NCALL
           TOUT = INT( T + 1.)
  210      ABSERR = CCINTG
           RELERR = CCINTG
C
           CALL ODERT (CMPRES, NEQN, DY, DT, TOUT, RELERR, ABSERR,
     &                  IFLAG, WORK, IWORK, GCMP, REROOT, AEROOT)
           CALL HELPHT (DT, DY, 2)
C
           CALL BUILD (DT, DY)
           T = DT
       TWRITE = T/TPRINT
       IF ( IFLAG .NE. 2 ) GO TO 215
       IF ( TWRITE .NE. INT(TWRITE) ) GO TO 216
  215      WRITE  (7,882)  DT, DY(12), IFLAG
           WRITE  (6,1211) DT, DY(12), DY(11), THTRAN,
     &                     DY(16), IFLAG
           WRITE (10,9210) DT,DY(23),CRMASD,CRMASG,DY(18),DY(19),
     &                     ZCRCOD,ZCRCOG
           WRITE (13,4210) DT, VELHTX, HTPARO, HTPASI, HTPAHO,
     &                     QFRRO, QFRSI, QFRHO
C
  216      IF (ABS( T - TEND ) .LE. REL) GO TO 250
           IF (IFLAG .EQ. 8) GO TO 220
           IF (IFLAG .NE. 2) GO TO 210
  220 CONTINUE
  230 TOUT = TEND
  240 ABSERR = CCINTG
      RELERR = CCINTG
```

```
C
      CALL ODERT (CMPRES, NEQN, DY, DT, TOUT, RELERR, ABSERR,
     &            IFLAG, WORK, IWORK, GCMP, REROOT, AEROOT)
      CALL HELPHT (DT, DY, 2)
C
      CALL BUILD (DT, DY)
      T = DT
       TWRITE = T/TPRINT
       IF ( IFLAG .NE. 2 ) GO TO 245
  245 WRITE  (7,882)  DT, DY(12), IFLAG
      WRITE  (6,1211) DT, DY(12), DY(11), THTRAN,
     &                DY(16), IFLAG
      WRITE (10,9210) DT,DY(23),CRMASD,CRMASG,DY(18),DY(19),
     &                ZCRCOD,ZCRCOG
      WRITE (13,4210) DT, VELHTX, HTPARO, HTPASI, HTPAHO,
     &                QFRRO, QFRSI, QFRHO
C
  246 IF (ABS( T - TEND ) .LE. REL) GO TO 250
      IF (IFLAG .NE. 2) GO TO 240
C
C#########################################################################
C
C        IF FIRING CASE, GO TO START OF COMBUSTION
C        IF MOTORING CASE, BEGIN EXHAUST PROCESS (TEPO - TIPO)
C
C#########################################################################
C
       XFRESH = Y(5)
  250 WRITE (6,3333)
      IF (FIRE) GO TO 330
      WRITE (6,2225)
      WRITE (6,1111)
      WRITE (6,4599)
      WRITE (6,3333)
      VEP = 0.0
      WRITE (6,1213) TEPO, DY(12), DY(11), DY(2), VEP,
     &               THTRAN, DY(16), IFLAG
C
      I = 0
      NEQN = 25
      IFLAG = 1
      T = TEPO
      TEND = 270.
      DT = T
  260 I = I + 1
      IFLAG = 1
      NCALL = IFIX( ABS(TEND - T) )
      IF (NCALL .LE. 0) GO TO 290
      DO 280 NC = 1, NCALL
           TOUT = INT( T + 1.)
  270      ABSERR = CEINTG
           RELERR = CEINTG
C
           CALL ODERT (EXAUST, NEQN, DY, DT, TOUT, RELERR, ABSERR,
     &                 IFLAG, WORK, IWORK, GEXH, REROOT, AEROOT)
```

```
           CALL HELPHT (DT, DY, 4)
C
           CALL BUILD (DT, DY)
           T = DT
       TWRITE = T/TPRINT
       IF ( IFLAG .NE. 2 ) GO TO 275
       IF ( TWRITE .NE. INT(TWRITE) ) GO TO 276
  275      WRITE  (7,882)  DT, DY(12), IFLAG
           WRITE  (6,1213) DT, DY(12), DY(11), DY(2), VEP,
     &                     THTRAN, DY(16), IFLAG
           WRITE (10,9210) DT,DY(23),CRMASD,CRMASG,DY(18),DY(19),
     &                     ZCRCOD,ZCRCOG
           WRITE (13,4210) DT, VELHTX, HTPARO, HTPASI, HTPAHO,
     &                     QFRRO, QFRSI, QFRHO
C
  276      IF (ABS(T/TEND - 1.0) .LE. REL) GO TO 310
           IF (IFLAG .NE. 2) GO TO 270
  280 CONTINUE
  290 TOUT = TEND
  300 ABSERR = CEINTG
      RELERR = CEINTG
C
      CALL ODERT (EXAUST,NEQN,DY,DT,TOUT,RELERR,ABSERR,IFLAG,
     &           WORK,IWORK,GEXH,REROOT,AEROOT)
      CALL HELPHT (DT, DY, 4)
C
      CALL BUILD (DT, DY)
      T = DT
       TWRITE = T/TPRINT
       IF ( IFLAG .NE. 2 ) GO TO 305
       IF ( I .EQ. 2  .AND.  ABS(T/TEND - 1.) .LE. REL ) GO TO 305
       IF ( TWRITE .NE. INT(TWRITE) ) GO TO 306
  305 WRITE  (7,882)  DT, DY(12), IFLAG
      WRITE  (6,1213) DT, DY(12), DY(11), DY(2), VEP,
     &                THTRAN, DY(16), IFLAG
      WRITE (10,9210) DT,DY(23),CRMASD,CRMASG,DY(18),DY(19),
     &                ZCRCOD,ZCRCOG
      WRITE (13,4210) DT, VELHTX, HTPARO, HTPASI, HTPAHO,
     &                QFRRO, QFRSI, QFRHO
C
  306 IF (ABS(T/TEND - 1.0) .LE. REL) GO TO 310
      IF (IFLAG .NE. 2) GO TO 300
  310 IF (I .EQ. 2) GO TO 320
C
      HEATCE = DY(8) + DY(9) + DY(10) - HEATI
      WORKCE = DY(16) - WORKI
      TEND = TIPO + 1080.
      GO TO 260
C
  320 HEATE = DY(8) + DY(9) + DY(10) - HEATCE - HEATI
      WORKE = DY(16) - WORKCE - WORKI
      WRITE (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 = DY(23)
      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
      DY(4)  = XBZERO
      DY(12) = PZERO
      DY(13) = TGUESU
      DY(14) = VOLUME - ( DY(4)*MASS/RHOB )
      DY(15) = TGUESB
C
      WRITE  (6,1212) TSPARK, DY(12), DY(15), DY(13),
     &                DY(4), THTRAN, DY(16), IFLAG
      DT = TSPARK
      CALL HELPHT (DT, DY, 3)
      WRITE (13,4210) TSPARK, VELHTX, HTPARO, HTPASI, HTPAHO,
     &                QFRRO, QFRSI, QFRHO
```

```
C
C#######################################################################
C
C        START OF COMBUSTION PROCESS (TSPARK - TEPO)
C
C#######################################################################
C
      IDCNT = 0
      IBCNT = 0
      NEQN = 25
      IFLAG = 1
      T = TSPARK
      TEND = TEPO
      DT = T
      NCALL = IFIX( ABS(TEND - T) )
      IF (NCALL .LE. 0) GO TO 360
      DO 350 NC = 1, NCALL
           TOUT = INT( T + 1.)
  340      ABSERR = CBINTG
           RELERR = CBINTG
           TOLDXB = T
           XBOLD = DY(4)
C
           CALL ODERT (CMBSTN,NEQN,DY,DT,TOUT,RELERR,ABSERR,IFLAG,
     &                 WORK,IWORK,GCMB,REROOT,AEROOT)
           CALL HELPHT (DT, DY, 3)
           IF (DY(4) .LE. 1.0) GO TO 344
           IF (DY(4) .GT. 1.0) XBSTOP = XBSTOP - 0.002
           GO TO 5
C
  344      CALL BUILD (DT, DY)
           T = DT
C
           IF ((IDCNT .GT. 0) .OR. (DY(4) .LT. 0.1)) GO TO 345
           TID = TOLDXB + (T - TOLDXB)*(0.1 - XBOLD)/(DY(4) - XBOLD)
           IDCNT = IDCNT + 1
  345      IF ((IBCNT .GT. 0) .OR. (DY(4) .LT. 0.9)) GO TO 347
           TBD = TOLDXB + (T - TOLDXB)*(0.9 - XBOLD)/(DY(4) - XBOLD)
           IBCNT = IBCNT + 1
  347      TWRITE = T/TPRINX
           IF (IFLAG .NE. 2 ) GO TO 348
           IF (TWRITE .NE. INT(TWRITE) ) GO TO 349
C
  348      WRITE  (7,883)  DT, DY(12), DY(4), IFLAG
           WRITE  (6,1212) DT, DY(12), DY(15), DY(13),
     &                     DY(4), THTRAN, DY(16), IFLAG
           WRITE (10,9210) DT,DY(23),CRMASD,CRMASG,DY(18),DY(19),
     &                     ZCRCOD,ZCRCOG
           WRITE (13,4210) DT, VELHTX, HTPARO, HTPASI, HTPAHO,
     &                     QFRRO, QFRSI, QFRHO
C
  349      IF (ABS(T/TEND - 1.0) .LE. REL) GO TO 380
           IF (IFLAG .NE. 2) GO TO 340
  350 CONTINUE
  360 TOUT = TEND
```

```
  370 ABSERR = CBINTG
      RELERR = CBINTG
      TOLDXB = T
      XBOLD = DY(4)
C
      CALL ODERT (CMBSTN,NEQN,DY,DT,TOUT,RELERR,ABSERR,IFLAG,
     &            WORK,IWORK,GCMB,REROOT,AEROOT)
      CALL HELPHT (DT, DY, 3)
      IF (DY(4) .LE. 1.0) GO TO 374
      IF (DY(4) .GT. 1.0) XBSTOP = XBSTOP - 0.02
      GO TO 5
C
  374 CALL BUILD (DT, DY)
      T = DT
C
      IF ((IDCNT .GT. 0) .OR. (DY(4) .LT. 0.1)) GO TO 375
      TID = TOLDXB + (T - TOLDXB)*(0.1 - XBOLD)/(DY(4) - XBOLD)
      IDCNT = IDCNT + 1
  375 IF ((IBCNT .GT. 0) .OR. (DY(4) .LT. 0.9)) GO TO 377
      TBD = TOLDXB + (T - TOLDXB)*(0.9 - XBOLD)/(DY(4) - XBOLD)
      IBCNT = IBCNT + 1
C
  377 WRITE  (7,883)  DT, DY(12), DY(4), IFLAG
      WRITE  (6,1212) DT, DY(12), DY(15), DY(13),
     &                DY(4), THTRAN, DY(16), IFLAG
      WRITE (10,9210) DT,DY(23),CRMASD,CRMASG,DY(18),DY(19),
     &                ZCRCOD,ZCRCOG
      WRITE (13,4210) DT, VELHTX, HTPARO, HTPASI, HTPAHO,
     &                QFRRO, QFRSI, QFRHO
C
      IF (ABS(T/TEND - 1.0) .LE. REL) GO TO 380
      IF (IFLAG .NE. 2) GO TO 370
C
C#######################################################################
C
C        START OF EXHAUST PROCESS (FIRING CASE) (TEPO - TIPO)
C
C#######################################################################
C
  380 WRITE (6,3333)
      WRITE (6,2225)
      WRITE (6,1111)
      WRITE (6,4599)
      WRITE (6,3333)
      VEP = 0.0
      WRITE (6,1213) TEPO, DY(12), DY(15), DY(2), VEP,
     &               THTRAN, DY(16), IFLAG
C
C        REINITIALIZE 'ODERT' FOR START OF EXHAUST
C
      DY(11) = DY(15)
      DY(5) = RESIDL * (1.-DY(4))
C
      I = 0
      NEQN = 25
```

```
      IFLAG = 1
      T = TEPO
      TEND = 270.
      DT = T
  390 I = I + 1
      NCALL = IFIX( ABS(TEND - T) )
      IF (NCALL .LE. 0) GO TO 420
      DO 410 NC = 1, NCALL
           TOUT = INT( T + 1.)
  400      ABSERR = CEINTG
           RELERR = CEINTG
C
           CALL ODERT (EXAUST,NEQN,DY,DT,TOUT,RELERR,ABSERR,IFLAG,
     &                 WORK,IWORK,GEXH,REROOT,AEROOT)
           CALL HELPHT (DT, DY, 4)
C
           CALL BUILD (DT, DY)
           T = DT
       TWRITE = T/TPRINT
       IF ( IFLAG .NE. 2 ) GO TO 405
       IF ( I .EQ. 2   .AND.  ABS(T/TEND - 1.) .LE. REL )
     &   GO TO 435
       IF ( TWRITE .NE. INT(TWRITE) ) GO TO 406
  405      WRITE  (7,882)  DT, DY(12), IFLAG
           WRITE  (6,1213) DT, DY(12), DY(11), DY(2), VEP,
     &                     THTRAN, DY(16), IFLAG
           WRITE (10,9210) DT,DY(23),CRMASD,CRMASG,DY(18),DY(19),
     &                     ZCRCOD,ZCRCOG
           WRITE (13,4210) DT, VELHTX, HTPARO, HTPASI, HTPAHO,
     &                     QFRRO, QFRSI, QFRHO
C
  406      IF (ABS(T/TEND - 1.0) .LE. REL) GO TO 440
           IF (IFLAG .NE. 2) GO TO 400
  410 CONTINUE
  420 TOUT = TEND
  430 ABSERR = CEINTG
      RELERR = CEINTG
C
      CALL ODERT (EXAUST,NEQN,DY,DT,TOUT,RELERR,ABSERR,IFLAG,
     &            WORK,IWORK,GEXH,REROOT,AEROOT)
      CALL HELPHT (DT, DY, 4)
C
      CALL BUILD (DT, DY)
      T = DT
       TWRITE = T/TPRINT
       IF ( IFLAG .NE. 2 ) GO TO 435
       IF ( I .EQ. 2  .AND.  ABS(T/TEND - 1.) .LE. REL ) GO TO 435
       IF ( TWRITE .NE. INT(TWRITE) ) GO TO 436
C
  435 WRITE  (7,882)  DT, DY(12), IFLAG
      WRITE  (6,1213) DT, DY(12), DY(11), DY(2), VEP,
     &                THTRAN, DY(16), IFLAG
      WRITE (10,9210) DT,DY(23),CRMASD,CRMASG,DY(18),DY(19),
     &                ZCRCOD,ZCRCOG
      WRITE (13,4210) DT, VELHTX, HTPARO, HTPASI, HTPAHO,
```

```
     &                    QFRRO, QFRSI, QFRHO
C
  436 IF (ABS(T/TEND - 1.0) .LE. REL) GO TO 440
      IF (IFLAG .NE. 2) GO TO 430
  440 IF (I .EQ. 2) GO TO 450
C
      HEATCE = DY(8) + DY(9) + DY(10) - HEATI
      WORKCE = DY(16) - WORKI
      TEND = TIPO + 1080.
      GO TO 390
C
C#######################################################################
C
C        END OF EXHAUST PROCESS (FIRING CASE)
C
C#######################################################################
C
  450 HEATE = DY(8) + DY(9) + DY(10) - HEATCE - HEATI
      WORKE = DY(16) - WORKCE - WORKI
      WRITE (6,3333)
C
C        CONVERGENCE CHECK
C
  455 Y(12) = DY(12)
      Y(11) = DY(11)
      Y(1) = DY(1)
      Y(2) = DY(2)
      IF (ITERAS .EQ. 1) GO TO 460
      IF (ABS( (Y(12) - PSTART)/PSTART ) .GT. 0.02) GO TO 460
      IF (ABS( (Y(11) - TSTART)/TSTART ) .GT. 0.02) GO TO 460
      IF (ABS( (Y(1) - Y(2))/MSTART )    .GT. 0.02) GO TO 460
      GO TO 480
  460 PSTART = DY(12)
      TSTART = DY(11)
C
C        INITIALIZE THE CREVICE GAS COMPOSITIONS
C
      X1LDIN = DY(22)
      X1LGIN = DY(21)
CN
C
CN470 CONTINUE
C
C***********************************************************************
C
C        END OF CURRENT CYCLE ITERATION
C
C***********************************************************************
C
C        CALCULATION RESULTS FOR THIS CYCLE
C
  480 THREFN = 0.0
      THREFG = 0.0
      HEATX  = 0.0
      IF (.NOT. FIRE) GO TO 490
```

```
      THREFN = 100. * DY(16)/(FMIN * QLOWER)
      THREFG = 100. * WORKCE/(FMIN * QLOWER)
      HEATX  = 100. * (DY(8) + DY(9) + DY(10))/(FMIN * QLOWER)
  490 ZPMEP  = 1.0E+06 * (WORKI + WORKE)/DVOLUM
      ZIMEP  = 1.0E+06 * WORKCE/DVOLUM
      ZISFC  = 3600. * FMIN/WORKCE
      RESFRK = 0.0
      IF (FIRE) RESFRK = 1.0
      AVREXH = DY(17)/DY(2)
      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
      DTHIGD = TID - TSPARK
      DTIGD  = DTHIGD * ESPDI * 1.0E+3
      DTHBRN = TBD - TID
      DTBURN = DTHBRN * ESPDI * 1.0E+3
C
C        ENERGY BALANCE
C
      TOHIN = 1.0E-10 * HIM * DY(1)
      TOHEX = 1.0E-10 * DY(17)
      TOHEAT = HEATI + HEATCE + HEATE
      TOWORK = WORKI + WORKCE + WORKE
C
      DY(20) = DY(20) * 1.E-10
      DY(3) = DY(3) * 1.E-10
C
      DECYCL = TOHEX + TOHEAT + TOWORK - TOHIN + DY(20) + DY(3)
      DEONHI = 100.0 * DECYCL/TOHIN
      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,DTBURN, AVREXT
      WRITE (6,3333)
      WRITE (6,9876) MSTART, ZMAST, 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) TOHIN, TOHEX, TOHEAT, TOWORK, DY(20), DY(3),
     &               DECYCL, DEONHI, DEONQ
      WRITE (6,3333)
C
C         NO CONVERGENCE CHECK IS PERFORMED AFTER THE FIRST ITERATION
C         BECAUSE THE CREVICE AND LEAKAGE MODEL IS NOT YET ACTIVATED
C
```

```
      IF (ITERAS .EQ. 1)  GO TO 470
      IF (ABS( (Y(12) - PSTART)/PSTART ) .GT. 0.02) GO TO 470
      IF (ABS( (Y(11) - TSTART)/TSTART ) .GT. 0.02) GO TO 470
      IF (ABS( (Y(1) - Y(2))/MSTART )    .GT. 0.02) GO TO 470
C
       GO TO 471
  470 CONTINUE
  471 CONTINUE
CJ
CJ    CALL WRITE
C
C@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
C
C        FORMAT STATEMENTS
C
 2225 FORMAT (1H1)
C
  881 FORMAT (1H ,2X,'CA = ',F8.2,10X,'P = ',F10.5,9X,'INFLAG = ',I2,
     &        8X,'IFG = ',I2)
C
  882 FORMAT (1H ,2X,'CA = ',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 ,13X,'START OF ITERATION  #',I2,2X,'OF ',I2,
     &        ' ALLOWED',//)
   77 FORMAT (//(54X,' >>>>> INPUT DATA <<<<< ' )//)
C
 4595 FORMAT (/////(1X,' >>>>> START OF INTAKE PROCESS      ')//)
C
 4596 FORMAT ((4X,'CA',7X,'P',9X,'TEMP',7X,'MIN',6X,'MEX',9X,'VIV',7X,
     &        'VEV',9X,'X1',9X,'Q DOT',9X,'WORK',8X,'IMF   IFG')/
     &        (2X,'(DEG)',4X,'(ATM)',7X,'(K)',8X,'(G)',6X,'(G)',7X,
     &        ' (CM/SEC)',2X,' (CM/SEC)',6X,'(-)',7X,'(KJ/DEG)',7X,
     &        '(KJ)'))
C
 4597 FORMAT ((4X,'CA',7X,'P',9X,'TEMP',61X,
     &        'Q DOT',9X,'WORK',14X,'IFG')/
     &        (2X,'(DEG)',4X,'(ATM)',7X,'(K)',61X,
     &        '(KJ/DEG)',7X,
     &        '(KJ)'))
C
 4598 FORMAT ((4X,'CA',7X,'P',22X,'TB ',7X,'TU ',4X,6X,4X,
     &        'XBURND',19X,'Q DOT',9X,'WORK',14X,'IFG')/
     &        (2X,'(DEG)',4X,'(ATM)',20X,'(K)',7X,'(K)',5X,
     &        3X,7X,'(-)',20X,'(KJ/DEG)',7X,
     &        '(KJ)'))
C
 4599 FORMAT ((4X,'CA',7X,'P',9X,'TEMP',16X,'MEX',19X,
     &        'VEV',20X,'Q DOT',9X,'WORK',14X,'IFG')/
     &        (2X,'(DEG)',4X,'(ATM)',7X,'(K)',17X,'(G)',17X,
     &        ' (M/SEC)',16X,'(KJ/DEG)',7X,
     &        '(KJ)'))
C
```

```
 1110 FORMAT (///(1X,' >>>>> START OF COMPRESSION PROCESS      ')//)
C
 1111 FORMAT (///(1X,' >>>>> START OF EXHAUST PROCESS      ')//)
C
 1277 FORMAT (1F7.1,2X,F9.4,2X,F9.2,2X,2F10.5,2X,F8.1,2X,11X,
     &        F9.5,16X,1F10.6)
C
 1210 FORMAT (1F7.1,2X,F9.4,2X,F9.2,2X,2F10.5,2X,F8.1,2X,F8.1,3X,
     &        F9.5,3X,1F10.6,3X,1F10.6,3X,1I4,1I6)
C
 1211 FORMAT (1F7.1,2X,F9.4,2X,F9.2,57X,
     &        1F10.6,3X,1F10.6,9X,1I4)
C
 1212 FORMAT (1F7.1,2X,F9.4,13X,2F10.2,2X,8X,2X,F8.5,15X,
     &        1F10.6,3X,1F10.6,9X,1I4)
C
 1213 FORMAT (1F7.1,2X,F9.4,2X,F9.2,12X,1F10.5,12X,F8.1,15X,
     &        1F10.6,3X,1F10.6,9X,1I4)
C
 9876 FORMAT ( /('     MASS IN CYLINDER AT TIVO = ',F8.5,' G')//
     &         ('     MASS IN CYLINDER AT TIVC = ',F8.5,' G')//
     &         ('     MASS OF FUEL INDUCTED    = ',F8.5,' G')//
     &         ('     RESIDUAL FRACTION        = ',F8.5)/)
C
 1890 FORMAT ( /('     TOTAL ENTHALPY IN / CYCLE   = ',F8.5,' KJ')//
     &         ('     TOTAL ENTHALPY OUT / CYCLE  = ',F8.5,' KJ')//
     &         ('     TOTAL HEAT LOSS / CYCLE     = ',F8.5,' KJ')//
     &         ('     TOTAL WORK OUTPUT / CYCLE   = ',F8.5,' KJ')//
     &         ('     HEAT LOSS TO CREVICE/CYCLE  = ',F8.5,' KJ')//
     &         ('     "LOST" FUEL ENERGY          = ',F8.5,' KJ')//
     &         ('     NET ENERGY GAIN / CYCLE     = ',F8.5,' KJ')//
     &         ('     (ENERGY GAIN)/(ENTHALPY IN) = ',F8.5,' %')//
     &         ('     (ENERGY GAIN)/(MFUEL*LHV)   = ',F8.5,' %')/)
C
 1261 FORMAT ( /('     HEATI   =  ',F10.6,' KJ',' (TIPO   -   -270)')/
     &          ('     WORKI   =  ',F10.6,' KJ')/ )
C
 1281 FORMAT (///('  VOLUMETRIC EFFICIENCY = ',1F5.1,' %')//)
C
 1262 FORMAT (  /('     HEATCE  =  ',F10.6,' KJ',' (TIPC   -    +270')/
     &          ('     WORKCE  =  ',F10.6,' KJ')/ )
C
 1263 FORMAT (  /('     HEATE   =  ',F10.6,' KJ',' (+270   -   TIPO)')/
     &          ('     WORKE   =  ',F10.6,' KJ')/ )
C
 1264 FORMAT (  /('     HEATC   =  ',F10.6,' KJ',' (-270   - TSPARK)')/
     &          ('     WORKC   =  ',F10.6,' KJ')/ )
C
 3210 FORMAT (5X,1F7.1,2X,2(1F12.1,2X),2(1F12.2,2X),
     &       2X,3(F10.5,4X),F9.4)
C
 4210 FORMAT (5X,1F7.1,2X,F10.1,3X,3(F11.1,3X),4X,3(F12.3,5X))
C
 9210 FORMAT (5X,1F7.1,6X,F8.4,4X,F10.6,1X,5(6X,F10.6))
 9211 FORMAT (5X,F7.1,6X,F8.4)
```

```
 1112 FORMAT (///(1X,' >>>>> START OF COMBUSTION AND EXPANSION PROCESSES
     &        ')///)
C
 4592 FORMAT (//(9X,'CA',7X,'VELHTX',7X,'HTPARO',7X,'HTPASI',7X,
     &        'HTPAHO',13X,'Q% ROTOR',10X,'Q% SIDE',8X,'Q% HOUSING')/
     &        (8X,'(DEG)',4X,'(CM/SEC)',5X,'(KW/M**2)',4X,'(KW/M**2)',
     &        4X,'(KW/M**2)',14X,'(%)',14X,'(%)',14X,'(%)'))
C
 4594 FORMAT (//(9X,'CA',7X,'MEANKE',8X,'TURBKE',8X,' VMKE ',8X,
     &        'UPRIME',10X,'MACRSC',8X,'MICRSC',9X,'SSUBL',8X,'BTIMSC')/
     &        (8X,'(DEG)',5X,'(ERG)',9X,'(ERG)',8X,'(CM/SEC)',6X,
     &       '(CM/SEC)',10X,'(CM)',10X,'(CM)',9X,'(CM/SEC)',7X,'(MS)'))
C
 9900 FORMAT (//(9X,'CA',9X,'CHAMBER',5X,'LEAD CREVICE',5X,
     &        'LAG CREVICE',5X,'LEAD LEAKAGE',4X,'LAG LEAKAGE',5X,
     &        'LEAD CREVICE',5X,'LAG CREVICE')/
     &        (20X,'MASS',8X,'MASS',13X,'MASS',12X,'MASS',12X,'MASS',
     &        12X,'COMPOSITION',6X,'COMPOSITION')/
     &        (7X,'(DEG)',10X,'(G)',12X,'(G)',13X,'(G)',14X,'( )',
     &        13X,'( )')//)
C
C3111 FORMAT (///,1H ,59X,'NOX FORMATION')
C
C5111 FORMAT (///,1H ,48X,'ADIABATIC CORE / BOUNDARY LAYER DATA')
C
C4111 FORMAT (///,1H ,54X,'FLAME PROPAGATION DATA')
C
C6111 FORMAT (///,1H ,55X,'TURBULENT FLOW MODEL')
C
 7111 FORMAT (///,1H ,56X,'HEAT TRANSFER DATA')
C
C
 8111 FORMAT (///,1H ,40X,'LEAKAGE AND CREVICE VOLUME DATA')
C
C3222 FORMAT (//,1H ,6X,'CA',7X,'YAC',7X,'YBL',7X,'YNOAC',5X,'YNOBL',5X,
C    &        'YNO',6X,'XNOAC',6X,'XNOBL',5X,'XNO',8X,'PPMAC',6X,
C    &        'PPMBL',6X,'PPMNO')
C
C4222 FORMAT (//,1H ,6X,'CA',5X,'VENONV',5X,'VBRONV',5X,'DFLONB',5X,
C    &        'AFLONB',5X,'AHUONB',5X,'AHBONB',5X,'APUONB',5X,'APBONB',
C    &        5X,'ACUONB',5X,'ACBONB')
C
C5222 FORMAT (//,1H ,6X,'CA',8X,'YAC',8X,'YBL',8X,'VACONV',6X,'VBLONV',
C    &        6X,'DBLONB',10X,'TWALLB',7X,'TB',9X,'TAC',8X,'TBLAYR')
C
 3333 FORMAT (1H ,1X,'_____________________________________________',
     &        '_____________________________________________________',
     &        '_______________________',/)
C
C3444 FORMAT (1H ,3X,F8.1,8(2X,F8.6),3(2X,F9.2))
C
C5444 FORMAT (1H ,2X,F8.1,5(4X,F8.6),2X,4(3X,F9.1))
C
C6444 FORMAT (1H ,2X,F8.1,10(3X,F8.5))
C
```

```
 5910 FORMAT (///(46X,'>--------------+--------------<')/
     &           (46X,'>                             <')/
     &           (46X,'>     CALCULATION RESULTS     <')/
     &           (46X,'>                             <')/
     &           (46X,'>--------------+--------------<')///)
C
 5920 FORMAT (/(33X,' -->  VOLUMETRIC EFFICIENCY; (%) ')/
     & (33X,'       BASED ON: INTAKE / ATM           ----> ',2(F8.1))///
     & (33X,' -->  PUMPING MEAN EFFECTIVE  ')/
     & (33X,'       PRESSURE; (KPA) : PEMP           ---->  ',1F6.0)///
     & (33X,' -->  GROSS INDICATED MEAN EFFECTIVE ')/
     & (33X,'       PRESSURE; (KPA) : IMEP           ---->  ',1F6.0)///
     & (33X,' -->  GROSS INDICATED SPECIFIC FUEL  ')/
     & (33X,'       CONSUMPTION; (G/IKW-HR) : ISFC   ---->  ',1F6.0)///
     & (33X,' -->  GROSS INDICATED THERMAL      ')/
     & (33X,'       EFFICIENCY; (%)                  ---->  ',1F7.1)///
     & (33X,' -->  NET INDICATED THERMAL        ')/
     & (33X,'       EFFICIENCY; (%)                  ---->  ',1F7.1)///
     & (33X,' -->  (HEAT TRANSFER PER CYCLE)/   ')/
     & (33X,'       (MASS OF FUEL TIMES LHV); (%)    ---->  ',1F7.1)//)
 5921 FORMAT ((33X,' -->  IGNITION DELAY (0 - 10%)     ')/
     & (33X,'       (CRANK ANGLE) / (MS)             ---->  ',2(F8.2))///
     & (33X,' -->  BURN DURATION (10 - 90%)     ')/
     & (33X,'       (CRANK ANGLE) / (MS)             ---->  ',2(F8.2))///
     & (33X,' -->  MEAN EXHAUST                 ')/
     & (33X,'       TEMPERATURE; (K)                 ---->  ',1F7.1)/)
 2901 FORMAT (/////,1H ,39X,'M.I.T. ZERO-DIMENSIONAL WANKEL ENGINE',
     &          ' CYCLE SIMULATION',/////)
 2902 FORMAT (/,1H ,10X,'>>>>> OPERATING MODE',/)
 2903 FORMAT (/,1H ,25X,'FIRING CYCLE')
 2904 FORMAT (/,1H ,25X,'MOTORED CYCLE',/)
 2905 FORMAT (/,1H ,25X,'SPECIFIED BURN RATE')
 2906 FORMAT (/,1H ,30X,'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',/)
 2914 FORMAT (/,1H ,10X,'>>>>> MANIFOLD CONDITIONS',/)
 2915 FORMAT (/,1H ,25X,'INTAKE MANIFOLD PRESSURE  = ',F10.4,' ATM',/
     &         /,1H ,25X,'EXHAUST MANIFOLD PRESSURE = ',F10.4,' ATM',/
     &         /,1H ,25X,'FRESH CHARGE TEMPERATURE  = ',F8.2,'   K',/
     &         /,1H ,25X,'EXHAUST GAS RECIRCULATION = ',F8.2,'   %',/
     &         /,1H ,25X,'EGR TEMPERATURE           = ',F8.2,'   K',/
     &         /,1H ,25X,'INTAKE CHARGE TEMPERATURE = ',F8.2,'   K',/
     &         /,1H ,25X,'ATMOSPHERIC PRESSURE      = ',F10.4,' ATM',/
     &         /,1H ,25X,'ATMOSPHERIC TEMPERATURE   = ',F8.2,'   K',/)
 2916 FORMAT (/,1H ,10X,'>>>>> HEAT TRANSFER AND TURBULENCE',
     &                    ' PARAMETERS',/)
 2917 FORMAT (/,1H ,25X,'HEAT TRANSFER CONSTANT         = ',F10.4,/
     &         /,1H ,25X,'HEAT TRANSFER EXPONENT         = ',F10.4,/
```

```
     &        /,1H ,25X,'ROTOR TEMPERATURE               =',F9.2,'   K',/
     &        /,1H ,25X,'SIDE WALL TEMPERATURE           =',F9.2,'   K',/
     &        /,1H ,25X,'HOUSING WALL TEMPERATURE        =',F9.2,'   K',/
     &        )
 2918 FORMAT (/,1H ,10X,'>>>>> ENGINE DESIGN PARAMETERS',/)
 2919 FORMAT (/,1H ,25X,'ECCENTRICITY OF ROTOR    = ',F9.3,' CM',/
     &        /,1H ,25X,'RADIUS OF ROTOR          = ',F9.3,' CM',/
     &        /,1H ,25X,'DEPTH OF CHAMBER         = ',F9.3,' CM',/
     &        /,1H ,25X,'COMPRESSION RATIO        = ',F9.3,/
     &        /,1H ,25X,'DISPLACED VOLUME         = ',F9.3,' CC',/
     &        /,1H ,25X,'VOLUME OF ROTOR POCKET   = ',F9.3,' CC',/
     &        /,1H ,25X,'INTAKE PORT OPENS       = ',F7.1,'   DEG CA',/
     &        /,1H ,25X,'INTAKE PORT CLOSES      = ',F7.1,'   DEG CA',/
     &        /,1H ,25X,'EXHAUST PORT OPENS      = ',F7.1,'   DEG CA',/
     &        /,1H ,25X,'EXHAUST PORT CLOSES     = ',F7.1,'   DEG CA',/)
 2920 FORMAT (/,1H ,10X,'>>>>> COMPUTATIONAL PARAMETERS',/)
 2921 FORMAT (/,1H ,25X,'MAXIMUM # OF ITERATIONS =   ',I4,/
     &        /,1H ,25X,'OUTPUT AT ITERATION #   =   ',I4,/
     &        /,1H ,25X,'TPRINT                   = ',F9.2,
     &        /,1H ,25X,'TPRINX                   = ',F9.2,
     &        /,1H ,25X,'XBZERO                   = ',F12.5,
     &        /,1H ,25X,'XESTOP                   = ',F12.5,
     &        /,1H ,25X,'XBSTOP                   = ',F12.5,
     &        /,1H ,25X,'CIINTG                   = ',F13.6,
     &        /,1H ,25X,'CCINTG                   = ',F13.6,
     &        /,1H ,25X,'CBINTG                   = ',F13.6,
     &        /,1H ,25X,'CEINTG                   = ',F13.6,
     &        /,1H ,25X,'AREROT                   = ',F13.6,
     &        /,1H ,25X,'REL                      = ',F13.6,
     &        /,1H ,25X,'ERMAX                    = ',F13.6,
     &        /,1H ,25X,'MAXERR                   = ',F13.6,
     &        /,1H ,25X,'MAXTRY                   = ',I6,/)
 2940 FORMAT (/,1H , 10X,'>>>>> LEAKAGE AND CREVICE VOLUME PARAMETERS'/)
 2941 FORMAT (/,1H , 25X,'LEAK AREA PER APEX     = ',F12.6,'  CM*CM'
     &        //,1H , 25X,'CREVICE VOLUME PER APEX= ',F12.6,'  CC    '
     &        //,1H , 25X,'CREVICE GAS TEMPERATURE= ',F12.6,'  K'/)
  999 FORMAT (///,1H ,15X,
     &        'WARNING!!  RESULTS FROM THIS CYCLE SIMULATION',/,16X,
     &        'MAY NOT BE ACCURATE FOR PHI > 1.3 OR PHI < 0.7',///)
      STOP
      END
C------------------------------------------------------------------------
C________________________________________________________________________
C
C     SUBROUTINE INTAKE
C
C     PURPOSE
C        CALCULATES OR ASSISTS THE CREVICE AND HEAT TRANSFER SUBROUTINES
C        CALCULATE THE TIME RATE OF CHANGE OF PRESSURE, TEMPERATURE,
C        MASS, HEAT TRANSFER,AND WORK TRANSFER IN THE CHAMBER DURING
C        INTAKE.
C
C     USAGE
C        CALL INTAKE (DT, DY, DYP)
C
```

```
C     DESCRIPTION OF PARAMETERS
C
C        PARAMETER  INPUT  OUTPUT   DESCRIPTION
C
C        DT         YES    NO       TIME (DEG)
C        DY(1)      NO     NO       MASS INDUCTED INTO CHAMBER THROUGH
C        -----      --     --       INTAKE PORT (G)
C        DY(2)      NO     NO       MASS EXHAUSTED FROM CHAMBER THROUGH
C        -----      --     --       EXHAUST PORT (G)
C        DY(5)      YES    NO       MASS FRACTION OF FRESH CHARGE (-)
C        DY(8)      NO     NO       HEAT TRANSFER TO ROTOR (KJ)
C        DY(9)      NO     NO       HEAT TRANSFER TO SIDE PLATES (KJ)
C        DY(10)     NO     NO       HEAT TRANSFER TO HOUSING (KJ)
C        DY(11)     YES    NO       CHAMBER TEMPERATURE (K)
C        DY(12)     YES    NO       CHAMBER PRESSURE (ATM)
C        DY(16)     NO     NO       TOTAL WORK TRANSFER (KJ)
C        DY(17)     NO     NO       TOTAL ENTHALPY EXHAUSTED (KJ)
C        DY(18)     NO     NO       TOTAL MASS LEAKED PAST LEAD
C        ------     --     --       APEX SEAL  (G)
C        DY(19)     NO     NO       TOTAL MASS LEAKED PAST TRAILING
C        ------     --     --       APEX SEAL  (G)
C        DY(20)     NO     NO       TOTAL HEAT LOSS TO CREVICE VOLUME
C        ------     --     --       WALLS (KJ)
C        DY(21)     NO     NO       MASS FRACTION OF FRESH CHARGE
C        ------     --     --       IN LEAD CREVICE  (-)
C        DY(22)     NO     NO       MASS FRACTION OF FRESH CHARGE
C        ------     --     --       IN TRAILING CREVICE  (-)
C        DY(23)     YES    NO       TOTAL MASS IN CHAMBER  (G)
C        DY(24)     NO     NO       TOTAL MASS THAT HAS LEFT AND ENTERED
C        ------     --     --       LEADING CHAMBER OR CREVICE (G)
C        DY(25)     NO     NO       TOTAL MASS THAT HAS LEFT AND ENTERED
C        ------     --     --       TRAILING CHAMBER OR CREVICE (G)
C
C        ---------------------------------------------------------------
C
C        DYP(1)     NO     YES      RATE AT WHICH MASS IS INDUCTED
C        ------     --     ---      THROUGH THE INTAKE PORT  (G/DEG)
C        DYP(2)     NO     YES      RATE AT WHICH MASS IS EXHAUSTED
C        ------     --     ---      THROUGH THE EXHAUST PORT (G/DEG)
C        DYP(5)     NO     YES      RATE OF CHANGE OF MASS FRACTION OF
C        ------     --     ---      FRESH CHARGE (1/DEG)
C        DYP(8)     NO     YES      RATE OF HEAT TRANSFER THROUGH
C        -------    --     ---      ROTOR WALL  (KJ/DEG)
C        DYP(9)     NO     YES      RATE OF HEAT TRANSFER THROUGH
C        -------    --     ---      SIDE PLATES (KJ/DEG)
C        DYP(10)    NO     YES      RATE OF HEAT TRANSFER THROUGH
C        -------    --     ---      HOUSING  (KJ/DEG)
C        DYP(11)    NO     YES      RATE OF CHANGE OF CHAMBER
C        ------     --     ---      TEMPERATURE (K/DEG)
C        DYP(12)    NO     YES      RATE OF CHANGE OF CHAMBER
C        ------     --     ---      PRESSURE (ATM/DEG)
C        DYP(16)    NO     YES      RATE OF TOTAL WORK TRANSFER (KJ/DEG)
C        DYP(17)    NO     YES      RATE AT WHICH TOTAL ENTHALPY IS
C        -------    --     ---      EXHAUSTED (KJ/DEG)
C        DYP(18)    NO     YES      RATE OF CHANGE OF MASS LEAKED PAST
```

148

```
C        -------    --     ---       LEAD APEX SEAL (G/DEG)
C        DYP(19)    NO     YES       RATE OF CHANGE OF MASS LEAKED PAST
C        -------    --     ---       TRAILING APEX SEAL (G/DEG)
C        DYP(20)    NO     YES       RATE OF HEAT TRANSFER TO CREVICE
C        -------    --     ---       VOLUME WALLS (KJ/DEG)
C        DYP(21)    NO     YES       RATE OF CHANGE OF FRESH CHARGE MASS
C        -------    --     ---       FRACTION IN LEAD CREVICE  ( )
C        DYP(22)    NO     YES       RATE OF CHANGE OF FRESH CHARGE MASS
C        -------    --     ---       FRACTION IN TRAILING CREVICE ( )
C        DYP(23)    NO     YES       RATE OF CHANGE OF TOTAL CHAMBER
C        -------    --     ---       MASS (G/DEG)
C        DYP(24)    NO     YES       NET RATE OF CHANGE OF MASS LEAVING
C        -------    --     ---       CHAMBER TO ENTER LEAD CREVICE AND
C        -------    --     ---       LEAD CHAMBER (G/DEG)
C        DYP(25)    NO     YES       NET RATE OF CHANGE OF MASS LEAVING
C        -------    --     ---       CHAMBER TO ENTER TRAILING CREVICE
C        -------    --     ---       AND TRAILING CHAMBER (G/DEG)
C
C
C
C     REMARKS
C        NONE
C
C     SUBROUTINE AND FUNCTION SUBPROGRAMS REQUIRED
C        UTHRMO      UTRANS      IPACD       MFLRT
C        CSAVDV      EPACD       CREVIC      HEATTX
C
C
C     METHOD
C        SEE REPORT
C
C     WRITTEN BY S. H. MANSOURI, S. G. POULOS, AND T. J. NORMAN
C     EDITED BY T. J. NORMAN
C
      SUBROUTINE INTAKE (DT, DY, DYP)
C
      REAL*8 DT, DY(25), DYP(25)
      REAL MW, MWIM, MWIMM, MASS, MDOT, MDOTFR, MSTART,
     &     MAXERR, MWBL, MWAC, IPA
      DIMENSION Y(25), YP(25)
      COMMON/EPARAM/ ECCEN, ROTRAD, DEPTH, AFLANK, VFLANK
      COMMON/TEMPS/TROTOR,TSIDE,THOUS
      COMMON/DTDTH/ ESPDI, RPM
      COMMON/MANFP/ PIM, TIM, EGR, PEM, MSTART
      COMMON/TIMES/ TIPO, TIPC, TEPO, TEPC, THIPO, THEPO, TSPARK
      COMMON/IMTHP/ HIM, MWIM, GIM, RHOIM
      COMMON/FIXX/ INFLAG
      COMMON/HEATS/VELHTX, HTRCOE, HTPARO, HTPASI, HTPAHO, HTXRO,
     &             HTXSI, HTXHO,  QFRRO, QFRSI, QFRHO
      COMMON/HTRAN/THTRAN
      COMMON/YYYY1/ VIP, VEP
      COMMON/RHMAS/ RHO, MASS, VOLUME, H, GAMMA
      COMMON/CREV/DRHODP,CSUBT,MW,ITERAS,DVDT,CSUBP,DRHODT,HIMM,RESIDL,
     &            RESFIM
      COMMON/BURN/SPBURN,FIRE,FIREFL
```

```
C
      VIP = 0.0
      VEP = 0.0
C
      DO 10  I = 1, 25
           Y(I) = DY(I)
   10 CONTINUE
      T = DT
      DO 20 I = 1, 25
           YP(I) = 0.0
   20 CONTINUE
C
C        FIND THERMODYNAMIC AND TRANSPORT PROPERTIES IN CHAMBER
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)
      MASS = Y(23)
C
C        FIND OUT IF INTAKE PORT IS OPEN.
C
      IF (T .GE. TIPC) GO TO 50
C
C        YES IT IS.
C        FIND OUT IF ANY MASS FLOWS ACROSS INTAKE PORT.
C
      IF (PIM - Y(12)) 30, 50, 40
C
C        REVERSE FLOW PAST PORT.
C        CALCULATE CD AND EFFECTIVE AREA.
C
   30 PR = Y(12)/PIM
      CALL IPACD (T, AREA, CD)
C
C        CALCULATE MASS FLOW RATE FROM CHAMBER TO INTAKE MANIFOLD.
C
      CALL MFLRT (CD, AREA, Y(12), MW, Y(11), PIM, GAMMA, FRAIV)
C
C        CALCULATE RATES DUE TO THIS FLOW.
C
      YP(1) = -FRAIV
      IF (AREA .LE. 0.0) GO TO 35
      VIP = -FRAIV/(RHO * AREA)
   35 HIMM = H
      GO TO 50
C
C        FLOW INTO CHAMBER.
C        CALCULATE CD AND AREA.
C
   40 PR = PIM/Y(12)
      CALL IPACD (T, AREA, CD)
C
C        CALCULATE THERMODYNAMIC STATE OF MATERIAL FLOWING
C        INTO CHAMBER.
C        INFLAG = 0; CHAMBER GASES IN INTAKE MANIFOLD FLOWING BACK
```

```
C         INFLAG = 1; FRESH CHARGE (I.E. AIR, FUEL, AND EGR).
C
      TIMM = TIM * INFLAG + Y(11) * (1 - INFLAG)
      HIMM = HIM * INFLAG + H * (1 - INFLAG)
      MWIMM = MWIM * INFLAG + MW * (1 - INFLAG)
      GIMM = GIM * INFLAG + GAMMA * (1 - INFLAG)
      RHOIMM = RHOIM * INFLAG + RHO * (1 - INFLAG)
C
C         CALCULATE MASS FLOW RATE
C
      CALL MFLRT (CD, AREA, PIM, MWIMM, TIMM, Y(12), GIMM, FRAIV)
C
C         CALCULATE RATES DUE TO THIS FLOW
C
      YP(1) = FRAIV
      IF (AREA .LE. 0.0) GO TO 50
      VIP = FRAIV/(RHOIMM * AREA)
C
C         IS EXHAUST PORT STILL OPEN ?
C
   50 IF ((T + 1080.) .GE. TEPC) GO TO 80
C
C         YES IT IS.
C         ANY FLOW ACROSS IT ?
C
      IF (Y(12) - PEM) 60, 80, 70
C
C         YES, FLOW INTO CHAMBER.
C         FIND CD AND AREA FOR EXHAUST PORT.
C
   60 PR = PEM/Y(12)
CT
CT         FOR A CORRECT CALCULATION OF THE EXHAUST PORT OPEN
CT         AREA AN ADJUSTED TIME MUST BE USED.
      TEP = T + 1080.
CT
      CALL EPACD (TEP, AREA, CD)
C
C         FIND MASS FLOW RATE.
C
      CALL MFLRT (CD, AREA, PEM, MW, Y(11), Y(12), GAMMA, FRAEV)
C
C         CALCULATE RATES DUE TO THIS FLOW.
C
      YP(2) = -FRAEV
      IF (AREA .LE. 0.0) GO TO 80
      VEP = -FRAEV/(RHO * AREA)
      GO TO 80
C
C         FLOW FROM CHAMBER INTO EXHAUST MANIFOLD.
C         FIND AREA AND CD FOR EXHAUST PORT.
C
   70 PR = Y(12)/PEM
C
C          FOR A CORRECT CALCULATION OF THE EXHAUST PORT OPEN AREA
```

```
C         AN ADJUSTED TIME MUST BE USED.
C
      TEP = T + 1080.
      CALL EPACD (TEP, AREA, CD)
C
C        FIND MASS FLOW RATE.
C
      CALL MFLRT (CD, AREA, Y(12), MW, Y(11), PEM, GAMMA, FRAEV)
C
C        CALCULATE RATES DUE TO THIS FLOW.
C
      YP(2) = FRAEV
      IF (AREA .LE. 0.0) GO TO 75
      VEP = FRAEV/(RHO * AREA)
   75 CONTINUE
C
C        FIND SURFACE AREAS AND VOLUME OF CHAMBER
C
   80 CALL CSAVDV (T, VOLUME, DVDT)
      MDOT = YP(1) - YP(2)
      MDOTFR = YP(1) * (1. - EGR/100.) * INFLAG - YP(2) * Y(5)
     &          + YP(1) * Y(5) * (1 - INFLAG)
C
C              CALCULATE HEAT TRANSFER RATES
C
C
        CALL HEATTX (T,Y,YP,THTRAN,XX1,XX2)
C
C
C
C        CALCULATE RATES OF CHANGE OF TEMPERATURE AND PRESSURE IN
C        THE CHAMBER.  THEN CALCULATE RATE OF DOING WORK.
C
   90 CALL CREVIC (T,Y,YP)
      YP(16) = Y(12) * DVDT * .101325E-3
C
      YP(8)  = YP(8) * 1.E-10
      YP(9)  = YP(9) * 1.E-10
      YP(10) = YP(10) * 1.E-10
      THTRAN = THTRAN * 1.E-10 * ESPDI
C
      YP(17) = YP(2) * H
C
C        CONVERT ALL TIME DERIVATIVES TO RATE PER CRANK
C        ANGLE DEGREE.
C
      DO 100 I = 1, 25
          DYP(I) = YP(I) * ESPDI
  100 CONTINUE
C
      RETURN
      END
C______________________________________________________________________
C
C     SUBROUTINE CMPRES
```

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

```
C        -------    --     ---      TRAILING APEX SEAL (G/DEG)
C        DYP(20)    NO     YES      RATE OF HEAT TRANSFER TO CREVICE
C        -------    --     ---      VOLUME WALLS  (KJ/DEG)
C        DYP(21)    NO     YES      RATE OF CHANGE OF FRESH CHARGE MASS
C        -------    --     ---      FRACTION IN LEAD CREVICE  (/DEG)
C        DYP(22)    NO     YES      RATE OF CHANGE OF FRESH CHARGE MASS
C        -------    --     ---      FRACTION IN TRAILING CREVICE (/DEG)
C        DYP(23)    NO     YES      RATE OF CHANGE OF TOTAL CHAMBER
C        -------    --     ---      MASS (G/DEG)
C        DYP(24)    NO     YES      NET RATE OF CHANGE OF MASS LEAVING
C        -------    --     ---      CHAMBER TO ENTER LEAD CREVICE AND
C        -------    --     ---      LEAD CHAMBER (G/DEG)
C        DYP(25)    NO     YES      NET RATE OF CHANGE OF MASS LEAVING
C        -------    --     ---      CHAMBER TO ENTER TRAILING CREVICE
C        -------    --     ---      AND TRAILING CHAMBER (G/DEG)
C
C
C
C     REMARKS
C        NONE
C
C     SUBROUTINE AND FUNCTION SUBPROGRAMS REQUIRED
C        UTHRMO     UTRANS    CSAVDV    CREVIC    HEATTX
C
C
C     METHOD
C        SEE REPORT
C
C     WRITTEN BY S. H. MANSOURI, S. G. POULOS, AND T. J. NORMAN
C     EDITED BY T. J. NORMAN
C
      SUBROUTINE CMPRES (DT,DY,DYP)
C
      REAL*8 DT, DY(25), DYP(25)
      REAL MW, MWIM, MWIMM, MASS, MDOT, MDOTFR, MSTART
      DIMENSION Y(25), YP(25)
      COMMON/EPARAM/ ECCEN, ROTRAD, DEPTH, VFLANK
      COMMON/TEMPS/TROTOR,TSIDE,THOUS
      COMMON/DTDTH/ ESPDI, RPM
      COMMON/MANFP/ PIM, TIM, EGR, PEM, MSTART
      COMMON/TIMES/ TIPO, TIPC, TEPO, TEPC, THIPO, THEPO, TSPARK
      COMMON/IMTHP/ HIM, MWIM, GIM, RHOIM
      COMMON/FIXX/ INFLAG
      COMMON/HEATS/VELHTX, HTRCOE, HTPARO, HTPASI, HTPAHO, HTXRO,
     &             HTXSI, HTXHO,  QFRRO, QFRSI, QFRHO
      COMMON/HTRAN/THTRAN
      COMMON/YYYY1/ VIP, VEP
      COMMON/RHMAS/ RHO, MASS, VOLUME, H, GAMMA
      COMMON/CREV/DRHODP,CSUBT,MW,ITERAS,DVDT,CSUBP,DRHODT,HIMM,RESIDL,
     &            RESFIM
      COMMON/BURN/SPBURN,FIRE,FIREFL
C
C
      DO 10  I = 1, 25
           Y(I) = DY(I)
```

```
   10 CONTINUE
      T = DT
      DO 20 I = 1, 25
           YP(I) = 0.0
   20 CONTINUE
C
C         FIND THERMODYNAMIC AND TRANSPORT PROPERTIES IN CHAMBER
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)
      MASS = Y(23)
C
C         FIND SURFACE AREAS AND VOLUME OF CHAMBER
C
      CALL CSAVDV (T, VOLUME, DVDT)
C
C                  CALCULATE HEAT TRANSFER RATES
C
C
         CALL HEATTX (T,Y,YP,THTRAN,XX1,XX2)
C
C
C
C        CALCULATE RATES OF CHANGE OF TEMPERATURE AND PRESSURE IN
C        THE CHAMBER.  THEN CALCULATE RATE OF DOING WORK.
C
   30 CALL CREVIC (T,Y,YP)
      YP(16) = Y(12) * DVDT * .101325E-3
C
C         CONVERT THE HEAT TRANSFER RATES TO KILO JOULES
C
      YP(8)  = YP(8) * 1.E-10
      YP(9)  = YP(9) * 1.E-10
      YP(10) = YP(10) * 1.E-10
      THTRAN = THTRAN * 1.E-10 * ESPDI
C
C        CONVERT ALL TIME DERIVATIVES TO RATE PER CRANK
C        ANGLE DEGREE.
C
      DO 40 I = 1, 25
           DYP(I) = YP(I) * ESPDI
   40 CONTINUE
C
      RETURN
      END
C________________________________________________________________________
C
C     SUBROUTINE CMBSTN
C
C     PURPOSE
C        CALCULATES OR ASSISTS THE CREVICE AND HEAT TRANSFER SUBROUTINES
C        CALCULATE THE TIME RATE OF CHANGE OF PRESSURE, TEMPERATURE,
C        MASS, HEAT TRANSFER,AND WORK TRANSFERIN THE CHAMBER DURING
C        COMBUSTION.
```

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

```
C         DY(24)      YES    NO        TOTAL MASS THAT HAS LEFT AND ENTERED
C         ------      ---    --        LEADING CHAMBER OR CREVICE (G)
C         DY(25)      YES    NO        TOTAL MASS THAT HAS LEFT AND ENTERED
C         ------      ---    --        TRAILING CHAMBER OR CREVICE (G)
C
C         ----------------------------------------------------------------
C
C         DYP(3)      NO     YES       RATE OF FUEL ENTERING EXHAUST
C         -------     --     ---       CHAMBER.
C         DYP(4)      NO     YES       RATE OF CHANGE OF MASS FRACTION
C         -------     --     ---       BURNED (1/DEG)
C         DYP(8)      NO     YES       RATE OF HEAT TRANSFER THROUGH
C         --------    --     ---       ROTOR WALL  (KJ/DEG)
C         DYP(9)      NO     YES       RATE OF HEAT TRANSFER THROUGH
C         --------    --     ---       SIDE PLATES (KJ/DEG)
C         DYP(10)     NO     YES       RATE OF HEAT TRANSFER THROUGH
C         --------    --     ---       HOUSING  (KJ/DEG)
C         DYP(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 MASS LEAKED PAST
C         --------    --     ---       LEAD APEX SEAL (G/DEG)
C         DYP(19)     NO     YES       RATE OF CHANGE OF MASS LEAKED PAST
C         --------    --     ---       TRAILING APEX SEAL  (G/DEG)
C         DYP(20)     NO     YES       RATE OF HEAT TRANSFER TO CREVICE
C         --------    --     ---       VOLUME WALLS  (KJ/DEG)
C         DYP(21)     NO     YES       RATE OF CHANGE OF FRESH CHARGE MASS
C         --------    --     ---       FRACTION IN LEAD CREVICE  (/DEG)
C         DYP(22)     NO     YES       RATE OF CHANGE OF FRESH CHARGE MASS
C         --------    --     ---       FRACTION IN TRAILING CREVICE (/DEG)
C         DYP(23)     NO     YES       RATE OF CHANGE OF TOTAL CHAMBER
C         --------    --     ---       MASS (G/DEG)
C         DYP(24)     NO     YES       NET RATE OF CHANGE OF MASS LEAVING
C         --------    --     ---       CHAMBER TO ENTER LEAD CREVICE AND
C         --------    --     ---       LEAD CHAMBER (G/DEG)
C         DYP(25)     NO     YES       NET RATE OF CHANGE OF MASS LEAVING
C         --------    --     ---       CHAMBER TO ENTER TRAILING CREVICE
C         --------    --     ---       AND TRAILING CHAMBER (G/DEG)
C
C
C
C     REMARKS
C        NONE
C
C     SUBROUTINE AND FUNCTION SUBPROGRAMS REQUIRED
C        UTHRMO     UTRANS     CSAVDV     CREVIC     HEATTX
C
```

```
C
C     METHOD
C        SEE REPORT
C
C     WRITTEN BY S. H. MANSOURI, K. RADHAKRISHNAN, S. G. POULOS, AND
C                T. J. NORMAN
C     EDITED BY T. J. NORMAN
C
      SUBROUTINE CMBSTN (DT,DY,DYP)
C
      LOGICAL SPBURN,BURN,FIREFL
      REAL*8 DT,DY(25),DYP(25), D(4), XMOFR(14), TMP, PRS
      REAL MW,MWIM,MWIMM,MASS,MDOT,MDOTFR,MSTART,
     &     MASSU
      DIMENSION Y(25),YP(25)
      COMMON/EPARAM/ ECCEN, ROTRAD, DEPTH, VFLANK
      COMMON/TEMPS/TROTOR,TSIDE,THOUS
      COMMON/BURN/ SPBURN, FIRE, FIREFL
      COMMON/DTDTH/ ESPDI, RPM
      COMMON/MANFP/ PIM,TIM,EGR,PEM, MSTART
      COMMON/TIMES/ TIPO, TIPC, TEPO, TEPC, THIPO, THEPO, TSPARK
      COMMON/IMTMP/ HIM,MWIM,GIM,RHOIM
      COMMON/FIXX/ INFLAG
      COMMON/HEATS/VELHTX, HTRCOE, HTPARO, HTPASI, HTPAHO, HTXRO,
     &             HTXSI, HTXHO,  QFRRO, QFRSI, QFRHO
      COMMON/HTRAN/THTRAN
      COMMON/UBHEAT/ UHTRCO, BHTRCO
      COMMON/YYYY1/ VIP, VEP
      COMMON/CHEM/ D
      COMMON/SPECB/ DTBRN, CONSPB, EXSPB
      COMMON/XSTOP/ XBSTOP
      COMMON/CREV/DRHODP,CSUBT,MW,ITERAS,DVDT,CSUBP,DRHODT,HIMM,RESIDL,
     &            RESFIM
      COMMON/RHMAS/RHO,MASS,VOLUME,H,GAMMA,GAMAB
      COMMON/CREVCB/HU,HB,DRODPU,DRODPB,RHOU,RHOB,DRODTU,DRODTB,
     &              CSUBPU,CSUBPB,CSUBTU,CSUBTB,UHTRAN,BHTRAN
C
C
CJ    DATA CONSAM,CONSEM/1.0,1.0/
C
C
      FIREFL = .TRUE.
C
      DO 10  I = 1, 25
           Y(I) = DY(I)
   10 CONTINUE
      T = DT
      DO 20 I = 1, 25
           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, XXXA, XXXB, XXC, XXD)
      CALL THERMO (T, Y(15), Y(12), 1., HB, CSUBPB, CSUBTB,
     & RHOB, DRODTB, DRODPB, GAMAB, XXB, XXXA, XXXB, XXC, XXD)
C
C
      MASS  = Y(23)
      MASSU = MASS*(1.- Y(4) )
C
C
      CALL CSAVDV (T, VOLUME, DVDT)
      VBURND = VOLUME - Y(14)
C
C        SPECIFIED BURN RATE COMBUSTION MODEL
C
   30 TONDTB = (T - TSPARK)/DTBRN
      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
C
   40 CONTINUE
C
      CALL HEATTX (T, Y, YP, THTRAN, UHTRAN, BHTRAN)
C
C        CALCULATE RATES OF CHANGE OF TEMPERATURE AND PRESSURE IN
C        THE CYLINDER.  THEN CALCULATE RATE OF DOING WORK.
C
      CALL CREVIC (T,Y,YP)
C
      YP(16) = Y(12) * DVDT * .101325E-3
C
C        CONVERT TTHE HEAT TRANSFER RATES TO KILO JOULES
C
      YP(8)  = YP(8) * 1.E-10
      YP(9)  = YP(9) * 1.E-10
      YP(10) = YP(10) * 1.E-10
      THTRAN = THTRAN * 1.E-10 * ESPDI
C
C        CONVERT ALL TIME DERIVATIVES TO RATE PER CRANK
C        ANGLE DEGREE.
C
   70 DO 80 I = 1, 25
           DYP(I) = YP(I) * ESPDI
   80 CONTINUE
C
      FIREFL = .FALSE.
C
      RETURN
      END
C-----------------------------------------------------------------------
C
C     SUBROUTINE EXAUST
C
```

```
C     PURPOSE
C        CALCULATES OR ASSISTS THE CREVICE AND HEAT TRANSFER SUBROUTINES
C        CALCULATE THE TIME RATE OF CHANGE OF PRESSURE, TEMPERATURE,
C        MASS, HEAT TRANSFER, AND WORK TRANSFERIN THE CHAMBER DURING
C        EXAUST.
C
C     USAGE
C        CALL EXAUST (DT, DY, DYP)
C
C     DESCRIPTION OF PARAMETERS
C
C        PARAMETER  INPUT  OUTPUT   DESCRIPTION
C
C        DT         YES    NO       TIME (DEG)
C        DY(2)      NO     NO       MASS EXHAUSTED FROM CHAMBER THROUGH
C        ------     ---    --       EXHAUST PORT (G)
C        DY(3)      NO     NO       FUEL ENERGY THAT ENTERS EXAUST (KJ)
C        DY(8)      NO     NO       HEAT TRANSFER TO ROTOR (KJ)
C        DY(9)      NO     NO       HEAT TRANSFER TO SIDE PLATES (KJ)
C        DY(10)     NO     NO       HEAT TRANSFER TO HOUSING (KJ)
C        DY(11)     YES    NO       CHAMBER TEMPERATURE (K)
C        DY(12)     YES    NO       CHAMBER PRESSURE (ATM)
C        DY(16)     NO     NO       TOTAL WORK TRANSFER (KJ)
C        DY(17)     NO     NO       TOTAL ENTHALPY EXHAUSTED (KJ)
C        DY(18)     NO     NO       TOTAL MASS LEAKED PAST LEAD
C        ------     --     --       APEX SEAL  (G)
C        DY(19)     NO     NO       TOTAL MASS LEAKED PAST TRAILING
C        -------    --     --       APEX SEAL  (G)
C        DY(20)     NO     NO       TOTAL HEAT LOSS TO CREVICE VOLUME
C        -------    --     --       WALLS (KJ)
C        DY(21)     NO     NO       MASS FRACTION OF FRESH CHARGE
C        -------    --     --       IN LEAD CREVICE  (-)
C        DY(22)     NO     NO       MASS FRACTION OF FRESH CHARGE
C        ------     --     --       IN TRAILING CREVICE  (-)
C        DY(23)     YES    NO       TOTAL MASS IN CHAMBER  (G)
C        DY(24)     NO     NO       TOTAL MASS THAT HAS LEFT AND ENTERED
C        ------     --     --       LEADING CHAMBER OR CREVICE (G)
C        DY(25)     NO     NO       TOTAL MASS THAT HAS LEFT AND ENTERED
C        -------    --     --       TRAILING CHAMBER OR CREVICE (G)
C
C        ---------------------------------------------------------------
C
C        DYP(2)     NO     YES      RATE AT WHICH MASS IS EXHAUSTED
C        -------    --     ---      THROUGH THE EXHAUST PORT (G/DEG)
C        DYP(3)     NO     YES      RATE OF FUEL ENERGY ENTERING
C        -------    ---    ---      EXHAUST CHAMBER (KJ/DEG)
C        DYP(8)     NO     YES      RATE OF HEAT TRANSFER THROUGH
C        --------   --     ---      ROTOR WALL  (KJ/DEG)
C        DYP(9)     NO     YES      RATE OF HEAT TRANSFER THROUGH
C        --------   --     ---      SIDE PLATES (KJ/DEG)
C        DYP(10)    NO     YES      RATE OF HEAT TRANSFER THROUGH
C        --------   --     ---      HOUSING  (KJ/DEG)
C        DYP(11)    NO     YES      RATE OF CHANGE OF CHAMBER
C        -------    --     ---      TEMPERATURE (K/DEG)
C        DYP(12)    NO     YES      RATE OF CHANGE OF CHAMBER
```

```
C          ------     --      ---        PRESSURE (ATM/DEG)
C          DYP(16)    NO      YES        RATE OF TOTAL WORK TRANSFER (KJ/DEG)
C          DYP(17)    NO      YES        RATE AT WHICH TOTAL ENTHALPY IS
C          -------    --      ---        EXHAUSTED (KJ/DEG)
C          DYP(18)    NO      YES        RATE OF CHANGE OF MASS LEAKED PAST
C          -------    --      ---        LEAD APEX SEAL (G/DEG)
C          DYP(19)    NO      YES        RATE OF CHANGE OF MASS LEAKED PAST
C          -------    --      ---        TRAILING APEX SEAL (G/DEG)
C          DYP(20)    NO      YES        RATE OF HEAT TRANSFER TO CREVICE
C          -------    --      ---        VOLUME WALLS (KJ/DEG)
C          DYP(21)    NO      YES        RATE OF CHANGE OF FRESH CHARGE MASS
C          -------    --      ---        FRACTION IN LEAD CREVICE (/DEG)
C          DYP(22)    NO      YES        RATE OF CHANGE OF FRESH CHARGE MASS
C          -------    --      ---        FRACTION IN TRAILING CREVICE (/DEG)
C          DYP(23)    NO      YES        RATE OF CHANGE OF TOTAL CHAMBER
C          -------    --      ---        MASS (G/DEG)
C          DYP(24)    NO      YES        NET RATE OF CHANGE OF MASS LEAVING
C          -------    --      ---        CHAMBER TO ENTER LEAD CREVICE AND
C          -------    --      ---        LEAD CHAMBER (G/DEG)
C          DYP(25)    NO      YES        NET RATE OF CHANGE OF MASS LEAVING
C          -------    --      ---        CHAMBER TO ENTER TRAILING CREVICE
C          -------    --      ---        AND TRAILING CHAMBER  (G/DEG)
C
C
C
C     REMARKS
C        NONE
C
C     SUBROUTINE AND FUNCTION SUBPROGRAMS REQUIRED
C        UTHRMO     BTRANS     MFLRT     CREVIC
C        CSAVDV     EPACD      HEATTX
C
C
C     METHOD
C        SEE REPORT
C
C     WRITTEN BY S. H. MANSOURI, S. G. POULOS, AND T. J. NORMAN
C     EDITED BY T. J. NORMAN
C
      SUBROUTINE EXAUST (DT, DY, DYP)
C
      LOGICAL FIRE
      REAL*8 DT, DY(25), DYP(25)
      REAL MW, MWIM, MWIMM, MASS, MDOT, MDOTFR, MSTART
      DIMENSION Y(25), YP(25)
      COMMON/EPARAM/ ECCEN, ROTRAD, DEPTH, VFLANK
      COMMON/BURN/ SPBURN, FIRE, FIREFL
      COMMON/TEMPS/TROTOR,TSIDE,THOUS
      COMMON/DTDTH/ ESPDI, RPM
      COMMON/MANFP/ PIM, TIM, EGR, PEM, MSTART
      COMMON/TIMES/ TIPO, TIPC, TEPO, TEPC, THIPO, THEPO, TSPARK
      COMMON/IMTHP/ HIM, MWIM, GIM, RHOIM
      COMMON/FIXX/ INFLAG
      COMMON/HEATS/VELHTX, HTRCOE, HTPARO, HTPASI, HTPAHO, HTXRO,
     &             HTXSI, HTXHO,  QFRRO, QFRSI, QFRHO
```

```
      COMMON/HTRAN/THTRAN
      COMMON/YYYY1/ VIP, VEP
      COMMON/RHMAS/ RHO, MASS, VOLUME, H, GAMMA
      COMMON/CREV/DRHODP,CSUBT,MW,ITERAS,DVDT,CSUBP,DRHODT,HIMM,RESIDL,
     &            RESFIM
C
      VEP = 0.0
C
      DO 10  I = 1, 25
           Y(I) = DY(I)
   10 CONTINUE
      T = DT
      DO 20 I = 1, 25
           YP(I) = 0.0
   20 CONTINUE
C
C        FIND THERMODYNAMIC AND TRANSPORT PROPERTIES IN CHAMBER
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)
      MASS = Y(23)
C
C        IS EXHAUST PORT STILL OPEN ?
C
      IF (T .GE. TEPC) GO TO 50
C
C        YES IT IS.
C        ANY FLOW ACROSS IT ?
C
      IF (Y(12) - PEM) 30, 50, 40
C
C        YES, FLOW INTO CHAMBER.
C        FIND CD AND AREA FOR EXHAUST PORT.
C
   30 PR = PEM/Y(12)
      CALL EPACD (T, AREA, CD)
C
C        FIND MASS FLOW RATE.
C
      CALL MFLRT (CD, AREA, PEM, MW, Y(11), Y(12), GAMMA, FRAEV)
C
C        CALCULATE RATES DUE TO THIS FLOW.
C
      YP(2) = -FRAEV
      IF (AREA .LE. 0.0) GO TO 35
      VEP = -FRAEV/(RHO * AREA)
   35 CONTINUE
      GO TO 50
C
C        FLOW FROM CHAMBER INTO EXHAUST MANIFOLD.
C        FIND AREA AND CD FOR EXHAUST PORT.
C
   40 PR = Y(12)/PEM
```

```
      CALL EPACD (T, AREA, CD)
C
C        FIND MASS FLOW RATE.
C
      CALL MFLRT (CD, AREA, Y(12), MW, Y(11), PEM, GAMMA, FRAEV)
C
C        CALCULATE RATES DUE TO THIS FLOW
C
      YP(2) = FRAEV
      IF (AREA .LE. 0.0) GO TO 45
      VEP = FRAEV/(RHO * AREA)
   45 CONTINUE
C
C        FIND SURFACE AREAS AND VOLUME OF CHAMBER
C
   50 CALL CSAVDV (T, VOLUME, DVDT)
C
C               CALCULATE HEAT TRANSFER RATES
C
C
C
      CALL HEATTX (T, Y, YP, THTRAN, XX, XXX)
C
C        CALCULATE RATES OF CHANGE OF TEMPERATURE AND PRESSURE IN
C        THE CHAMBER.  THEN CALCULATE RATE OF DOING WORK.
C
   60 CALL CREVIC(T,Y,YP)
      YP(16) = Y(12) * DVDT * .101325E-3
C
      YP(8)  = YP(8) * 1.E-10
      YP(9)  = YP(9) * 1.E-10
      YP(10) = YP(10) * 1.E-10
      THTRAN = THTRAN * 1.E-10 * ESPDI
C
      YP(17) = YP(2) * H
C
C        CONVERT ALL TIME DERIVATIVES TO RATE PER CRANK
C        ANGLE DEGREE.
C
      DO 70 I = 1, 25
           DYP(I) = YP(I) * ESPDI
   70 CONTINUE
C
CJ
CJ    DY(21) = Y(21)
CJ    DY(22) = Y(22)
CJ
      RETURN
      END
C-----------------------------------------------------------------------
C
C
C     SUBROUTINE CREVICE
C
C     PURPOSE
```

```
C        TO CALCULATE THE LEAKAGE AND CREVICE VOLUME MASS FLOW RATES
C        AND COMPOSITIONS. BECAUSE AN ASSUMPTION FOR NET FLOW DIRECTION
C        AT EACH APEX MUST BE MADE, AND THEN CHECKED, SEVERAL OF THE
C        INTEGRATION VARIABLES ARE EVALUATED IN THIS SUBROUTINE
C        RATHER THAN THE PROCESS SUBROUTINES.
C
C     USAGE
C        CALL CREVIC (T,Y,YP)
C
C     DESCRIPTION OF PARAMETERS
C
C        PARAMETER  INPUT  OUTPUT   DESCRIPTION
C
C        DT         YES    NO       TIME (DEG)
C        DY(3)      NO     NO       FUEL ENERGY THAT ENTERS EXAUST
C        -----      --     --       CHAMBER (KJ)
C        DY(4)      NO     NO       MASS FRACTION BURNED (-)
C        DY(5)      YES    NO       MASS FRACTION OF FRESH CHARGE (-)
C        DY(11)     YES    NO       CHAMBER TEMPERATURE (K)
C        DY(12)     YES    NO       CHAMBER PRESSURE (ATM)
C        DY(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        ------     --     ---      (K/DEG)
C        DY(18)     NO     NO       TOTAL MASS LEAKED PAST LEAD
C        ------     --     --       APEX SEAL  (G)
C        DY(19)     NO     NO       TOTAL MASS LEAKED PAST TRAILING
C        ------     --     --       APEX SEAL  (G)
C        DY(20)     NO     NO       TOTAL HEAT LOSS TO CREVICE VOLUME
C        -------    --     --       WALLS (KJ)
C        DY(21)     YES    NO       MASS FRACTION OF FRESH CHARGE
C        ------     ---    --       IN LEAD CREVICE  (-)
C        DY(22)     YES    NO       MASS FRACTION OF FRESH CHARGE
C        ------     ---    --       IN TRAILING CREVICE  (-)
C        DY(23)     YES    NO       TOTAL MASS IN CHAMBER  (G)
C        ---------------------------------------------------------------
C
C        DYP(1)     YES    NO       RATE AT WHICH MASS IS INDUCTED
C        ------     --     --       THROUGH THE INTAKE PORT
C        DYP(2)     YES    NO       RATE AT WHICH MASS IS EXHAUSTED
C        ------     --     --       THROUGH THE EXHAUST PORT
C        DYP(3)     NO     YES      RATE OF FUEL ENTERING EXHAUST
C        ------     --     ---      CHAMBER.
C        DYP(4)     YES    NO       RATE OF CHANGE OF MASS FRACTION
C        ------     --     ---      BURNED
C        DYP(5)     NO     YES      RATE OF CHANGE OF MASS FRACTION OF
C        ------     --     ---      FRESH CHARGE IN CHAMBER
C        DYP(11)    NO     YES      RATE OF CHANGE OF CHAMBER
C        -------    --     ---      TEMPERATURE
C        DYP(12)    NO     YES      RATE OF CHANGE OF CHAMBER
C        -------    --     ---      PRESSURE
C        DYP(13)    NO     YES      RATE OF CHANGE OF UNBURNED MIXTURE
```

```
C          ------      --      ---       TEMPERATURE DURING COMBUSTION
C          DYP(14)     NO      YES       RATE OF CHANGE OF UNBURNED MIXTURE
C          -------     --      ---       VOLUME DURING COMBUSTION
C          DYP(15)     NO      YES       RATE OF CHANGE OF BURNED PRODUCTS
C          ------      --      ---       TEMPERATURE DURING COMBUSTION
C          DYP(18)     NO      YES       RATE OF CHANGE OF MASS LEAKED PAST
C          -------     --      ---       LEAD APEX SEAL
C          DYP(19)     NO      YES       RATE OF CHANGE OF MASS LEAKED PAST
C          -------     --      ---       TRAILING APEX SEAL
C          DYP(20)     NO      YES       RATE OF HEAT TRANSFER TO CREVICE
C          -------     --      ---       VOLUME WALLS
C          DYP(21)     NO      YES       RATE OF CHANGE OF FRESH CHARGE MASS
C          -------     --      ---       FRACTION IN LEAD CREVICE
C          DYP(22)     NO      YES       RATE OF CHANGE OF FRESH CHARGE MASS
C          -------     --      ---       FRACTION IN TRAILING CREVICE
C          DYP(23)     NO      YES       RATE OF CHANGE OF TOTAL CHAMBER
C          -------     --      ---       MASS
C          DYP(24)     NO      YES       NET RATE OF CHANGE OF MASS LEAVING
C          -------     --      ---       CHAMBER TO ENTER LEAD CREVICE AND
C          -------     --      ---       LEAD CHAMBER
C          DYP(25)     NO      YES       NET RATE OF CHANGE OF MASS LEAVING
C          -------     --      ---       CHAMBER TO ENTER TRAILING CREVICE
C          -------     --      ---       AND TRAILING CHAMBER
C
C
C     REMARKS
C       - LEAD CHAMBER REFERS TO THE CHAMBER AHEAD (IN THE DIRECTION
C         OF ROTATION) OF THE THERMODYNAMIC SYSTEM.
C
C       - LAG (OR TRAILING) CHAMBER REFERS TO THE CHAMBER BEHIND.
C
C       - REFER TO PROCESS ROUTINES FOR UNITS OF INTEGRATION VARIABLES.
C
C     SUBROUTINE AND FUNCTION SUBPROGRAMS REQUIRED
C        THERMO     MFLRT      TABLE
C
C
C     METHOD
C        SEE REPORT
C
C     WRITTEN BY T. J. NORMAN
C
      SUBROUTINE CREVIC (T,Y,YP)
C
      LOGICAL FIRE,FIREFL
      REAL MW, MW1, MW2, MWLDC, MWLAGC, MASS, MASLDC, MDOTDC, MASLGC,
     &     MDOTGC, LDLEAK, LGLEAK,MASSB,MASSU,MDOTLD,MDOTLG,MDOTCB
      DIMENSION Y(25), YP(25)
      COMMON/RHMAS/RHO,MASS,VOLUME,H,GAMMA
      COMMON/TEMPS/TPSTON,THEAD,TCW
      COMMON/HEATS/VELHTX, HTRCOE, HTPARO, HTPASI, HTPAHO, HTXRO,
     &             HTXSI, HTXHO,  QFRRO, QFRSI, QFRHO
      COMMON/HTRAN/THTRAN
      COMMON/CREV/DRHODP,CSUBT,MW,ITERAS,DVDT,CSUBP,DRHODT,HIMM,RESIDL,
     &            RESFIM
```

```
      COMMON/CREV2/ MASLDC, MASLGC
      COMMON/BURN/ SPBURN, FIRE, FIREFL
      COMMON/FIXX/ INFLAG
      COMMON/MANFP/ PIM, TIM, EGR, PEM, MSTART
      COMMON/CREVCB/HU,HB,DRODPU,DRODPB,RHOU,RHOB,DRODTU,DRODTB,
     &              CSUBPU,CSUBPB,CSUBTU,CSUBTB,UHTRAN,BHTRAN
      COMMON/CREVQ/CRMASD,CRMASG,X1LDC,X1LAGC,ZMAST,ZMASS,ZLEAKD,ZLEAKG,
     &             ZCRCOD,ZCRCOG
      COMMON/CREVIN/AREALK,CREVOL,TCREV,X1LDIN,X1LGIN
C
C       FIND THE THERMODYNAMIC PROPERTIES OF THE FRESH CHARGE AND THE
C       BURNED GASES IN THE CHAMBER.
C
      TCR  = TCREV
      AREA = AREALK
      MASS = Y(23)
      VOLLDC = CREVOL
      VOLLGC = CREVOL
C
      RES = RESIDL
      IF ( T .LE. TIPC) RES = RESFIM
      CALL THERMO (T,Y(11),Y(12),RES,H1,XXA,XXB,XXC,XXD,XXE,XXF,
     &             MW1,XXG,XXH,XXI,XXJ)
      CALL THERMO (T,Y(11),Y(12),1.0,H2,XXA,XXB,XXC,XXD,XXE,XXF,MW2,
     &             XXG,XXH,XXI,XXJ)
C
C       DURING THE FIRST ITERATION THE CREVICE AND LEAKAGE MODELS
C       ARE INACTIVE BECAUSE NO PRESSURE HISTORY IS AVAILABLE.
C
            IF (ITERAS .NE. 1) GO TO 300
                   MASLDC = 0.0
                   MDOTDC = 0.0
                   MASLGC = 0.0
                   MDOTGC = 0.0
                   LDLEAK = 0.0
                   LGLEAK = 0.0
C
            IF ( FIREFL ) GO TO 150
            GO TO 90
C
C       FIND THE PRESSURES IN THE ADJACENT CHAMBERS AND THE COMPOSITION
C       OF THE TWO CREVICE VOLUMES FROM THE STORED VALUES OF THE LAST
C       ITERATION
C
  300 CALL TABLE (T,Y,PLEAD,PLAG,X1LDC,X1LAGC)
C
C       BECAUSE OF CHAMBER PRESSURE DIFFERENCES BETWEEN ITERATIONS
C       IT IS POSSIBLE THAT THE TABLE DOES NOT HOLD THE NECESSARY
C       CREVICE COMPOSITION INFORMATION NEAR THE 'SWITCHOVER' POINT
C       IF THIS OCCURS THE PROGRAM ASSIGNS THE LAST KNOWN VALUE OF
C       THE COMPOSITION FROM THE PREVIOUS ITERATION.
C
            IF (X1LDC .LE. 0.0) X1LDC = X1LDIN
            IF (X1LDC .GT. 1.0) X1LDC = X1LDIN
            IF (X1LAGC .LE. 0.0) X1LAGC = X1LGIN
```

```
            IF (X1LAGC .GT. 1.0) X1LAGC = X1LGIN
C
C
C       DETERMINE THE PRESSURE DIFFERENCE ACROSS EACH APEX SEAL
C
C
      IF (PLEAD .GE. Y(12)) GO TO 10
C
C         THE CHAMBER HAS A HIGHER PRESSURE THAN THE LEAD CHAMBER
C         SO THE LEAD CREVICE IS ASSOCIATED WITH THE CHAMBER AND
C         LEAKAGE FLOWS FROM THE LEAD CREVICE TO THE LEAD CHAMBER.
C
      PLEADC = Y(12)
      IF ( MASLDC .GT. 0.0   .AND.  Y(21) .NE. 0.0 )  X1LDC = Y(21)
           IF (CREVOL .GT. 0.0  .OR.  AREALK .LE. 0.0) GO TO 15
              X1LDC = Y(5)
              IF (FIREFL) X1LDC = 1.- Y(4)
              Y(21) = X1LDC
   15      CONTINUE
C
      CALL THERMO (T,TCR,PLEADC,1.-X1LDC,HLEADC,XXA,XXB,RHOLDC,XXD,XXE,
     &             GAMLDC,MWLDC,XXF,XXG,XXH,XXI)
      CALL MFLRT (1.0,AREA,PLEADC,MWLDC,TCR,PLEAD,GAMLDC,LDLEAK)
      MASLDC = RHOLDC * VOLLDC
      GO TO 20
C
C
C         THE LEAD CHAMBER HAS A HIGHER PRESSURE THAN THE  CHAMBER
C         CONSEQUENTLY THE LEAD CREVICE IS ASSOCIATED WITH THE LEAD
C         CHAMBER. THERE IS NO CREVICE FLOW AND LEAKAGE FLOWS FROM THE
C         LEAD CREVICE TO THE CHAMBER.
C
C
   10 PLEADC = PLEAD
      CALL THERMO (T,TCR,PLEADC,1.-X1LDC,HLEADC,XXA,XXB,XXC,XXD,XXE,
     &             GAMLDC,MWLDC,XXF,XXG,XXH,XXI)
      CALL MFLRT (1.0,AREA,PLEADC,MWLDC,TCR,Y(12),GAMLDC,LDLEAK)
      LDLEAK = -LDLEAK
      MASLDC = 0.0
      MDOTDC = 0.0
C
C
   20 IF (PLAG .GE. Y(12)) GO TO 30
C
C         THE CHAMBER HAS A HIGHER PRESSURE THAN THE LAG CHAMBER
C         SO THE LAG CREVICE IS ASSOCIATED WITH THE CHAMBER AND
C         LEAKAGE FLOWS FROM THE LAG CREVICE TO THE LAG CHAMBER.
C
      PLAGC = Y(12)
      IF ( MASLGC .GT. 0.0   .AND.  Y(22) .NE. 0.0 ) X1LAGC = Y(22)
           IF (CREVOL .GT. 0.0  .OR.  AREALK .LE. 0.0) GO TO 25
              X1LAGC = Y(5)
              IF (FIREFL) X1LAGC = 1.- Y(4)
              Y(22) = X1LAGC
   25      CONTINUE
```

```
C
      CALL THERMO (T,TCR,PLAGC,1.-X1LAGC,HLAGC,XXA,XXB,RHOLGC,XXD,XXE,
     &             GAMLGC,MWLAGC,XXF,XXG,XXH,XXI)
      CALL MFLRT (1.0,AREA,PLAGC,MWLAGC,TCR,PLAG,GAMLGC,LGLEAK)
      MASLGC = RHOLGC * VOLLGC
      GO TO 40


C
C         THE LAG CHAMBER HAS A HIGHER PRESSURE THAN THE  CHAMBER
C         CONSEQUENTLY THE LAG CREVICE IS ASSOCIATED WITH THE LAG
C         CHAMBER. THERE IS NO CREVICE FLOW, AND LEAKAGE FLOWS
C         FROM THE LAG CREVICE TO THE CHAMBER.
C
   30 PLAGC = PLAG
      CALL THERMO (T,TCR,PLAGC,1.-X1LAGC,HLAGC,XXA,XXB,XXC,XXD,XXE,
     &             GAMLGC,MWLAGC,XXF,XXG,XXH,XXI)
      CALL MFLRT (1.0,AREA,PLAGC,MWLAGC,TCR,Y(12),GAMLGC,LGLEAK)
      LGLEAK = -LGLEAK
      MASLGC = 0.0
      MDOTGC = 0.0
C
C          DURING COMBUSTION A DIFFERENT SET OF EQUATIONS
C          ARE USED.
C
   40         IF ( FIREFL ) GO TO 100
C
C
C          ASSUME THAT LEAD AND LAG MASS FLOWS (ALGEBRAIC SUM OF
C          LEAKAGE AND CREVICE VOLUME MASS FLOW) HAVE THE SAME SENSE
C          AS AT THE LAST TIME STEP.
C
      IF (MDOTLD .LE. 0.0) GO TO 50
C
C          LEAD FLOW IS ASSUMED TO BE OUT OF THE CHAMBER
C
              LDFLAG = +1
              X1LEAD = Y(5)
              HLEAD  = H
              GO TO 60
C
C          LEAD FLOW IS ASSUMED TO BE FROM THE LEAD CREVICE TO
C          THE CHAMBER.
C
   50         LDFLAG = -1
              X1LEAD = X1LDC
              HLEAD  = HLEADC
C
   60 IF (MDOTLG .LE. 0.0) GO TO 70
C
C          LAG FLOW IS ASSUMED TO BE OUT OF THE CHAMBER.
C
              LGFLAG = +1
              X1LAG = Y(5)
              HLAG  = H
```

```
            GO TO 90
C
C         LAG FLOW IS ASSUMED TO BE FROM THE LAG CREVICE TO
C         THE CHAMBER
C
   70       LGFLAG = -1
            X1LAG = X1LAGC
            HLAG  = HLAGC
C
C
   90 Y(12) = Y(12) * 1.01325E+6
C
C
      X1INT = (1.- RESFIM) * INFLAG + Y(5) * (1 - INFLAG)
      ASTAR = (1./MASS) * ( YP(1)*( X1INT-Y(5) ) - LDLEAK*( X1LEAD-Y(5))
     &        - LGLEAK*( X1LAG-Y(5) ) )
      BSTAR = 1./(MASS*Y(12)) * ( MASLDC*( X1LEAD-Y(5) ) + MASLGC*
     &        (X1LAG-Y(5) ) )
      CSTAR = (1./Y(12)) * ( MASLDC + MASLGC )
      DSTAR = YP(1) - YP(2) - LDLEAK - LGLEAK
      ESTAR = YP(1)*HIMM - YP(2)*H - LDLEAK*HLEAD - LGLEAK*HLAG
      FSTAR = (1./Y(12)) * ( MASLDC*HLEAD + MASLGC*HLAG )
      ZSTAR = 1./( DRHODP/RHO + BSTAR*MW*(1./MW1 - 1./MW2) +
     &        CSTAR/MASS)
      WSTAR = VOLUME - FSTAR + H*CSTAR + MASS*BSTAR*(H1-H2) - CSUBT*MASS
      A1STAR = ASTAR * MW * (1./MW1 - 1./MW2)
C
C
      YP(5)  = ASTAR - BSTAR
      YP(11) = ( 1./(MASS*CSUBP + DRHODT*WSTAR*ZSTAR/RHO) ) *
     &         ( WSTAR*ZSTAR* ( A1STAR - DVDT/VOLUME + DSTAR/MASS ) -
     &         MASS*ASTAR*(H1-H2) - H*DSTAR + ESTAR - THTRAN )
      YP(12) = ZSTAR * ( A1STAR - DVDT/VOLUME - YP(11)*DRHODT/RHO +
     &         DSTAR/MASS )
C
C
      Y(12) = Y(12) / 1.01325E+6
      YP(12) = YP(12)/1.01325E+6
C
      MDOTDC = YP(12) * MASLDC/Y(12)
      MDOTGC = YP(12) * MASLGC/Y(12)
C
C         CHECK THAT THE ASSUMPTIONS MADE ABOUT THE NET FLOW
C         DIRECTIONS AT EACH APEX ARE CORRECT.  IF EITHER OF THE
C         FLOWS HAVE REVERSED THEN FLOW COMPOSITION AND ENTHALPY
C         MUST BE REASSIGNED.
C
      MDOTLD = MDOTDC + LDLEAK
      ICHECD = -1
      IF (MDOTLD .GT. 0.0 ) ICHECD = +1
      MDOTLG = MDOTGC + LGLEAK
      ICHECG = -1
      IF (MDOTLG .GT. 0.0 ) ICHECG = +1
      IF ( ICHECD .NE. LDFLAG .OR. ICHECG .NE. LGFLAG ) GO TO 40
C
```

```
C        THE FLOW ASSUMPTIONS HAVE BEEN CONFIRMED AS CORRECT.  THE
C        RATE OF CHANGE IN CREVICE COMPOSITIONS CAN NOW BE EVALUATED.
C
      IF (MASLDC .LE. 0.0 ) GO TO 93
           YP(21) = (X1LEAD - X1LDC) * (MDOTLD/MASLDC)
           IF ( MDOTLD .LE. 0.0 ) YP(21) = 0.0
           GO TO 94
C
   93 YP(21) = 0.0
   94 IF ( Y(21) .LE. 0.0  .AND. MASLDC .GT. 0.0 )   Y(21) = X1LDC
      IF ( Y(21) .LE. 0.0  .AND. CREVOL .EQ. 0.0 )   Y(21) = X1LDC
C
C
C
      IF (MASLGC .LE. 0.0) GO TO 95
           YP(22) = (X1LAG - X1LAGC) * (MDOTLG/MASLGC)
           IF (MDOTLG .LE. 0.0) YP(22) = 0.0
           GO TO 96
C
   95 YP(22) = 0.0
   96 IF ( Y(22) .LE. 0.0  .AND.  MASLGC .GT. 0.0 )   Y(22) = X1LAGC
      IF ( Y(22) .LE. 0.0  .AND.  CREVOL .EQ. 0.0 )   Y(22) = X1LAGC
C
C
      YP(23) = YP(1) - YP(2) - MDOTLD - MDOTLG
      YP(18) = LDLEAK
      YP(19) = LGLEAK
      YP(24) = MDOTLD
      YP(25) = MDOTLG
      YP(20) = MDOTLD*HLEAD + MDOTLG*HLAG
C
C
C         CALCULATE THE FUEL ENERGY THAT ENTERS THE EXHAUST CHAMBER
C
C
      IF ( T .LT. TEPO  .OR.  .NOT. FIRE ) GO TO 500
      IF ( MDOTLD .LE. 0.0 ) YP(3) = MDOTLD * X1LDC
      IF ( MDOTLG .LE. 0.0 ) YP(3) = YP(3) + MDOTLG * X1LAGC
      YP(3) = ABS( YP(3) * (H1 - H2))
C
      GO TO 500
C#######################################################################
C
C         THE GOVERNING EQUATIONS DURING THE COMBUSTION PROCESS
C         REQUIRE DIFFERENT TREATMENT AND ARE SOLVED IN THE
C         FOLLOWING SECTION.
C
C#######################################################################
C
C         FIND THE THERMODYNAMIC PROPERTIES OF THE BURNED AND THE
C         UNBURNED GASSES IN THE CREVICES
C
C
  100 CALL THERMO (T,TCR,Y(12),1.-Y(5),HUC,XXA,XXB,XXC,XXD,XXE,XXF,XXG,
     &             XXH,XXI,XXJ,XXK)
```

```
      CALL THERMO (T,TCR,Y(12),1.0,HBC,XXA,XXB,XXC,XXD,XXE,XXF,XXG,XXH,
     &             XXI,XXJ,XXK)
C
C
C
C         ASSUME THAT NET FLOWS HAVE THE SAME SENSE AS THE LAST
C         TIME STEP.
C
C           LEAD AND LAG FLOWS ARE FROM THE CHAMBER TO THE CREVICES
C
      IF (MDOTLD .LE. 0.0  .OR.  MDOTLG .LE. 0.0) GO TO 210
              ALPHLD = 1.- Y(4)
              ALPHLG = 1.- Y(4)
              HLEADU = HU
              HLEADB = HB
              HLAGU  = HU
              HLAGB  = HB
              GO TO 150
C
C           LEAD FLOW IS FROM THE CREVICE TO THE CHAMBER
C           LAG FLOW IS FROM THE CHAMBER TO THE CREVICE
C
  210 IF ( MDOTLG .LE. 0.0 ) GO TO 220
              ALPHLG = 1.- Y(4)
              ALPHLD =  Y(21)/Y(5)
              HLEADU = HU
              HLEADB = HB
              HLAGU  = HUC
              HLAGB  = HBC
              GO TO 150
C
C           LEAD AND LAG FLOWS ARE FROM THE CREVICE TO THE CHAMBER.
C
C
  220         ALPHLD = Y(21)/Y(5)
              ALPHLG = Y(22)/Y(5)
              HLEADU = HUC
              HLEADB = HBC
              HLAGU  = HUC
              HLAGB  = HBC
C
C
C          CALCULATE THE NECESSARY QUANTITIES TO SOLVE THE GOVERNING
C          EQUATIONS.
C
  150 Y(12) = Y(12) * 1.01325E+6
      MASSB = Y(4) * MASS
      MASSU = MASS - MASSB
      VOLB  = VOLUME - Y(14)
C
C
C              THE MASS BURNING RATE IS NOT EXACTLY YP(4)*MASS BUT
C               IS ALSO AFFECTED BY THE OTHER MASS FLOW RATES.
C
      MDOTCB = YP(4)*MASS + Y(4)*(-MDOTLD-MDOTLG) + (1.- ALPHLD)*
```

```
     &          MDOTLD + (1. - ALPHLG)*MDOTLG
C
C
C
      CSTARU = ( ALPHLD*MASLDC + ALPHLG*MASLGC ) * (1./Y(12))
      CSTARB = ((1.- ALPHLD)*MASLDC + (1.- ALPHLG)*MASLGC) * (1./Y(12))
      DSTARU = -ALPHLD*LDLEAK - ALPHLG*LGLEAK - MDOTCB
      DSTARB = (ALPHLD-1.)*LDLEAK + (ALPHLG-1.)*LGLEAK + MDOTCB
      ESTARU = -ALPHLD*LDLEAK*HLEADU - ALPHLG* LGLEAK*HLAGU -
     &         MDOTCB*HU
      ESTARB = (ALPHLD-1.)*LDLEAK*HLEADB + (ALPHLG-1.)*LGLEAK*HLAGB +
     &         MDOTCB*HU
      FSTARU = (1./Y(12)) * (ALPHLD*MASLDC*HLEADU + ALPHLG*MASLGC*HLAGU)
      FSTARB = (1./Y(12)) * ((1.-ALPHLD)*MASLDC*HLEADB + (1.-ALPHLG)*
     &         MASLGC*HLAGB)
      ZSTARU = 1./( DRODPU/RHOU + CSTARU/MASSU )
      ZSTARB = 1./( DRODPB/RHOB + CSTARB/MASSB )
      WSTARU = Y(14) - FSTARU + HU*CSTARU - CSUBTU*MASSU
C
C            IF THE UNBURNED GAS TEMPERATURE DROPS BELOW THE CREVICE
C            TEMPERATURE WSTARU CAN GO NEGATIVE AND CONSEQUENTLY CAN
C            TAKE ON A VALUE OF ZERO.  THIS LEADS TO AN INFINITE
C            VALUE OF YP(12).
C
          IF (WSTARU .LE. Y(14)) WSTARU = Y(14) - CSUBTU*MASSU
C
      WSTARB = VOLB - FSTARB + HB*CSTARB - CSUBTB*MASSB
      GSTARU = 1.- (WSTARU*ZSTARU*DRODTU)/(RHOU*MASSU*CSUBPU +
     &         WSTARU*ZSTARU*DRODTU)
      GSTARB = 1. - (WSTARB*ZSTARB*DRODTB)/(RHOB*MASSB*CSUBPB +
     &         WSTARB*ZSTARB*DRODTB)
C
C         CALCULATE THE TIME RATE OF CHANGE IN CHAMBER PRESSURE
C
      YP(12) = ( DSTARU/MASSU + (1.-1./GSTARU)*(ESTARU - HU*DSTARU -
     &           UHTRAN)/(ZSTARU*WSTARU) + (VOLB/Y(14))*(DSTARB/MASSB -
     &           DVDT/VOLB + (1.-1./GSTARB)*(ESTARB - HB*DSTARB -BHTRAN)/
     &           (ZSTARB*WSTARB)) ) / ( (VOLB/( Y(14)*GSTARB)) *
     &           (CSTARB/MASSB + DRODPB/RHOB) + (1./GSTARU)*
     &           (CSTARU/MASSU + DRODPU/RHOU) )
C
C
C
      MDOTDC = YP(12)*MASLDC/Y(12)
      MDOTGC = YP(12)*MASLGC/Y(12)
      MDOTLD = MDOTDC + LDLEAK
      MDOTLG = MDOTGC + LGLEAK
C
C
C
      YP(13) = ( YP(12) * (Y(14) - MASSU*CSUBTU + CSTARU*HU - FSTARU)
     &           - HU*DSTARU + ESTARU - UHTRAN )/ (MASSU*CSUBPU)
C
      YP(15) = ( YP(12) * (VOLB - MASSB*CSUBTB + CSTARB*HB - FSTARB)
     &           - HB*DSTARB + ESTARB - BHTRAN )/ (MASSB*CSUBPB)
```

```
C
      YP(14) = Y(14) * ((DSTARU-CSTARU*YP(12))/MASSU - (DROD TU*YP(13)+
     &         DRODPU*YP(12))/RHOU)
C
C
      IF ( ITERAS .EQ. 1 ) GO TO 400
C
C
      IF (MASLDC .LE. 0.0) GO TO 103
           YP(21) = (MDOTLD/MASLDC) * (ALPHLD*Y(5) - Y(21))
           IF (MDOTLD .LE. 0.0) YP(21) = 0.0
           GO TO 104
  103 YP(21) = 0.0
C
C
  104 IF (MASLGC .LE. 0.0) GO TO 105
           YP(22) = (MDOTLG/MASLGC) * (ALPHLG*Y(5) - Y(21))
           IF (MDOTLG .LE. 0.0) YP(22) = 0.0
           GO TO 400
  105 YP(22) = 0.0
C
C
  400 YP(23) = -MDOTLD - MDOTLG
      YP(18) = LDLEAK
      YP(19) = LGLEAK
      YP(20) = MDOTLD*ALPHLD*HLEADU + MDOTLG*ALPHLG*HLAGU   +
     &         MDOTLD*(1.- ALPHLD)*HLEADB + MDOTLG*(1.- ALPHLG)*HLAGB
      YP(24) = MDOTLD
      YP(25) = MDOTLG
      YP(12) = YP(12)/1.01325E+6
      Y(12)  = Y(12)/1.01325E+6
C
C
  500 CRMASD = MASLDC
      CRMASG = MASLGC
      ZMASS  = MASS
      ZLEAKD = Y(18)
      ZLEAKG = Y(19)
      ZCRCOD = Y(21)
      ZCRCOG = Y(22)
      IF (MASLDC .LE. 0.0) ZCRCOD = 0.0
      IF (MASLGC .LE. 0.0) ZCRCOG = 0.0
      RETURN
      END
C_______________________________________________________________________
C
C     SUBROUTINE TABLE
C
C     PURPOSE
C        TO INTERPOLATE BETWEEN THE STORED VALUES OF CHAMBER PRESSURE
C        AND CREVICE COMPOSITION AND THEN TO RETURN THE INTERPOLATED
C        VALUES TO SUBROUTINE CREVICE.
C
C     USAGE
C        CALL TABLE (T,Y,PLEAD,PLAG,X1LDC,X1LAGC)
```

```
C
C     DESCRIPTION OF PARAMETERS
C
C        PARAMETER  INPUT  OUTPUT   DESCRIPTION
C
C        DT         YES    NO       TIME (DEG)
C        PLEAD      NO     YES      LEADING CHAMBER PRESSURE (ATM)
C        PLAG       NO     YES      TRAILING CHAMBER PRESSURE (ATM)
C        X1LDC      NO     YES      LEAD CREVICE COMPOSITION ( )
C        X1LAGC     NO     YES      LAG CREVICE COMPOSITION ( )
C
C
C     REMARKS
C        NONE
C
C
C     METHOD
C        SEE REPORT
C
C     WRITTEN BY T. J. NORMAN
C
      SUBROUTINE TABLE (T,Y,PLEAD,PLAG,X1LDC,X1LAGC)
C
C
      LOGICAL FIREFL, FIRE
      DIMENSION Y(25)
      COMMON/TABLES/ PRES(1080), X1LD(1080), X1LG(1080)
      COMMON/TIMES/ TIPO, TIPC, TEPO, TEPC, THIPO, THEPO, TSPARK
      COMMON/CREV/DRHODP,CSUBT,MW,ITERAS,DVDT,CSUBP,DRHODT,HIMM
      COMMON/BURN/ SPBURN, FIRE, FIREFL
      COMMON/CREVIN/AREALK,CREVOL,TCREV,X1LDIN,X1LGIN
C
C         IN THIS SUBROUTINE THE CYCLE BEGINS AT TIPO = 0.0 AND
C         ENDS AT TIPO = 1080.0 DEG. THE LEADING CHAMBER IS 360 CRANK
C         ANGLES AHEAD (TLEAD),AND THE TRAILING CHAMBER IS
C         360 DEGREES BEHIND (TLAG).
C
C
      ABST = T + ABS(TIPO)
      TLEAD = ABST + 360.
      IF ( TLEAD .GE. 1080.) TLEAD = TLEAD - 1080.
      TLAG = ABST - 360.
      IF ( TLAG .LT. 0.0 ) TLAG = TLAG + 1080.
      ITLEAD = INT(TLEAD)
      ITLAG = INT(TLAG)
C
      PLEAD = PRES(ITLEAD) + (TLEAD - ITLEAD)*( PRES(ITLEAD+1) -
     &        PRES(ITLEAD) )
      PLAG = PRES(ITLAG) + (TLAG - ITLAG)*( PRES(ITLAG+1) -
     &       PRES(ITLAG) )
      IABST = INT(ABST)
      X1LDC = X1LD(IABST) + (ABST - IABST)*( X1LD(IABST+1) -
     &        X1LD(IABST) )
      X1LAGC = X1LG(IABST) + (ABST - IABST)*( X1LG(IABST+1) -
     &        X1LG(IABST) )
```

```
C
C            DURING THE FIRST ITERATION NO  VALUES OF CREVICE
C            COMPOSITION ARE STORED TO INTERPOLATE BETWEEN.SO
C            FOR THE SECOND ITERATION ASSUME THE CREVICE GAS HAS THE
C            ARBITRARY COMPOSITION OF 0.75 .
C
      IF ( ITERAS .NE. 2 ) GO TO 200
C
      IF ( CREVOL .LE. 0.0  .AND.  AREALK .GT. 0.0 ) GO TO 200
C
              X1LDC = 0.75
              X1LAGC = 0.75
C
C
C        FOR A MOTORING RUN THE INITIAL VALUE OF CREVICE COMPOSITION
C        SHOULD BE 1.0
C
      IF ( FIRE )  GO TO 250
              X1LDC  = 1.0
              X1LAGC = 1.0
  250 CONTINUE
C
C       FOR A FIRING CASE WITH ZERO CREVICE VOLUME THE LEAKAGE
C       COMPOSITION IS ASSUMED TO BE RELATED TO THE MASS FRACTION
C       BURNED.
C
      IF ( FIREFL ) GO TO 300
           GO TO 200
C
  300         X1LDC = 1.- Y(4)
              X1LAGC = 1.- Y(4)
  200 RETURN
      END
C________________________________________________________________________
C
C     SUBROUTINE BUILD
C
C     PURPOSE
C        TO STORE THE CHAMBER PRESSURE AND CREVICE COMPOSITIONS
C        FROM ONE ITERATION TO THE NEXT.
C
C     USAGE
C        CALL BUILD  (DT, DY)
C
C     DESCRIPTION OF PARAMETERS
C
C        PARAMETER  INPUT  OUTPUT   DESCRIPTION
C
C        DT          YES    NO       TIME (DEG)
C
C     REMARKS
C        IT IS ASSUMED IN BUILD THAT THE STEP SIZE FOR ODERT IS
C        ONE (1.0) DEGREE.  IF THE MAIN PROGRAM IS CHANGED SO THAT
C        THE STEP SIZE IS ALTERED THEN SUBROUTINE BUILD MUST ALSO
C        BE ALTERED.
```

```
C
C
C
C     METHOD
C        SEE REPORT
C
C     WRITTEN BY T. J. NORMAN
C
      SUBROUTINE BUILD (DT,DY)
C
      LOGICAL FIREFL, FIRE
      REAL*8 DT,DY(25)
      REAL MASLDC, MASLGC
      DIMENSION Y(25)
      COMMON/TABLES/ PRES(1080), X1LD(1080), X1LG(1080)
      COMMON/TIMES/ TIPO, TIPC, TEPO, TEPC, THIPO, THEPO, TSPARK
      COMMON/CREV2/ MASLDC, MASLGC
      COMMON/BURN/ SPBURN, FIRE, FIREFL
      COMMON/CREVIN/AREALK,CREVOL,TCREV,X1LDIN,X1LGIN
C
      T = DT
      DO 10 I = 1,25
           Y(I) = DY(I)
   10 CONTINUE
      ABST = T + ABS(TIPO)
      IABST = INT(ABST)
      IF ( IABST .NE. ABST ) GO TO 30
      PRES(IABST) = Y(12)
C
C        IF THE CREVICE BELONGS TO THE CHAMBER THEN ITS MASS, AND
C        COMPOSITION ARE KNOWN. THIS CREVICE ALSO CORRESPONDS TO THE
C        ADJACENT CHAMBER AT TLAG OR TLEAD.
C
      ITLEAD = INT( ABST+360.)
      IF (ITLEAD .GE. 1080.)ITLEAD = ITLEAD-1080
      ITLAG = INT( ABST-360.)
      IF (ITLAG .LT. 0.0) ITLAG = ITLAG+1080
C
C       CHECK TO SEE IF LEAD CREVICE BELONGS TO CHAMBER
C
      IF (MASLDC .LE. 0.0  .OR. Y(21) .LE. 0.1 ) GO TO 20
      X1LD(IABST) = Y(21)
      X1LG(ITLEAD) = Y(21)
C
C        CHECK TO SEE IF LAG CREVICE BELONGS TO CHAMBER
C
   20 IF (MASLGC .LE. 0.0  .OR. Y(22) .LE. 0.1 ) GO TO 30
      X1LG(IABST) = Y(22)
      X1LD(ITLAG) = Y(22)
C
C        IF A LEAKAGE AREA IS SPECIFIED BUT NOT A CREVICE
C        VOLUME THEN STORE THE CHAMBER COMPOSITION.  DURING
C        COMBUSTION THIS IS DEFINED TO BE THE MASS FRACTION
C        UNBURNED.
C
```

```
   30 IF (CREVOL .GT. 0.0  .OR.  AREALK .LE. 0.0) GO TO 40
      COMP = Y(5)
      IF (FIRE    .AND.  T .GT. TSPARK )  COMP = 1. - Y(4)
      X1LD(IABST)  = COMP
      X1LG(ITLEAD) = COMP
      X1LG(IABST)  = COMP
      X1LD(ITLAG)  = COMP
C
C
   40 RETURN
      END
C-----------------------------------------------------------------------
C
C     SUBROUTINE IPACD
C
C     PURPOSE
C        CALCULATES AREA AND DISCHARGE COEFFICIENT
C        OF THE INTAKE PORTS.
C
C     USAGE
C        CALL IPACD  (T, AREA, CD)
C
C     DESCRIPTION OF PARAMETERS
C
C        PARAMETER  INPUT  OUTPUT   DESCRIPTION
C
C        T          YES    NO       TIME (DEG)
C        AREA       NO     YES      EFFECTIVE AREA OF INTAKE
C        ----       --     ---      PORT (CM**2)
C        CD         NO     YES      DISCHARGE COEFFICIENT
C
C
C     REMARKS
C
C        THIPO =   NUMBER OF CRANK ANGLES REQUIRED TO FULLY OPEN
C                  OR CLOSE THE PORT.
C
C        - IT IS ASSUMED THAT THE PORTS OPEN AND CLOSE LINEARLY AND
C          THE DISCHARGE COEFFICIENT IS CONSTANT
C
C        - SEE WARNING ABOUT PORT AREA CHANGES 1/21/83
C
C
C     SUBROUTINE AND FUNCTION SUBPROGRAMS REQUIRED
C        NONE
C
C     METHOD
C        SEE REPORT
C
C     WRITTEN BY T. J. NORMAN
C     EDITED BY T. J. NORMAN
C
      SUBROUTINE IPACD (T, AREA, CD)
      REAL IPA
      COMMON/TIMES/ TIPO, TIPC, TEPO, TEPC, THIPO, THEPO, TSPARK
```

```
      COMMON/PORTS/ IPA, EPA
CJ
CJ !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
CJ        THIS ROUTINE HAS BEEN CHANGED SUBSTANTIALLY IN ORDER TO MODEL
CJ        THE ENLARGED INTAKE PORT INSTALLED IN THE NASA TEST ENGINE.
CJ        ANY CHANGES WHATSOEVER TO THE PORT CONFIGURATION MUST BE
CJ        REFLECTED IN THIS ROUTINE
CJ
CJ !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
      IF ( T .GT. (TIPO + 120.0)) GO TO 20
      AREA = IPA *(T - TIPO)/120.0
      GO TO 40
   20 IF ( T .LT. (TIPC - 180.0)) GO TO 30
      IF ( T .LT. -240.0)   AREA  =   (-12.2/120.0)*(T+360.) + 13.8
      IF (T .GT. -240.) AREA = (1.600073*EXP(-10./60.*(T+240.))-.000073)
      GO TO 40
   30 AREA = IPA
   40 CD= 0.75
C
C     IN ORDER TO AVOID ANY DIVISION BY ZERO THE PORT AREA SHALL BE
C     ASSIGNED AN ARBITRARILY SMALL VALUE
C
      IF (AREA .EQ. 0.0) AREA=1.E-6
C
      RETURN
      END
C_______________________________________________________________________
C
C     SUBROUTINE EPACD
C
C     PURPOSE
C        CALCULATES AREA AND DISCHARGE COEFFICIENT
C        OF EXHAUST VALVE
C
C     USAGE
C        CALL EPACD  (T, AREA, CD)
C
C     DESCRIPTION OF PARAMETERS
C
C        PARAMETER  INPUT  OUTPUT   DESCRIPTION
C
C        T          YES    NO       TIME (DEG)
C        AREA       NO     YES      EFFECTIVE AREA OF EXHAUST
C        ----       --     ---      PORT (CM**2)
C        CD         NO     YES      DISCHARGE COEFFICIENT
C
C     REMARKS
C
C        THEVO    = NUMBER OF CRANK ANGLES REQUIRED TO OPEN OR CLOSE
C                   THE EXHAUST PORT
C
C        -  IT IS ASSUMED THAT THE PORT OPENS AND CLOSES LINEARLY AND
C           THE DISCHARGE COEFFICIENT IS CONSTANT.
C     SUBROUTINE AND FUNCTION SUBPROGRAMS REQUIRED
C        NONE
```

```
C
C     METHOD
C        SEE REPORT
C
C     WRITTEN BY T. J. NORMAN
C     EDITED BY T. J. NORMAN
C
      SUBROUTINE EPACD (T, AREA, CD)
      REAL IPA
      COMMON/TIMES/ TIPO, TIPC, TEPO, TEPC, THIPO, THEPO, TSPARK
      COMMON/PORTS/ IPA, EPA
      IF (T .GT. (TEPO + THEPO)) GO TO 20
      AREA = EPA *(T - TEPO)/THEPO
      GO TO 40
   20 IF (T .LT. (TEPC - THEPO)) GO TO 30
      AREA = EPA *(TEPC - T)/THEPO
      GO TO 40
   30 AREA = EPA
   40 CD = 0.65
C
C     IN ORDER TO AVOID ANY DIVISION BY ZERO THE PORT AREA SHALL BE
C     ASSIGNED AN ARBITRARILY SMALL VALUE
C
      IF(AREA .EQ. 0.0) AREA = 1.E-6
C
      RETURN
      END
C
C----------------------------------------------------------------------
C     SUBROUTINE HEATTX
C
C     PURPOSE
C        CALCULATES THE RATE OF HEAT TRANSFER FROM THE CHAMBER
C        THROUGH THE WALLS OF THE ROTOR, SIDE PLATES, AND HOUSING.
C
C     USAGE
C        CALL HEATTX (T,Y,YP,THTRAN,UHTRAN,BHTRAN)
C
C     DESCRIPTION OF PARAMETERS
C
C        PARAMETER  INPUT  OUTPUT   DESCRIPTION
C
C        DT         YES    NO       TIME (DEG)
C        DY(11)     YES    NO       CYLINDER TEMPERATURE (K)
C        DY(12)     YES    NO       CYLINDER PRESSURE (ATM)
C        DY(13)     YES    NO       UNBURNED MIXTURE TEMPERATURE
C        ------     ---    --       DURING COMBUSTION  (K)
C        DY(14)     YES    NO       VOLUME OF UNBURNED MIXTURE
C        ------     ---    --       DURING COMBUSTION (CM**3)
C        DY(15)     YES    NO       BURNED PRODUCTS TEMPERATURE
C        ------     ---    --       DURING COMBUSTION  (K)
C ---------------------------------------------------------------------
C        DYP(8)     NO     YES      RATE OF HEAT TRANSFER THROUGH
C        -------    --     ---      ROTOR WALL
C        DYP(9)     NO     YES      RATE OF HEAT TRANSFER THROUGH
```

```
C       -------    --     ---      SIDE PLATES
C       DYP(10)    NO     YES      RATE OF HEAT TRANSFER THROUGH
C       -------    --     ---      HOUSING
C
C     REMARKS
C        SEE THE PROCESS SUBROUTINE FOR THE UNITS OF THE INTEGRATION
C        VARIABLES.
C
C     SUBROUTINE AND FUNCTION SUBPROGRAMS REQUIRED
C        UTRANS     BTRANS
C
C
C     METHOD
C        SEE REPORT
C
C     WRITTEN BY T. J. NORMAN
C     EDITED BY  T. J. NORMAN
C
C
C
C
      SUBROUTINE HEATTX (T,Y,YP,THTRAN,UHTRAN,BHTRAN)
C
C
      LOGICAL FIRE, FIREFL
      REAL MW, MASS, KINVIS
      DIMENSION Y(25),YP(25)
C
      COMMON/HEATXG/AROTOR,ASIDE,AHOUS,ROTVEL,DCHAR
      COMMON/BURN/SPBURN,FIRE,FIREFL
      COMMON/TIMES/ TIPO, TIPC, TEPO, TEPC, THIPO, THEPO, TSPARK
      COMMON/CREV/DRHODP,CSUBT,MW,ITERAS,DVDT,CSUBP,DRHODT,HIMM
      COMMON/HTTXIN/CONHT,EXPHT,CON1,CON2
      COMMON/RHMAS/RHO, MASS, VOLUME, H, GAMMA, GAMAB
      COMMON/TEMPS/TROTOR,TSIDE,THOUS
      COMMON/CREVCB/HU,HB,DRODPU,DRODPB,RHOU,RHOB,DRODTU,DRODTB,
     &              CSUBPU,CSUBPB,CSUBTU,CSUBTB
      COMMON/HEATS/VELHTX, HTRCOE, HTPARO, HTPASI, HTPAHO, HTXRO,
     &             HTXSI, HTXHO,  QFRRO, QFRSI, QFRHO
      COMMON/UBHEAT/ UHTRCO, BHTRCO
C
C        CALCULATE THE CONSTANTS OF THE POLYTROPIC COMPRESSION
C        ( PV**CONST2 = CONST1)
C
      IF ( T .NE. TIPC ) GO TO 5
           PIPC = Y(12)
           VIPC = VOLUME
    5 IF ( T .NE. INT(TSPARK) ) GO TO 7
           PSPARK = Y(12)
           VSPARK = VOLUME
           TEMPSP = Y(11)
C
      CONST2 = (LOG(PSPARK/PIPC)) / (LOG(VIPC/VSPARK))
      CONST1 = PIPC*VIPC**CONST2
    7 CONTINUE
```

```
C
C
      IF ( T .GE. TSPARK .AND. FIREFL ) GO TO 9
           VELHTX = CON1*ROTVEL
           GO TO 11
C
C
    9 PMOTOR = CONST1/(VOLUME**CONST2)
      VELHTX = CON1*ROTVEL + CON2*( Y(12) - PMOTOR ) * (VOLUME*TEMPSP/
     &         (PSPARK*VSPARK))
C
C
   11 IF ( FIREFL ) GO TO 30
      IF ( FIRE   .AND.  T .GE. TEPO ) GO TO 10
C
C        INTAKE, COMPRESS, AND EXPANSION-EXHAUST (MOTORING CASE)
C
         CALL UTRANS (Y(11),DYNVIS,THRCON)
         GO TO 20
C
C        EXHAUST (FIRING CASE)
C
   10 CALL BTRANS (Y(11),GAMAB,CSUBPB,DYNVIS,THRCON)
C
   20 KINVIS = DYNVIS/RHO
      HTRCOE = (CONHT*((VELHTX*DCHAR)/KINVIS)**EXPHT) * (THRCON/DCHAR)
C
C        CALCULATE THE HEAT TRANSFER RATES PER UNIT AREA
C
              HTPARO = HTRCOE * (Y(11) - TROTOR)
              HTPASI = HTRCOE * (Y(11) - TSIDE)
              HTPAHO = HTRCOE * (Y(11) - THOUS)
C
              HTXRO = HTPARO * AROTOR
              HTXSI = HTPASI * ASIDE
              HTXHO = HTPAHO * AHOUS
C
C
      YP(8)  =  HTXRO
      YP(9)  =  HTXSI
      YP(10) =  HTXHO
C
C     FIND THE TOTAL HEAT TRANSFER FROM THE CHAMBER
C
      THTRAN = HTXRO + HTXSI + HTXHO
C
               IF (ABS(THTRAN) .LE. .0002) GO TO 40
               QFRRO = 100.* HTXRO/THTRAN
               QFRSI = 100.* HTXSI/THTRAN
               QFRHO = 100.* HTXHO/THTRAN
C
      GO TO 40
C
C
C     CALCULATE THE HEAT TRANSFER RATE FROM BOTH ZONES DURING
```

```
C     COMBUSTION.
C
CJ
   30 VOLU = Y(14)
      VOLB = VOLUME - VOLU
C
C       CALCULATE THE BURNED AND UNBURNED WALL AREAS
C
      UAROT = AROTOR/( (VOLB/VOLU)**(2./3.) + 1.)
      UARSI = ASIDE/( (VOLB/VOLU)**(2./3.) + 1.)
      UARHO = AHOUS/( (VOLB/VOLU)**(2./3.) + 1.)
C
      BAROT = AROTOR - UAROT
      BARSI = ASIDE - UARSI
      BARHO = AHOUS - UARHO
C
      CALL UTRANS(Y(13),UDYVIS,UTHCON)
      CALL BTRANS(Y(15),GAMAB,CSUBPB,BDYVIS,BTHCON)
      UKNVIS = UDYVIS/RHOU
      BKNVIS = BDYVIS/RHOB
C
      UHTRCO = (CONHT*((VELHTX*DCHAR)/UKNVIS)**EXPHT) * (UTHCON/DCHAR)
      BHTRCO = (CONHT*((VELHTX*DCHAR)/BKNVIS)**EXPHT) * (BTHCON/DCHAR)
C
C        CALCULATE THE BURNED AND UNBURNED HEAT TRANSFER RATES PER
C        UNIT AREA
C
              UHPARO = UHTRCO * (Y(13) - TROTOR)
              UHPASI = UHTRCO * (Y(13) - TSIDE)
              UHPAHO = UHTRCO * (Y(13) - THOUS)
C
              BHPARO = BHTRCO * (Y(15) - TROTOR)
              BHPASI = BHTRCO * (Y(15) - TSIDE)
              BHPAHO = BHTRCO * (Y(15) - THOUS)
C
              UHTRRO = UHPARO * UAROT
              UHTRSI = UHPASI * UARSI
              UHTRHO = UHPAHO * UARHO
C
              BHTRRO = BHPARO * BAROT
              BHTRSI = BHPASI * BARSI
              BHTRHO = BHPAHO * BARHO
C
C
      YP(8)  = UHTRRO + BHTRRO
      YP(9)  = UHTRSI + BHTRSI
      YP(10) = UHTRHO + BHTRHO
C
C     FIND THE TOTAL HEAT TRANSFER RATE FROM EACH ZONE
C
      UHTRAN = UHTRRO + UHTRSI + UHTRHO
      BHTRAN = BHTRRO + BHTRSI + BHTRHO
C
C     THE TOTAL HEAT TRANSFER RATE FROM THE CHAMBER IS:
C
```

```
      THTRAN = UHTRAN + BHTRAN
C
   40 CONTINUE
C
CJ    QTOTAL = THTRAN
      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
C     SUBROUTINE CSAVDV
C
C     PURPOSE
C        CALCULATES SURFACE AREA, VOLUME, AND TIME RATE OF CHANGE OF
C        VOLUME OF COMBUSTION CHAMBER.
C
C     USAGE
C        CALL CSAVDV (T, VOLUME, DVDT)
C
C     DESCRIPTION OF PARAMETERS
C
C        PARAMETER  INPUT  OUTPUT   DESCRIPTION
C
C        T          YES    NO       TIME (DEG)
C        ASIDE      NO     YES      SIDE SURFACE AREA (CM**2)
C        AROTOR     NO     YES      ROTOR SURFACE AREA (CM**2)
C        AHOUS      NO     YES      HOUSING SURFACE AREA (CM**2)
C        VOLUME     NO     YES      CHAMBER VOLUME (CM**3)
C        DVDT       NO     YES      TIME RATE OF CHANGE OF VOLUME OF
C        -----      --     ---      CHAMBER (CM**3/SEC)
C        ROTVEL     NO     YES      AVERAGE ROTOR SPEED (CM/SEC)
C        DCHAR      NO     YES      CHARACTERISTIC DIMENSION FOR
C        ------     --     ---      HEAT TRANSFER CALCULATIONS (CM)
C
C     REMARKS
C        NONE
C
C     SUBROUTINE AND FUNCTION SUBPROGRAMS REQUIRED
C        NONE
C
C     METHOD
C        SEE REPORT
C
C     WRITTEN BY T. J. NORMAN
```

```
C     EDITED BY T. J. NORMAN
C
      SUBROUTINE CSAVDV (T, VOLUME, DVDT)
      COMMON/EPARAM/ ECCEN, ROTRAD, DEPTH, VFLANK
      COMMON/DTDTH/ ESPDI, RPM
      COMMON/HEATXG/AROTOR, ASIDE, AHOUS, ROTVEL, DCHAR
C
      PI=3.14159265358979323
      ROOT3 = SQRT(3.)
C
C     THETA IS THE CRANK ANGLE (OFFSET BY 90 DEGREES) IN RADIANS
C     ALPHA IS THE "FOLLOWING" APEX SEAL ANGLE IN RADIANS
C
      THETA =(T+90.) * PI/180.
      ALPHA = THETA/3.
      BETA  = 2.* ALPHA
C
C          ALEAN IS THE MAXIMUM ANGLE OF INCLINATION OF THE APEX SEAL
C          FROM THE NORMAL TO THE HOUSING.
C
      ALEAN = ASIN(3.* ECCEN/ROTRAD )
      FT    = (ECCEN*ECCEN + ROTRAD*ROTRAD/3.) * PI -
     &        ROOT3 * ECCEN * ROTRAD * SIN( BETA+PI/6.)
      DFTDTH = -2*ROOT3/3.* ECCEN * ROTRAD * COS( BETA + PI/6.)
C
      FR     = PI/3.* (ROTRAD*ROTRAD + 2.*ECCEN*ECCEN)
     &         -2. * ECCEN * ROTRAD * COS(ALEAN)
     &         -ALEAN * (ROTRAD*ROTRAD*2./9. + 4.*ECCEN*ECCEN )
      DFRDTH = 0.0
C
      FR1     = ECCEN * ROTRAD * SIN(BETA)/2.
      DFR1DT  = (1/3.) * ECCEN * ROTRAD * COS( BETA )
C
      FR2     = ECCEN * ROTRAD * SIN(BETA+PI/3.)/2.
      DFR2DT  = (1/3.) * ECCEN * ROTRAD * COS( BETA + PI/3.)
C
      ASIDE   = FT-FR-FR1-FR2
      DASDTH  = DFTDTH - DFRDTH - DFR1DT  - DFR2DT
C
      VOLUME  = ASIDE * DEPTH + VFLANK
      DVDTH   = DASDTH * DEPTH
      DVDT    = DVDTH * RPM * PI/30.
C
C           FIND THE SURFACE AREAS OF THE HOUSING, ROTOR AND SIDES.
C
      ASIDE  = 2.* ASIDE
      RPRIME = ROTRAD - ECCEN + 3.*ECCEN*ROTRAD/(ROTRAD - 4.*ECCEN)
      BETA2  = ROOT3*ROTRAD/((6.*ECCEN*ROTRAD)/(ROTRAD-4.*ECCEN) +
     &         ROTRAD + 2.*ECCEN)
      ROTORL = RPRIME * 2.* BETA2
      AROTOR = ROTORL * DEPTH
C
C           AN APPROXIMATION IS USED TO FIND THE TOTAL SURFACE AREA
C           THE CORRECTION FACTOR SHOULD BE CHECKED IF THE ENGINE
C           GEOMETRY DIFFERS GREATLY FROM THE TEST CONDITIONS:
```

```
C            (ROTRAD = 10.5 , ECCEN = 1.5 , DEPTH = 7.0).
C
C
       AREA  = 2.* (VOLUME/ROTORL + VOLUME/DEPTH + ROTORL*DEPTH )
     &          + .151 * VOLUME
       AHOUS = AREA - AROTOR - ASIDE
C
C          DEFINE A CHARACTERISTIC ROTOR VELOCITY AND DIMENSION
C          FOR HEAT TRANSFER PURPOSES.
C
      ROTVEL = RPM*PI*ROTRAD/90.
      DCHAR  = DEPTH
C
C          COMPONENT AREAS ARE PASSED IN THE CALL STATEMENT AND
C          IN THE COMMON STATEMENT HEATXG.
C
      RETURN
      END
C_____________________________________________________________________
      FUNCTION GINT1 (DT, DY, DYP)
      REAL*8 DT,DY(25),DYP(25),GINT1
C
      GINT1 = DYP(1)
C
      RETURN
      END
C_____________________________________________________________________
C
      FUNCTION GINT2 (DT, DY, DYP)
      REAL*8 DT,DY(25),DYP(25),GINT2
C
      GINT2 = DY(1)
C
      RETURN
      END
C_____________________________________________________________________
C
      FUNCTION GCMP (DT, DY, DYP)
      REAL*8 DT,DY(25),DYP(25),GCMP
C
      GCMP =DYP(12)
C
      RETURN
      END
C_____________________________________________________________________
C
      FUNCTION GEXH (DT, DY, DYP)
      REAL*8 DT,DY(25),DYP(25),GEXH
C
      GEXH =10.00
C
      RETURN
      END
C_____________________________________________________________________
      FUNCTION GCMB (DT, DY, DYP)
```

```
      REAL*8 DT,DY(25),DYP(25),GCMB1
      COMMON/CREV/DRHODP,CSUBT,MW,ITERAS,DVDT,CSUBP,DRHODT,HIMM,RESIDL,
     &            RESFIM
C
      GCMB = DYP(24)
      IF (ITERAS .EQ. 1 ) GCMB = 10.0
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 OVERSHOOT 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(25), XXX(25)
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 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 MANSOURI PHD 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, PHICON, 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 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 BURNED ZONE  )
C        ENTHLP     NO     YES     ENTHALPY  ------
C        CSUBP      NO     YES     --------
C        CSUBT      NO     YES     --------
C        RHO        NO     YES     DENSITY
C        DRHODT     NO     YES     --------
C        DRHODP     NO     YES     --------
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        THE DUMMY VARIABLES ARE NOT USED IN THE WANKEL PROGRAM
C        BUT HAVE BEEN LEFT INTACT FOR FUTURE USE, IF NECESSARY.
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, AND T. J. NORMAN
C
C
      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/ TIPO, TIPC, TEPO, TEPC, THIPO, THEPO, TSPARK
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
CJ    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. TIPC) GO TO 20
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 )
CJ    GDUMY = (R1 - R2)/R
CJ    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
CJ    BDUMY = (1. - RHO*CSUBT)/DRHODP
C
C        CONVERT TO UNITS NEEDED IN MAIN PROGRAM
C
   20 CONTINUE
      CSUBP = CSUBP * 4.184E+7
CJ    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________________ 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        SUBROUTINES AND FUNCTION SUBPROGRAMS NEEDED
C           NONE
C
C        METHOD
C           DESCRIBED IN APPENDIX A OF HIRES ET AL, SAE PAPER #760161
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
      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), TABLE(7), AF(6), X(7)
      COMMON/OXDANT/ XI
      COMMON/FUEL/ FUELTP, ENW, CX, HY, OZ, DEL, PSI, PHICON, 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 BIG OR TOO SMALL
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/
```

```
      DATA TABLE /-1.,1.,1.,-1.,0.,0.,0./
C
C        ENTER INTO ARRAYS A1 AND A2 THE FUEL PARAMETERS
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 WRITEUP, 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)
      DIMENSION TABLE(7)
      COMMON/FUEL/ FUELTP, ENW, CX, HY, OZ, DEL, PSI, PHICON, 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/
      DATA TABLE /-1.,1.,1.,-1.,0.,0.,0./
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________________________________________________________________________
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, PHICON, 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
C     ALSO GET THE COEFFICIENTS FOR T & TV TERMS IN 3.15 USING 5.3 & 5.4
C
      HF   = 1000.*((121.5 + 29.59*EPS)*Y + 117.5*U)
      HF   = HF + (20372.*EPS - 114942.)*PHI
      C1   = 7.*PSI + 5.*Y + 3.*U
      C2   = 2.*(PSI - 3.*Y - U)
C
      IF (LEAN) GO TO 10
C
C        RICH CASE
C
      HF = HF + 1000.*(134.39 - 6.5/EPS)*(PHI - 1.)
      C1 = 2. + 2.*(7.- 4.*EPS)*PHI + C1
      C2 = 8. + 2.*(2.- 3.*EPS)*PHI + C2
      GO TO 20
C
```

```
C        LEAN CASE
C
   10 C1 = 7. +     (9.- 8.*EPS)*PHI + C1
      C2 = 2. + 2.* (5.- 3.*EPS)*PHI + C2
C
C        ADD IN TRANSLATIONAL, VIBRATIONAL, AND ROTATIONAL TERMS
C        TO GET TOTAL ENTHALPY, USING EQS. 3.16, 5.6, 3.11, & 3.15
C
   20 TV     = (3256.- 2400.*EPS + 300.*PSI)/(1.- .5*EPS + .09*PSI)
      EXPTVT = EXP(TV/T)
      TVTIL  = TV/(EXPTVT - 1.)
      MCP    = (8.*EPS + 4.)*PHI + 32. + 28.*PSI
C
      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 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
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______________________________________________________________________
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 PROPERTY ROUTINES), AND
C        THE FUEL HEATING VALUE AND STOICHIOMETRIC FUEL/AIR RATIO;
C        II) THE ATOM RATIOS REQUIRED BY SUBROUTINE 'PTCHEM' FOR
C        CALCULATION OF EQUILIBRIUM BURNED GAS COMPOSITION.
C
C     USAGE
C        CALL FUELDT
C
C     DESCRIPTION OF PARAMETERS
C        PARAMETER  INPUT  OUTPUT  DESCRIPTION
C
C        FUELTP     YES    NO      FUEL TYPE
C        PSI        NO     YES     MOLAR N2 TO O2 RATIO FOR AIR
C        XI         NO     YES     MOLAR N2 TO O2 RATIO FOR AIR
C        CX         NO     YES     # OF CARBON ATOMS/FUEL MOLECULE
C        DEL        NO     YES     CARBON/HYDROGEN RATIO OF FUEL
C        HY         NO     YES     HYDROGEN ATOMS PER FUEL MOLECULE
C        ENW        NO     YES     NITROGEN ATOMS PER FUEL MOLECULE
C        OZ         NO     YES     OXYGEN ATOMS PER FUEL MOLECULE
C        QLOWER     NO     YES     LOWER HEATING VALUE OF THE FUEL
C        FASTO      NO     YES     STOICHIOMETRIC FUEL/AIR RATIO
C        AF(I)      NO     YES     FUEL COEFFICIENT ARRAY
C        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
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, PHICON, 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
      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
   20 PHICON = (32. + 28. * PSI) * (DEL + .25)/(12. * DEL + 1.0)
C
```

```
C        CALCULATE ATOM RATIOS FOR USE BY 'PTCHEM'
C
      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
      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) , NGO
  448 T = T + T
```

```
      IF (T - 1.0D15) 446, 446, 908
  908 ISENT = 7
      GO TO 5000
  458 T1 = T
      NGO = 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 H0 = 0.0D0
```

```
      DO 26 I = 1, N
   26    H0 = H0 + XNU(I)**2
      H2 = H0
      T0 = 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     H0 = SUM*SUM
C     DIF1 = 100.0D0
C     H2 = H0
C     T0 = 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
      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     LOOP TO FIND LARGEST
      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                                  $ IF DIAG NOT LARGEST INTERCHANGE ROWS
   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       LAST COLUMN HAS NOT BEEN DONE YET
      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
      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   *
C   * THIS REPORT WAS PREPARED AS AN ACCOUNT OF WORK SPONSORED BY THE
C   * UNITED STATES GOVERNMENT.  NEITHER THE UNITED STATES NOR THE
C   * UNITED STATES ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION,
C   * NOR ANY OF THEIR EMPLOYEES, NOR ANY OF THEIR CONTRACTORS,
C   * SUBCONTRACTORS, OR THEIR EMPLOYEES, MAKES ANY WARRANTY, EXPRESS
C   * OR IMPLIED, OR ASSUMES ANY LEGAL LIABILITY OR RESPONSIBILITY
C   * FOR THE ACCURACY, COMPLETENESS OR USEFULNESS OF ANY INFORMATION,
C   * APPARATUS, PRODUCT OR PROCESS DISCLOSED, OR REPRESENTS THAT ITS
C   * USE WOULD NOT INFRINGE PRIVATELY OWNED RIGHTS.
C   *
C   * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C   *                                                                *
C   * THE PRIMARY DOCUMENT FOR THE LIBRARY OF WHICH THIS ROUTINE IS   *
C   * A PART IS SAND75-0545.                                          *
C   *                                                                *
C   * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C
      SUBROUTINE ERRCHK(N,M)
      INTEGER*2 M
      DIMENSION M(100)
      NWDS = (IABS(N)+1)/2
      PRINT 10, (M(I), I=1,NWDS)
   10 FORMAT(1H0, 60A2)
      IF (N .GT. 0) RETURN
      STOP
      END
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   *
C   * THIS REPORT WAS PREPARED AS AN ACCOUNT OF WORK SPONSORED BY THE
C   * UNITED STATES GOVERNMENT.  NEITHER THE UNITED STATES NOR THE
C   * UNITED STATES ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION,
C   * NOR ANY OF THEIR EMPLOYEES, NOR ANY OF THEIR CONTRACTORS,
C   * SUBCONTRACTORS, OR THEIR EMPLOYEES, MAKES ANY WARRANTY, EXPRESS
C   * OR IMPLIED, OR ASSUMES ANY LEGAL LIABILITY OR RESPONSIBILITY
C   * FOR THE ACCURACY, COMPLETENESS OR USEFULNESS OF ANY INFORMATION,
C   * APPARATUS, PRODUCT OR PROCESS DISCLOSED, OR REPRESENTS THAT ITS
C   * USE WOULD NOT INFRINGE PRIVATELY OWNED RIGHTS.
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
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(25),YOUT(25),YPOUT(25),PHI(25,16),PSI(12)
      DIMENSION G(13),W(13),RHO(13)
      DATA G(1)/1.0/,RHO(1)/1.0/
C
      HI = XOUT - X
      KI = KOLD + 1
      KIP1 = KI + 1
C
C   INITIALIZE W(*) FOR COMPUTING G(*)
C
      DO 5 I = 1,KI
        TEMP1 = I
 5      W(I) = 1.0/TEMP1
      TERM = 0.0
C
C   COMPUTE G(*)
C
      DO 15 J = 2,KI
        JM1 = J - 1
        PSIJM1 = PSI(JM1)
        GAMMA = (HI + TERM)/PSIJM1
        ETA = HI/PSIJM1
        LIMIT1 = KIP1 - J
        DO 10 I = 1,LIMIT1
 10       W(I) = GAMMA*W(I) - ETA*W(I+1)
        G(J) = W(1)
        RHO(J) = GAMMA*RHO(JM1)
 15     TERM = PSIJM1
C
C   INTERPOLATE
C
      DO 20 L = 1,NEQN
        YPOUT(L) = 0.0
 20     YOUT(L) = 0.0
      DO 30 J = 1,KI
        I = KIP1 - J
        TEMP2 = G(I)
        TEMP3 = RHO(I)
        DO 25 L = 1,NEQN
          YOUT(L) = YOUT(L) + TEMP2*PHI(L,I)
 25       YPOUT(L) = YPOUT(L) + TEMP3*PHI(L,I)
 30     CONTINUE
      DO 35 L = 1,NEQN
 35     YOUT(L) = Y(L) + HI*YOUT(L)
      RETURN
      END
C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C
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 DEPARTMENT OF ENERGY               *
C  *                                                                   *
C  * * * * * * * * * * * * * * * * NOTICE  * * * * * * * * * * * * * * *
C  *                                                                   *
C  * THIS REPORT WAS PREPARED AS AN ACCOUNT OF WORK SPONSORED BY THE   *
C  * UNITED STATES GOVERNMENT.  NEITHER THE UNITED STATES NOR THE      *
C  * UNITED STATES DEPARTMENT OF ENERGY NOR ANY OF THEIR EMPLOYEES,    *
C  * NOR ANY OF THEIR CONTRACTORS, SUBCONTRACTORS, OR THEIR EMPLOYEES  *
C  * MAKES ANY WARRANTY, EXPRESS OR IMPLIED, OR ASSUMES ANY LEGAL      *
C  * LIABILITY OR RESPONSIBILITY FOR THE ACCURACY, COMPLETENESS OR     *
C  * USEFULNESS OF ANY INFORMATION, APPARATUS, PRODUCT OR PROCESS      *
C  * DISCLOSED, OR REPRESENTS THAT ITS USE WOULD NOT INFRINGE          *
C  * OWNED RIGHTS.                                                     *
C  *                                                                   *
C  * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C  *                                                                   *
C  * THE PRIMARY DOCUMENT FOR THE LIBRARY OF WHICH THIS ROUTINE IS     *
C  * PART IS SAND77-1441.                                              *
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(25),WORK(625),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(25),YY(25),WT(25),PHI(25,16),P(25),YP(25),
     1  YPOUT(25),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   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   *
C   * THIS REPORT WAS PREPARED AS AN ACCOUNT OF WORK SPONSORED BY THE
C   * UNITED STATES GOVERNMENT.  NEITHER THE UNITED STATES NOR THE
C   * UNITED STATES ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION,
C   * NOR ANY OF THEIR EMPLOYEES, NOR ANY OF THEIR CONTRACTORS,
C   * SUBCONTRACTORS, OR THEIR EMPLOYEES, MAKES ANY WARRANTY, EXPRESS
C   * OR IMPLIED, OR ASSUMES ANY LEGAL LIABILITY OR RESPONSIBILITY
C   * FOR THE ACCURACY, COMPLETENESS OR USEFULNESS OF ANY INFORMATION,
C   * APPARATUS, PRODUCT OR PROCESS DISCLOSED, OR REPRESENTS THAT ITS
C   * USE WOULD NOT INFRINGE PRIVATELY OWNED RIGHTS.
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(25),WT(25),PHI(25,16),P(25),YP(25),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
```

SAMPLE INPUT FOR CYCLE SIMULATION

```
FILE: FIRE     DATA     A


 $INPUT
 FIRE   = .TRUE.
 SPBURN = .TRUE.
 FUELTP = 1
 PHI    = 1.00
 ECCEN  = 1.50
 ROTRAD= 10.5
 DEPTH  = 7.00
 VFLANK = 35.00
 RPM    = 3000.
 TIPO   = -530.0
 TIPC   = -180.0
 TEPO   = 199.0
 TEPC   = 588.5
 TSPARK = -30.0
 THIPO  = 120.0
 THEPO  = 40.0
 IPA    = 13.8
 EPA    = 6.5
 XBZERO = 0.0003
 XBSTOP = 0.995
 DTBRN  = 90.0
 CONSPB =  5.0
 EXSPB  = 1.50
 PATM   = 1.000
 TATM   = 300.0
 PIM    = 0.980
 TFRESH = 300.0
 TEGR   = 300.0
 EGR    = 0.0
 PEM    = 1.02
 TROTOR = 370.
 TSIDE  = 370.
 THOUS  = 370.
 CONHT  = 0.0350
 EXPHT  = .8
 TPRINT = 10.00
 TPRINX = 1.0
 AREROT = .0002
 CIINTG = 0.0001
 CCINTG = 0.0001
 CBINTG = 0.00005
 CEINTG = 0.0001
 MXTRY  = 1
 REL    = .0002
 MAXITS = 3
 MAXERR = 0.03
 MAXTRY = 2
 AREALK = 0.0100
 CREVOL = 0.875
 TCREV  = 370
 CON1   = 0.75
 CON2   = 0.324
 $END
```

SAMPLE MOTORING OUTPUT

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


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


   >>>>> OPERATING MODE

             MOTORED CYCLE


   >>>>> OPERATING CONDITIONS

             ENGINE SPEED          =  2052.0 RPM


   >>>>> MANIFOLD CONDITIONS

             INTAKE MANIFOLD PRESSURE  =     0.9300 ATM
             EXHAUST MANIFOLD PRESSURE =     1.0200 ATM
             FRESH CHARGE TEMPERATURE  =   312.70    K
             EXHAUST GAS RECIRCULATION =     0.00    %
```

```
        EGR TEMPERATURE            =   300.00   K
        INTAKE CHARGE TEMPERATURE =   312.70   K
        ATMOSPHERIC PRESSURE       =     0.9810 ATM
        ATMOSPHERIC TEMPERATURE    =   300.60   K
---------------------------------------------------------------------------

>>>>> HEAT TRANSFER AND TURBULENCE PARAMETERS

        HEAT TRANSFER CONSTANT         =     0.3770
        HEAT TRANSFER EXPONENT         =     0.8000
        ROTOR TEMPERATURE              =   350.00   K
        SIDE WALL TEMPERATURE          =   350.00   K
        HOUSING WALL TEMPERATURE       =   350.00   K
---------------------------------------------------------------------------

>>>>> ENGINE DESIGN PARAMETERS

        ECCENTRICITY OF ROTOR   =     1.500 CM
        RADIUS OF ROTOR         =    10.500 CM
        DEPTH OF CHAMBER        =     7.000 CM
        COMPRESSION RATIO       =     9.407
        DISPLACED VOLUME        =   572.875 CC
        VOLUME OF ROTOR POCKET  =    35.000 CC
        INTAKE PORT OPENS      =  -530.0   DEG CA
        INTAKE PORT CLOSES     =  -180.0   DEG CA
        EXHAUST PORT OPENS     =   199.0   DEG CA
        EXHAUST PORT CLOSES    =   588.5   DEG CA
---------------------------------------------------------------------------
```

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

             LEAK AREA PER APEX     =     0.010000  CM*CM

             CREVICE VOLUME PER APEX=     0.875000  CC

             CREVICE GAS TEMPERATURE=   350.000000  K
```

```
>>>>> COMPUTATIONAL PARAMETERS

             MAXIMUM # OF ITERATIONS =       2

             OUTPUT AT ITERATION #   =       1

             TPRINT                  =      10.00
             TPRINX                  =       1.00
             XBZERO                  =       0.00050
             XESTOP                  =       0.00000
             XBSTOP                  =       0.99500
             CIINTG                  =       0.000100
             CCINTG                  =       0.000100
             CBINTG                  =       0.000010
             CEINTG                  =       0.000100
             AREROT                  =       0.000200
             REL                     =       0.000200
             ERMAX                   =       0.000000
             MAXERR                  =       0.030000
             MAXTRY                  =       2
```

```
>>>>> START OF INTAKE PROCESS

   CA        P         TEMP      MIN       MEX        VIV        VEV        X1       Q DOT        WORK      IMF  IFG
 (DEG)     (ATM)       (K)       (G)       (G)      (CM/SEC)   (CM/SEC)    (-)     (KJ/DEG)      (KJ)
-----------------------------------------------------------------------------------------------------------------
 -530.0    1.1000    330.00   0.00000   0.00000       0.0               1.00000                0.000000
 -520.0    1.0045    325.32  -0.00452  -0.00474   -8484.6    -3499.6    1.00000   -0.000030    0.000596    0    2
 -510.0    0.9588    324.43  -0.01515  -0.02177   -5528.6    -7087.2    1.00000   -0.000030    0.001547    0    2
 -501.1    0.9294    324.43  -0.01989  -0.03538     812.9    -8745.1    1.00000   -0.000030    0.002641    0    8
 -500.0    0.9280    324.63  -0.01962  -0.03659    1509.3    -8822.5    1.00000   -0.000030    0.002800    0    2
 -490.0    0.9127    325.79  -0.00948  -0.04088    4473.9        0.0    1.00000   -0.000029    0.004354    0    2
 -484.7    0.9120    326.97  -0.00000  -0.04088    4568.4        0.0    1.00000   -0.000028    0.005293    0    8
 -480.0    0.9124    327.40   0.00941  -0.04088    4332.2        0.0    1.00000   -0.000027    0.006192    1    2
 -470.0    0.9140    327.19   0.03217  -0.04088    4137.6        0.0    1.00000   -0.000029    0.008307    1    2
 -460.0    0.9161    326.94   0.05777  -0.04088    3864.7        0.0    1.00000   -0.000030    0.010672    1    2
 -450.0    0.9169    326.59   0.08560  -0.04088    3744.6        0.0    1.00000   -0.000032    0.013257    1    2
 -440.0    0.9186    326.34   0.11558  -0.04088    3503.9        0.0    1.00000   -0.000033    0.016025    1    2
 -430.0    0.9197    326.11   0.14706  -0.04088    3334.6        0.0    1.00000   -0.000035    0.018941    1    2
 -420.0    0.9212    325.97   0.17981  -0.04088    3086.1        0.0    1.00000   -0.000037    0.021964    1    2
 -410.0    0.9222    325.86   0.21316  -0.04088    2903.4        0.0    1.00000   -0.000039    0.025054    1    2
 -400.0    0.9225    325.74   0.24654  -0.04088    2848.1        0.0    1.00000   -0.000040    0.028168    1    2
 -390.0    0.9228    325.70   0.27966  -0.04088    2790.0        0.0    1.00000   -0.000042    0.031260    1    2
 -380.0    0.9234    325.76   0.31215  -0.04088    2670.9        0.0    1.00000   -0.000043    0.034291    1    2
 -370.0    0.9236    325.83   0.34334  -0.04088    2629.9        0.0    1.00000   -0.000044    0.037220    1    2
 -360.0    0.9243    326.00   0.37311  -0.04088    2485.8        0.0    1.00000   -0.000045    0.040007    1    2
 -350.0    0.9242    326.15   0.40054  -0.04088    2503.0        0.0    1.00000   -0.000046    0.042614    1    2
 -340.0    0.9247    326.42   0.42582  -0.04088    2389.5        0.0    1.00000   -0.000047    0.045005    1    2
 -330.0    0.9252    326.73   0.44830  -0.04088    2287.9        0.0    1.00000   -0.000047    0.047147    1    2
 -320.0    0.9261    327.15   0.46795  -0.04088    2051.7        0.0    1.00000   -0.000047    0.049012    1    2
 -310.0    0.9268    327.59   0.48411  -0.04088    1877.2        0.0    1.00000   -0.000047    0.050575    1    2
 -300.0    0.9268    328.04   0.49639  -0.04088    1874.6        0.0    1.00000   -0.000046    0.051814    1    2
 -290.0    0.9286    328.71   0.50584  -0.04088    1230.7        0.0    1.00000   -0.000045    0.052712    1    2
 -280.3    0.9304    329.43   0.51130  -0.04088    -673.5        0.0    1.00000   -0.000044    0.053245    1    8
 -278.7    0.9301    329.51   0.51151  -0.04088    -276.6        0.0    1.00000   -0.000044    0.053300    0    8
 -270.0    0.9301    330.10   0.51185  -0.04088    -305.4        0.0    1.00000   -0.000043    0.053439    0    2
 -260.0    0.9315    330.89   0.50936  -0.04088   -1304.3        0.0    1.00000   -0.000041    0.053256    0    2
 -250.0    0.9360    331.96   0.50462  -0.04088   -2612.5        0.0    1.00000   -0.000039    0.052709    0    2
 -240.0    0.9464    333.59   0.49899  -0.04088   -4288.5        0.0    1.00000   -0.000035    0.051798    0    2
 -230.0    0.9700    336.45   0.49571  -0.04088   -6556.6        0.0    1.00000   -0.000029    0.050519    0    2
 -220.0    1.0078    340.51   0.49481  -0.04088   -8839.9        0.0    1.00000   -0.000021    0.048850    0    2
 -210.0    1.0573    345.43   0.49457  -0.04088  -10838.0        0.0    1.00000   -0.000010    0.046770    0    2
 -200.0    1.1192    351.10   0.49452  -0.04088  -12550.7        0.0    1.00000    0.000002    0.044251    0    2
 -190.0    1.1949    357.52   0.49450  -0.04088  -13995.2        0.0    1.00000    0.000017    0.041261    0    2
 -181.7    1.2703    363.44   0.49450  -0.04088  -14997.9        0.0    1.00000    0.000031    0.038392    0    8
 -180.0    1.2871    364.71   0.49450  -0.04088       0.0        0.0    1.00000    0.000034    0.037764    0    2
 -180.0    1.2871    364.71   0.49450  -0.04088       0.0        0.0    1.00000    0.000034    0.037764    0    2
-----------------------------------------------------------------------------------------------------------------
```

```
>>>>> START OF COMPRESSION PROCESS

   CA        P          TEMP                                        Q DOT        WORK        IFG
  (DEG)    (ATM)        (K)                                       (KJ/DEG)       (KJ)
------------------------------------------------------------------------------------------------
 -180.0    1.2871     364.71                                      0.000034     0.037764      2
 -170.0    1.3989     372.70                                      0.000054     0.033717      2
 -160.0    1.5347     381.52                                      0.000077     0.029071      2
 -150.0    1.6999     391.23                                      0.000105     0.023768      2
 -140.0    1.9016     401.84                                      0.000137     0.017742      2
 -130.0    2.1492     413.41                                      0.000175     0.010921      2
 -120.0    2.4547     425.96                                      0.000221     0.003224      2
 -110.0    2.8339     439.47                                      0.000276    -0.005435      2
 -100.0    3.3068     453.89                                      0.000343    -0.015140      2
  -90.0    3.8990     469.10                                      0.000424    -0.025964      2
  -80.0    4.6410     484.85                                      0.000522    -0.037953      2
  -70.0    5.5669     500.73                                      0.000640    -0.051086      2
  -60.0    6.7101     516.23                                      0.000779    -0.065237      2
  -50.0    8.0750     529.81                                      0.000935    -0.080064      2
  -40.0    9.6198     539.95                                      0.001096    -0.094935      2
  -30.0   11.2025     544.64                                      0.001236    -0.108815      2
  -20.0   12.5466     541.76                                      0.001317    -0.120296      2
  -10.0   13.2818     529.76                                      0.001296    -0.127879      2
   -6.7   13.3335     523.78                                      0.001262    -0.129308      8
    0.0   13.1140     508.64                                      0.001154    -0.130488      2
   10.0   12.0541     480.84                                      0.000920    -0.128040      2
   20.0   10.4106     449.55                                      0.000652    -0.121492      2
   30.0    8.5997     418.11                                      0.000404    -0.112351      2
   40.0    6.9279     388.85                                      0.000206    -0.102050      2
   50.0    5.5318     362.93                                      0.000061    -0.091619      2
   60.0    4.4279     340.64                                     -0.000039    -0.081658      2
   70.0    3.5779     321.81                                     -0.000106    -0.072450      2
   80.0    2.9295     306.04                                     -0.000151    -0.064090      2
   90.0    2.4347     292.91                                     -0.000179    -0.056566      2
  100.0    2.0549     282.04                                     -0.000198    -0.049826      2
  110.0    1.7611     273.08                                     -0.000209    -0.043798      2
  120.0    1.5316     265.76                                     -0.000216    -0.038408      2
  130.0    1.3508     259.83                                     -0.000220    -0.033589      2
  140.0    1.2073     255.11                                     -0.000222    -0.029281      2
  150.0    1.0926     251.44                                     -0.000222    -0.025433      2
  160.0    1.0005     248.71                                     -0.000221    -0.022001      2
  170.0    0.9264     246.80                                     -0.000220    -0.018949      2
  180.0    0.8669     245.64                                     -0.000217    -0.016247      2
  190.0    0.8194     245.15                                     -0.000215    -0.013871      2
------------------------------------------------------------------------------------------------
```

```
>>>>> START OF EXHAUST PROCESS

  CA        P        TEMP           MEX              VEV              Q DOT       WORK          IFG
 (DEG)    (ATM)      (K)            (G)             (M/SEC)         (KJ/DEG)      (KJ)

 199.0    0.7852    245.25        -0.04088              0.0         -0.000212   -0.011995       2
 200.0    0.7821    245.31        -0.04097         -13339.1         -0.000211   -0.011802       2
 210.0    0.7735    247.87        -0.05292         -13717.9         -0.000207   -0.010008       2
 220.0    0.8028    253.72        -0.08392         -12805.9         -0.000203   -0.008426       2
 230.0    0.8620    261.86        -0.12981         -10742.2         -0.000196   -0.007026       2
 240.0    0.9364    270.75        -0.18160          -7649.8         -0.000187   -0.005827       2
 250.0    0.9944    277.77        -0.22022          -4171.1         -0.000178   -0.004892       2
 260.0    1.0199    281.93        -0.23596           -285.7         -0.000171   -0.004301       2
 270.0    1.0208    284.05        -0.23308            747.0         -0.000165   -0.004101       2
 280.0    1.0227    286.19        -0.22608           1355.4         -0.000159   -0.004301       2
 290.0    1.0256    288.36        -0.21510           1960.6         -0.000153   -0.004901       2
 300.0    1.0296    290.55        -0.20023           2552.8         -0.000146   -0.005896       2
 310.0    1.0344    292.78        -0.18156           3127.3         -0.000139   -0.007276       2
 320.0    1.0400    295.02        -0.15925           3680.4         -0.000131   -0.009026       2
 330.0    1.0463    297.27        -0.13346           4205.4         -0.000124   -0.011129       2
 340.0    1.0529    299.51        -0.10438           4696.2         -0.000116   -0.013550       2
 350.0    1.0598    301.74        -0.07226           5147.1         -0.000109   -0.016291       2
 360.0    1.0666    303.94        -0.03738           5551.7         -0.000101   -0.019290       2
 370.0    1.0730    306.07        -0.00007           5904.0         -0.000094   -0.022516       2
 380.0    1.0786    308.13         0.03929           6196.0         -0.000087   -0.025929       2
 390.0    1.0830    310.08         0.08026           6420.1         -0.000080   -0.029478       2
 400.0    1.0860    311.91         0.12233           6568.4         -0.000074   -0.033114       2
 410.0    1.0870    313.61         0.16492           6632.3         -0.000068   -0.036782       2
 420.0    1.0860    315.16         0.20741           6603.3         -0.000062   -0.040425       2
 430.0    1.0827    316.57         0.24912           6473.8         -0.000057   -0.043987       2
 440.0    1.0775    317.89         0.28935           6239.3         -0.000052   -0.047413       2
 450.0    1.0706    319.15         0.32741           5904.3         -0.000048   -0.050653       2
 460.0    1.0628    320.44         0.36267           5482.7         -0.000044   -0.053661       2
 470.0    1.0551    321.88         0.39456           5017.9         -0.000040   -0.056397       2
 480.0    1.0466    323.39         0.42286           4416.1         -0.000036   -0.058830       2
 490.0    1.0382    325.04         0.44722           3686.8         -0.000033   -0.060932       2
 500.0    1.0313    326.98         0.46730           2933.2         -0.000029   -0.062679       2
 510.0    1.0270    329.26         0.48296           2336.3         -0.000026   -0.064055       2
 520.0    1.0231    331.58         0.49434           1561.2         -0.000022   -0.065048       2
 530.0    1.0212    333.98         0.50130            979.4         -0.000019   -0.065647       2
 540.0    1.0199    336.21         0.50396           -314.3         -0.000016   -0.065847       2
 550.0    1.0199    338.24         0.50234           -276.0         -0.000014   -0.065647       2
```

```
>-------------+-------------<
>                           <
>    CALCULATION RESULTS    <
>                           <
>-------------+-------------<


--> VOLUMETRIC EFFICIENCY; (%)
    BASED ON: INTAKE / ATM            ---->    82.6    75.3

--> PUMPING MEAN EFFECTIVE
    PRESSURE; (KPA) : PEMP            ---->   -14.

--> GROSS INDICATED MEAN EFFECTIVE
    PRESSURE; (KPA) : IMEP            ---->  -100.

--> GROSS INDICATED SPECIFIC FUEL
    CONSUMPTION; (G/IKW-HR) : ISFC    ---->     0.

--> GROSS INDICATED THERMAL
    EFFICIENCY; (%)                   ---->     0.0

--> NET INDICATED THERMAL
    EFFICIENCY; (%)                   ---->     0.0

--> (HEAT TRANSFER PER CYCLE)/
    (MASS OF FUEL TIMES LHV); (%)     ---->     0.0

--> IGNITION DELAY (0 - 10%)
    (CRANK ANGLE) / (MS)              ---->     0.00    0.00

--> BURN DURATION (10 - 90%)
    (CRANK ANGLE) / (MS)              ---->     0.00    0.00

--> MEAN EXHAUST
    TEMPERATURE; (K)                  ---->   328.0
```

```
MASS IN CYLINDER AT TIVO =  0.08210 G

MASS IN CYLINDER AT TIVC =  0.61748 G

MASS OF FUEL INDUCTED    =  0.00000 G

RESIDUAL FRACTION        =  0.00000
```

```
HEATI   =  -0.010014 KJ  (TIPO   -   -270)
WORKI   =   0.053439 KJ

HEATCE  =   0.088180 KJ  (TIPC   -    +270
WORKCE  =  -0.057539 KJ

HEATE   =  -0.021527 KJ  (+270   -   TIPO)
WORKE   =  -0.061546 KJ
```

```
TOTAL ENTHALPY IN / CYCLE    =  0.15581 KJ

TOTAL ENTHALPY OUT / CYCLE   =  0.16607 KJ

TOTAL HEAT LOSS / CYCLE      =  0.05664 KJ

TOTAL WORK OUTPUT / CYCLE    = -0.06565 KJ

HEAT LOSS TO CREVICE/CYCLE   =  0.00000 KJ

"LOST" FUEL ENERGY           =  0.00000 KJ

NET ENERGY GAIN / CYCLE      =  0.00125 KJ

(ENERGY GAIN)/(ENTHALPY IN)  =  0.80377 %

(ENERGY GAIN)/(MFUEL*LHV)    =  0.00000 %
```

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

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

>>>>> OPERATING MODE

          MOTORED CYCLE

>>>>> OPERATING CONDITIONS

          ENGINE SPEED           =  2052.0 RPM

>>>>> MANIFOLD CONDITIONS

          INTAKE MANIFOLD PRESSURE  =    0.9300 ATM
          EXHAUST MANIFOLD PRESSURE =    1.0200 ATM
          FRESH CHARGE TEMPERATURE  =  312.70   K
          EXHAUST GAS RECIRCULATION =    0.00   %
```

```
              EGR TEMPERATURE               =   300.00    K
              INTAKE CHARGE TEMPERATURE =   312.70    K
              ATMOSPHERIC PRESSURE          =     0.9810 ATM
              ATMOSPHERIC TEMPERATURE       =   300.60    K
```

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

              HEAT TRANSFER CONSTANT            =       0.3770
              HEAT TRANSFER EXPONENT            =       0.8000
              ROTOR TEMPERATURE                 =     350.00    K
              SIDE WALL TEMPERATURE             =     350.00    K
              HOUSING WALL TEMPERATURE          =     350.00    K
```

```
>>>>> ENGINE DESIGN PARAMETERS

              ECCENTRICITY OF ROTOR    =      1.500 CM
              RADIUS OF ROTOR          =     10.500 CM
              DEPTH OF CHAMBER         =      7.000 CM
              COMPRESSION RATIO        =      9.407
              DISPLACED VOLUME         =    572.875 CC
              VOLUME OF ROTOR POCKET   =     35.000 CC
              INTAKE PORT OPENS       =  -530.0    DEG CA
              INTAKE PORT CLOSES      =  -180.0    DEG CA
              EXHAUST PORT OPENS      =   199.0    DEG CA
              EXHAUST PORT CLOSES     =   588.5    DEG CA
```

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

          LEAK AREA PER APEX     =     0.010000  CM*CM

          CREVICE VOLUME PER APEX=     0.875000  CC

          CREVICE GAS TEMPERATURE=   350.000000  K
```

```
>>>>> COMPUTATIONAL PARAMETERS

          MAXIMUM # OF ITERATIONS =      2

          OUTPUT AT ITERATION #   =      2

          TPRINT                  =     10.00
          TPRINX                  =      1.00
          XBZERO                  =      0.00050
          XESTOP                  =      0.00000
          XBSTOP                  =      0.99500
          CIINTG                  =      0.000100
          CCINTG                  =      0.000100
          CBINTG                  =      0.000010
          CEINTG                  =      0.000100
          AREROT                  =      0.000200
          REL                     =      0.000200
          ERMAX                   =      0.000000
          MAXERR                  =      0.030000
          MAXTRY                  =      2
```

```
>>>>> START OF INTAKE PROCESS

   CA        P        TEMP       MIN        MEX         VIV        VEV        X1       Q DOT         WORK       IMF   IFG
  (DEG)    (ATM)      (K)        (G)        (G)      (CM/SEC)   (CM/SEC)     (-)     (KJ/DEG)       (KJ)
 --------------------------------------------------------------------------------------------------------------------------
 -530.0   1.0199    338.24    0.00000    0.00000        0.0                1.00000                0.000000
 -520.0   1.0041    338.50   -0.00441   -0.00912    -8634.8    -3616.3    1.00000   -0.000013    0.000594     0     2
 -510.0   0.9586    335.86   -0.01480   -0.02593    -5606.4    -7223.5    1.00000   -0.000016    0.001544     0     2
 -502.4   0.9301    334.50   -0.01960   -0.03786     -383.0    -8841.6    1.00000   -0.000018    0.002470     0     8
 -500.0   0.9287    334.81   -0.01914   -0.04051     1218.4    -8920.2    1.00000   -0.000017    0.002797     0     2
 -490.0   0.9131    334.92   -0.00932   -0.04473     4478.2        0.0    1.00000   -0.000018    0.004352     0     2
 -484.6   0.9127    335.69   -0.00000   -0.04473     4545.4        0.0    1.00000   -0.000017    0.005301     0     8
 -480.0   0.9126    334.96    0.00927   -0.04473     4307.2        0.0    1.00000   -0.000018    0.006191     1     2
 -470.0   0.9146    333.18    0.03174   -0.04473     4065.3        0.0    1.00000   -0.000021    0.008307     1     2
 -460.0   0.9163    331.76    0.05681   -0.04473     3832.6        0.0    1.00000   -0.000024    0.010674     1     2
 -450.0   0.9187    330.72    0.08426   -0.04473     3488.5        0.0    1.00000   -0.000026    0.013260     1     2
 -440.0   0.9197    329.82    0.11336   -0.04473     3325.8        0.0    1.00000   -0.000028    0.016030     1     2
 -430.0   0.9210    329.16    0.14394   -0.04473     3110.3        0.0    1.00000   -0.000031    0.018948     1     2
 -420.0   0.9220    328.65    0.17539   -0.04473     2948.2        0.0    1.00000   -0.000033    0.021973     1     2
 -410.0   0.9237    328.37    0.20750   -0.04473     2611.9        0.0    1.00000   -0.000034    0.025066     1     2
 -400.0   0.9235    328.06    0.23902   -0.04473     2649.3        0.0    1.00000   -0.000036    0.028182     1     2
 -390.0   0.9237    327.91    0.27005   -0.04473     2618.1        0.0    1.00000   -0.000038    0.031278     1     2
 -380.0   0.9239    327.87    0.30008   -0.04473     2561.6        0.0    1.00000   -0.000039    0.034312     1     2
 -370.0   0.9245    327.94    0.32883   -0.04473     2441.1        0.0    1.00000   -0.000040    0.037244     1     2
 -360.0   0.9254    328.10    0.35634   -0.04473     2228.2        0.0    1.00000   -0.000041    0.040034     1     2
 -350.0   0.9249    328.20    0.38109   -0.04473     2352.4        0.0    1.00000   -0.000042    0.042643     1     2
 -340.0   0.9252    328.43    0.40403   -0.04473     2284.2        0.0    1.00000   -0.000043    0.045036     1     2
 -330.0   0.9258    328.72    0.42468   -0.04473     2144.8        0.0    1.00000   -0.000043    0.047180     1     2
 -320.0   0.9264    329.07    0.44263   -0.04473     1979.3        0.0    1.00000   -0.000043    0.049047     1     2
 -310.0   0.9273    329.50    0.45768   -0.04473     1715.8        0.0    1.00000   -0.000043    0.050611     1     2
 -300.0   0.9279    329.96    0.46923   -0.04473     1525.2        0.0    1.00000   -0.000042    0.051850     1     2
 -290.0   0.9289    330.53    0.47748   -0.04473     1074.6        0.0    1.00000   -0.000041    0.052749     1     2
 -280.0   0.9301    331.17    0.48202   -0.04473     -278.9        0.0    1.00000   -0.000040    0.053294     1     2
 -277.8   0.9308    331.37    0.48272   -0.04473     -947.9        0.0    1.00000   -0.000040    0.053364     1     8
 -273.4   0.9299    331.55    0.48242   -0.04473      413.4        0.0    1.00000   -0.000039    0.053454     0     8
 -270.0   0.9302    331.80    0.48220   -0.04473     -462.0        0.0    1.00000   -0.000039    0.053476     0     2
 -260.0   0.9317    332.57    0.47935   -0.04473    -1413.2        0.0    1.00000   -0.000037    0.053293     0     2
 -250.0   0.9365    333.63    0.47437   -0.04473    -2721.9        0.0    1.00000   -0.000035    0.052746     0     2
 -240.0   0.9473    335.26    0.46865   -0.04473    -4416.5        0.0    1.00000   -0.000031    0.051835     0     2
 -230.0   0.9711    338.09    0.46520   -0.04473    -6654.9        0.0    1.00000   -0.000025    0.050554     0     2
 -220.0   1.0093    342.16    0.46429   -0.04473    -8933.8        0.0    1.00000   -0.000017    0.048883     0     2
 -210.0   1.0589    347.04    0.46406   -0.04473   -10912.6        0.0    1.00000   -0.000006    0.046800     0     2
 -200.0   1.1200    352.61    0.46401   -0.04473   -12594.7        0.0    1.00000    0.000006    0.044277     0     2
 -190.0   1.1944    358.88    0.46400   -0.04473   -14014.3        0.0    1.00000    0.000020    0.041287     0     2
 -180.0   1.2848    365.91    0.46400   -0.04473        0.0        0.0    1.00000    0.000037    0.037794     0     2
 -180.0   1.2848    365.91    0.46400   -0.04473        0.0        0.0    1.00000    0.000037    0.037794     0     2
 --------------------------------------------------------------------------------------------------------------------------
```

```
>>>>> START OF COMPRESSION PROCESS

   CA        P          TEMP                                                      Q DOT        WORK          IFG
 (DEG)     (ATM)        (K)                                                     (KJ/DEG)       (KJ)
-------------------------------------------------------------------------------------------------------------------
 -180.0     1.2848     365.91                                                   0.000037     0.037794         2
 -170.0     1.3942     373.72                                                   0.000056     0.033758         2
 -160.0     1.5267     382.34                                                   0.000079     0.029131         2
 -150.0     1.6876     391.80                                                   0.000105     0.023861         2
 -140.0     1.8836     402.16                                                   0.000137     0.017886         2
 -130.0     2.1233     413.42                                                   0.000174     0.011138         2
 -120.0     2.4178     425.60                                                   0.000218     0.003545         2
 -110.0     2.7815     438.68                                                   0.000270    -0.004969         2
 -100.0     3.2322     452.58                                                   0.000333    -0.014474         2
  -90.0     3.7922     467.16                                                   0.000409    -0.025029         2
  -80.0     4.4870     482.12                                                   0.000499    -0.036655         2
  -70.0     5.3434     497.00                                                   0.000606    -0.049308         2
  -60.0     6.3840     511.21                                                   0.000730    -0.062830         2
  -50.0     7.6055     523.48                                                   0.000866    -0.076868         2
  -40.0     8.9547     532.08                                                   0.001000    -0.090791         2
  -30.0    10.2957     535.21                                                   0.001110    -0.103630         2
  -20.0    11.3857     530.98                                                   0.001163    -0.114121         2
  -10.0    11.9209     518.17                                                   0.001125    -0.120966         2
   -7.9    11.9384     514.43                                                   0.001105    -0.121833         8
    0.0    11.6797     496.99                                                   0.000987    -0.123302         2
   10.0    10.6949     469.91                                                   0.000776    -0.121128         2
   20.0     9.2320     439.87                                                   0.000541    -0.115321         2
   30.0     7.6366     409.81                                                   0.000326    -0.107209         2
   40.0     6.1650     381.83                                                   0.000155    -0.098053         2
   50.0     4.9331     357.01                                                   0.000030    -0.088761         2
   60.0     3.9562     335.63                                                  -0.000056    -0.079869         2
   70.0     3.2018     317.53                                                  -0.000113    -0.071636         2
   80.0     2.6248     302.36                                                  -0.000150    -0.064149         2
   90.0     2.1837     289.73                                                  -0.000174    -0.057405         2
  100.0     1.8446     279.26                                                  -0.000190    -0.051357         2
  110.0     1.5819     270.65                                                  -0.000199    -0.045944         2
  120.0     1.3767     263.62                                                  -0.000204    -0.041101         2
  130.0     1.2150     257.96                                                  -0.000207    -0.036768         2
  140.0     1.0867     253.48                                                  -0.000208    -0.032892         2
  150.0     0.9846     250.08                                                  -0.000208    -0.029426         2
  160.0     0.9030     247.64                                                  -0.000206    -0.026331         2
  170.0     0.8376     246.03                                                  -0.000204    -0.023574         2
  180.0     0.7852     245.17                                                  -0.000202    -0.021129         2
  190.0     0.7436     244.97                                                  -0.000199    -0.018975         2
-------------------------------------------------------------------------------------------------------------------
```

```
>>>>> START OF EXHAUST PROCESS

  CA        P        TEMP           MEX               VEV              Q DOT       WORK         IFG
 (DEG)    (ATM)      (K)            (G)              (M/SEC)          (KJ/DEG)     (KJ)
--------------------------------------------------------------------------------------------------
 199.0    0.7138    245.32        -0.04473             0.0          -0.000196    -0.017271      2
 200.0    0.7111    245.41        -0.04484        -15870.5          -0.000196    -0.017095      2
 210.0    0.7079    248.57        -0.05765        -16086.6          -0.000192    -0.015460      2
 220.0    0.7444    255.46        -0.09090        -14980.2          -0.000187    -0.014004      2
 230.0    0.8134    265.00        -0.14083        -12689.4          -0.000179    -0.012695      2
 240.0    0.9014    275.49        -0.19907         -9353.8          -0.000169    -0.011552      2
 250.0    0.9751    283.99        -0.24569         -5634.1          -0.000158    -0.010644      2
 260.0    1.0157    289.32        -0.26958         -1730.4          -0.000150    -0.010060      2
 270.0    1.0208    291.62        -0.26919           751.2          -0.000144    -0.009860      2
 280.0    1.0227    293.60        -0.26232          1374.9          -0.000139    -0.010061      2
 290.0    1.0257    295.64        -0.25142          2001.9          -0.000133    -0.010661      2
 300.0    1.0299    297.73        -0.23656          2621.3          -0.000127    -0.011656      2
 310.0    1.0350    299.86        -0.21779          3227.8          -0.000120    -0.013036      2
 320.0    1.0410    302.04        -0.19523          3814.9          -0.000113    -0.014788      2
 330.0    1.0479    304.25        -0.16903          4376.0          -0.000106    -0.016893      2
 340.0    1.0552    306.47        -0.13936          4901.1          -0.000099    -0.019329      2
 350.0    1.0627    308.68        -0.10649          5378.5          -0.000092    -0.022067      2
 360.0    1.0700    310.83        -0.07076          5796.0          -0.000085    -0.025074      2
 370.0    1.0765    312.88        -0.03260          6143.7          -0.000079    -0.028311      2
 380.0    1.0818    314.80         0.00751          6413.0          -0.000072    -0.031734      2
 390.0    1.0856    316.57         0.04901          6603.0          -0.000066    -0.035294      2
 400.0    1.0878    318.17         0.09136          6712.4          -0.000061    -0.038937      2
 410.0    1.0880    319.61         0.13398          6737.1          -0.000056    -0.042610      2
 420.0    1.0862    320.90         0.17627          6673.5          -0.000051    -0.046254      2
 430.0    1.0825    322.06         0.21760          6518.0          -0.000047    -0.049816      2
 440.0    1.0769    323.11         0.25734          6264.9          -0.000043    -0.053241      2
 450.0    1.0699    324.11         0.29489          5913.8          -0.000040    -0.056479      2
 460.0    1.0619    325.12         0.32965          5471.8          -0.000037    -0.059485      2
 470.0    1.0536    326.21         0.36114          4950.3          -0.000034    -0.062220      2
 480.0    1.0448    327.37         0.38905          4295.5          -0.000031    -0.064652      2
 490.0    1.0367    328.72         0.41299          3557.1          -0.000028    -0.066752      2
 500.0    1.0326    330.55         0.43254          3109.9          -0.000025    -0.068499      2
 510.0    1.0276    332.38         0.44801          2433.7          -0.000022    -0.069875      2
 520.0    1.0234    334.30         0.45920          1639.4          -0.000019    -0.070867      2
 530.0    1.0210    336.32         0.46605           901.1          -0.000016    -0.071466      2
 540.0    1.0203    338.29         0.46862           503.4          -0.000014    -0.071667      2
 550.0    1.0194    339.96         0.46704          -693.7          -0.000012    -0.071467      2
--------------------------------------------------------------------------------------------------
```

```
                 >--------------+--------------<
                 >                             <
                 >     CALCULATION RESULTS     <
                 >                             <
                 >--------------+--------------<

-->  VOLUMETRIC EFFICIENCY; (%)
     BASED ON: INTAKE / ATM              ---->     77.5     70.6

-->  PUMPING MEAN EFFECTIVE
     PRESSURE; (KPA) : PEMP              ---->    -14.

-->  GROSS INDICATED MEAN EFFECTIVE
     PRESSURE; (KPA) : IMEP              ---->   -111.

-->  GROSS INDICATED SPECIFIC FUEL
     CONSUMPTION; (G/IKW-HR) : ISFC      ---->      0.

-->  GROSS INDICATED THERMAL
     EFFICIENCY; (%)                     ---->      0.0

-->  NET INDICATED THERMAL
     EFFICIENCY; (%)                     ---->      0.0

-->  (HEAT TRANSFER PER CYCLE)/
     (MASS OF FUEL TIMES LHV); (%)       ---->      0.0

-->  IGNITION DELAY (0 - 10%)
     (CRANK ANGLE) / (MS)                ---->      0.00     0.00

-->  BURN DURATION (10 - 90%)
     (CRANK ANGLE) / (MS)                ---->      0.00     0.00

-->  MEAN EXHAUST
     TEMPERATURE; (K)                    ---->    338.1
```

```
MASS IN CYLINDER AT TIVO =  0.07427 G

MASS IN CYLINDER AT TIVC =  0.61433 G

MASS OF FUEL INDUCTED    =  0.00000 G

RESIDUAL FRACTION        =  0.00000
```

```
HEATI    =   -0.008384 KJ  (TIPO   -   -270)
WORKI    =    0.053476 KJ

HEATCE   =    0.077640 KJ  (TIPC   -    +270
WORKCE   =   -0.063336 KJ

HEATE    =   -0.018311 KJ  (+270   -   TIPO)
WORKE    =   -0.061607 KJ
```

```
TOTAL ENTHALPY IN / CYCLE    =  0.14620 KJ

TOTAL ENTHALPY OUT / CYCLE   =  0.15920 KJ

TOTAL HEAT LOSS / CYCLE      =  0.05094 KJ

TOTAL WORK OUTPUT / CYCLE    = -0.07147 KJ

HEAT LOSS TO CREVICE/CYCLE   =  0.00704 KJ

"LOST" FUEL ENERGY           =  0.00000 KJ

NET ENERGY GAIN / CYCLE      = -0.00048 KJ

(ENERGY GAIN)/(ENTHALPY IN) = -0.33137 %

(ENERGY GAIN)/(MFUEL*LHV)    =  0.00000 %
```

LEAKAGE AND CREVICE VOLUME DATA

CA (DEG)	CHAMBER MASS (G)	LEAD CREVICE MASS (G)	LAG CREVICE MASS (G)	LEAD LEAKAGE MASS ( )	LAG LEAKAGE MASS ( )	LEAD CREVICE COMPOSITION	LAG CREVICE COMPOSITION
-520.0	0.0791	0.000000	0.000882	-0.000243	0.000150	0.000000	1.000000
-510.0	0.0857	0.000000	0.000842	-0.000525	0.000296	0.000000	1.000000
-502.4	0.0930	0.000000	0.000817	-0.000764	0.000394	0.000000	1.000000
-500.0	0.0961	0.000000	0.000816	-0.000843	0.000422	0.000000	1.000000
-490.0	0.1105	0.000000	0.000802	-0.001201	0.000521	0.000000	1.000000
-484.6	0.1200	0.000000	0.000802	-0.001413	0.000553	0.000000	1.000000
-480.0	0.1294	0.000000	0.000000	-0.001608	0.000545	0.000000	0.000000
-470.0	0.1525	0.000000	0.000000	-0.002076	0.000465	0.000000	0.000000
-460.0	0.1782	0.000000	0.000000	-0.002618	0.000357	0.000000	0.000000
-450.0	0.2064	0.000000	0.000000	-0.003255	0.000245	0.000000	0.000000
-440.0	0.2363	0.000000	0.000000	-0.004009	0.000133	0.000000	0.000000
-430.0	0.2679	0.000000	0.000000	-0.004911	0.000020	0.000000	0.000000
-420.0	0.3006	0.000000	0.000000	-0.005995	-0.000094	0.000000	0.000000
-410.0	0.3341	0.000000	0.000000	-0.007302	-0.000210	0.000000	0.000000
-400.0	0.3673	0.000000	0.000000	-0.008868	-0.000328	0.000000	0.000000
-390.0	0.4003	0.000000	0.000000	-0.010714	-0.000450	0.000000	0.000000
-380.0	0.4326	0.000000	0.000000	-0.012824	-0.000574	0.000000	0.000000
-370.0	0.4638	0.000000	0.000000	-0.015124	-0.000701	0.000000	0.000000
-360.0	0.4935	0.000000	0.000000	-0.017236	-0.000831	0.000000	0.000000
-350.0	0.5206	0.000000	0.000000	-0.019478	-0.000965	0.000000	0.000000
-340.0	0.5457	0.000000	0.000000	-0.021473	-0.001100	0.000000	0.000000
-330.0	0.5682	0.000000	0.000000	-0.023158	-0.001238	0.000000	0.000000
-320.0	0.5876	0.000000	0.000000	-0.024530	-0.001378	0.000000	0.000000
-310.0	0.6039	0.000000	0.000000	-0.025629	-0.001518	0.000000	0.000000
-300.0	0.6165	0.000000	0.000000	-0.026508	-0.001658	0.000000	0.000000
-290.0	0.6256	0.000000	0.000000	-0.027214	-0.001797	0.000000	0.000000
-280.0	0.6308	0.000000	0.000000	-0.027788	-0.001933	0.000000	0.000000
-277.8	0.6317	0.000000	0.000000	-0.027898	-0.001962	0.000000	0.000000
-273.4	0.6316	0.000000	0.000000	-0.028108	-0.002021	0.000000	0.000000
-270.0	0.6316	0.000000	0.000000	-0.028261	-0.002066	0.000000	0.000000
-260.0	0.6293	0.000000	0.000000	-0.028657	-0.002196	0.000000	0.000000
-250.0	0.6248	0.000000	0.000000	-0.028994	-0.002321	0.000000	0.000000
-240.0	0.6195	0.000000	0.000000	-0.029284	-0.002438	0.000000	0.000000
-230.0	0.6164	0.000000	0.000000	-0.029527	-0.002542	0.000000	0.000000
-220.0	0.6157	0.000000	0.000000	-0.029719	-0.002619	0.000000	0.000000
-210.0	0.6156	0.000000	0.000930	-0.029841	-0.002608	0.000000	1.000000
-200.0	0.6153	0.000984	0.000984	-0.029787	-0.002516	1.000000	1.000000
-190.0	0.6149	0.001050	0.001050	-0.029632	-0.002382	1.000000	1.000000
-180.0	0.6143	0.001129	0.001129	-0.029433	-0.002211	1.000000	1.000000

-170.0	0.6137	0.001225	0.001225	-0.029201	-0.002005	1.000000	1.000000
-160.0	0.6130	0.001342	0.001342	-0.028944	-0.001764	1.000000	1.000000
-150.0	0.6121	0.001483	0.001483	-0.028659	-0.001484	1.000000	1.000000
-140.0	0.6111	0.001655	0.001655	-0.028343	-0.001169	1.000000	1.000000
-130.0	0.6100	0.001866	0.001866	-0.027989	-0.000814	1.000000	1.000000
-120.0	0.6087	0.002125	0.002125	-0.027588	-0.000413	1.000000	1.000000
-110.0	0.6071	0.002444	0.002444	-0.027128	0.000047	1.000000	1.000000
-100.0	0.6053	0.002840	0.002840	-0.026597	0.000578	1.000000	1.000000
-90.0	0.6031	0.003332	0.003332	-0.025976	0.001199	1.000000	1.000000
-80.0	0.6004	0.003943	0.003943	-0.025245	0.001930	1.000000	1.000000
-70.0	0.5971	0.004695	0.004695	-0.024376	0.002798	1.000000	1.000000
-60.0	0.5932	0.005610	0.005610	-0.023340	0.003835	1.000000	1.000000
-50.0	0.5886	0.006683	0.006683	-0.022103	0.005072	1.000000	1.000000
-40.0	0.5833	0.007868	0.007868	-0.020637	0.006538	1.000000	1.000000
-30.0	0.5775	0.009047	0.009047	-0.018930	0.008245	1.000000	1.000000
-20.0	0.5718	0.010005	0.010005	-0.017003	0.010172	1.000000	1.000000
-10.0	0.5667	0.010475	0.010475	-0.014928	0.012247	1.000000	1.000000
-7.9	0.5658	0.010490	0.010490	-0.014491	0.012684	1.000000	1.000000
0.0	0.5629	0.010263	0.010263	-0.012825	0.014350	1.000000	1.000000
10.0	0.5606	0.009397	0.009397	-0.010833	0.016342	1.000000	1.000000
20.0	0.5597	0.008112	0.008112	-0.009063	0.018112	1.000000	1.000000
30.0	0.5595	0.006710	0.006710	-0.007569	0.019606	1.000000	1.000000
40.0	0.5596	0.005417	0.005417	-0.006349	0.020826	1.000000	1.000000
50.0	0.5598	0.004335	0.004335	-0.005370	0.021805	1.000000	1.000000
60.0	0.5600	0.003476	0.003476	-0.004586	0.022589	1.000000	1.000000
70.0	0.5600	0.002813	0.002813	-0.003954	0.023220	1.000000	1.000000
80.0	0.5600	0.002306	0.002306	-0.003440	0.023734	1.000000	1.000000
90.0	0.5600	0.001919	0.001919	-0.003016	0.024159	1.000000	1.000000
100.0	0.5598	0.001621	0.001621	-0.002661	0.024514	1.000000	1.000000
110.0	0.5597	0.001390	0.001390	-0.002364	0.024816	1.000000	1.000000
120.0	0.5596	0.001210	0.001210	-0.002124	0.025070	1.000000	1.000000
130.0	0.5595	0.001068	0.001068	-0.001939	0.025274	1.000000	1.000000
140.0	0.5594	0.000955	0.000955	-0.001816	0.025417	1.000000	1.000000
150.0	0.5595	0.000000	0.000000	-0.001790	0.025445	0.000000	0.000000
160.0	0.5598	0.000000	0.000000	-0.001916	0.025280	0.000000	0.000000
170.0	0.5601	0.000000	0.000000	-0.002047	0.025101	0.000000	0.000000
180.0	0.5604	0.000000	0.000000	-0.002197	0.024889	0.000000	0.000000
190.0	0.5608	0.000653	0.000000	-0.002357	0.024653	1.000000	0.000000

200.0	0.5614	0.000000	0.000000	-0.002522	0.024395	0.000000	0.000000
210.0	0.5746	0.000000	0.000000	-0.002682	0.024111	0.000000	0.000000
220.0	0.6083	0.000000	0.000000	-0.002824	0.023795	0.000000	0.000000
230.0	0.6587	0.000000	0.000000	-0.002946	0.023440	0.000000	0.000000
240.0	0.7173	0.000000	0.000000	-0.002948	0.023039	0.000000	0.000000
250.0	0.7643	0.000857	0.000000	-0.002901	0.022579	1.000000	0.000000
260.0	0.7886	0.000892	0.000000	-0.002800	0.022048	1.000000	0.000000
270.0	0.7887	0.000897	0.000000	-0.002689	0.021427	1.000000	0.000000
280.0	0.7825	0.000899	0.000000	-0.002576	0.020696	1.000000	0.000000
290.0	0.7723	0.000901	0.000000	-0.002463	0.019828	1.000000	0.000000
300.0	0.7584	0.000905	0.000000	-0.002349	0.018792	1.000000	0.000000
310.0	0.7407	0.000909	0.000000	-0.002233	0.017555	1.000000	0.000000
320.0	0.7195	0.000915	0.000000	-0.002114	0.016089	1.000000	0.000000
330.0	0.6949	0.000921	0.000000	-0.001992	0.014382	1.000000	0.000000
340.0	0.6670	0.000927	0.000000	-0.001867	0.012455	1.000000	0.000000
350.0	0.6361	0.000934	0.000000	-0.001738	0.010380	1.000000	0.000000
360.0	0.6023	0.000940	0.000000	-0.001607	0.008276	1.000000	0.000000
370.0	0.5660	0.000946	0.000000	-0.001472	0.006284	1.000000	0.000000
380.0	0.5275	0.000951	0.000000	-0.001334	0.004514	1.000000	0.000000
390.0	0.4874	0.000954	0.000000	-0.001195	0.003020	1.000000	0.000000
400.0	0.4461	0.000956	0.000000	-0.001054	0.001800	1.000000	0.000000
410.0	0.4043	0.000956	0.000000	-0.000914	0.000821	1.000000	0.000000
420.0	0.3627	0.000954	0.000000	-0.000774	0.000037	1.000000	0.000000
430.0	0.3219	0.000951	0.000000	-0.000635	-0.000594	1.000000	0.000000
440.0	0.2825	0.000946	0.000000	-0.000499	-0.001108	1.000000	0.000000
450.0	0.2452	0.000940	0.000000	-0.000365	-0.001533	1.000000	0.000000
460.0	0.2107	0.000933	0.000000	-0.000236	-0.001888	1.000000	0.000000
470.0	0.1794	0.000926	0.000000	-0.000112	-0.002185	1.000000	0.000000
480.0	0.1516	0.000918	0.000000	0.000005	-0.002425	1.000000	0.000000
490.0	0.1278	0.000911	0.000000	0.000108	-0.002610	1.000000	0.000000
500.0	0.1083	0.000907	0.000000	0.000185	-0.002733	1.000000	0.000000
510.0	0.0928	0.000000	0.000903	0.000176	-0.002740	0.000000	1.000000
520.0	0.0816	0.000000	0.000899	0.000084	-0.002639	0.000000	1.000000
530.0	0.0748	0.000000	0.000897	-0.000051	-0.002507	0.000000	1.000000
540.0	0.0722	0.000000	0.000897	-0.000222	-0.002357	0.000000	1.000000
550.0	0.0739	0.000000	0.000896	-0.000428	-0.002197	0.000000	1.000000

HEAT TRANSFER DATA

CA (DEG)	VELHTX (CM/SEC)	HTPARO (KW/M**2)	HTPASI (KW/M**2)	HTPAHO (KW/M**2)	Q% ROTOR (%)	Q% SIDE (%)	Q% HOUSING (%)
-520.0	564.1	-5059139.0	-5059139.0	-5059139.0	43.831	3.556	52.613
-510.0	564.1	-6018203.0	-6018203.0	-6018203.0	43.160	4.320	52.520
-502.4	564.1	-6453169.0	-6453169.0	-6453169.0	42.499	5.074	52.427
-500.0	564.1	-6314220.0	-6314220.0	-6314220.0	42.267	5.338	52.395
-490.0	564.1	-6184264.0	-6184264.0	-6184264.0	41.191	6.564	52.245
-484.6	564.1	-5859177.0	-5859177.0	-5859177.0	40.555	7.289	52.156
-480.0	564.1	-6162520.0	-6162520.0	-6162520.0	39.976	7.949	52.075
-470.0	564.1	-6922887.0	-6922887.0	-6922887.0	38.665	9.443	51.892
-460.0	564.1	-7534995.0	-7534995.0	-7534995.0	37.299	10.999	51.702
-450.0	564.1	-7996087.0	-7996087.0	-7996087.0	35.916	12.576	51.508
-440.0	564.1	-8389617.0	-8389617.0	-8389617.0	34.546	14.137	51.317
-430.0	564.1	-8682727.0	-8682727.0	-8682727.0	33.213	15.656	51.131
-420.0	564.1	-8909711.0	-8909711.0	-8909711.0	31.937	17.110	50.953
-410.0	564.1	-9043981.0	-9043981.0	-9043981.0	30.732	18.483	50.785
-400.0	564.1	-9177048.0	-9177048.0	-9177048.0	29.608	19.764	50.628
-390.0	564.1	-9244900.0	-9244900.0	-9244900.0	28.569	20.948	50.483
-380.0	564.1	-9263492.0	-9263492.0	-9263492.0	27.620	22.029	50.350
-370.0	564.1	-9235696.0	-9235696.0	-9235696.0	26.762	23.008	50.231
-360.0	564.1	-9174860.0	-9174860.0	-9174860.0	25.993	23.883	50.123
-350.0	564.1	-9126136.0	-9126136.0	-9126136.0	25.314	24.658	50.029
-340.0	564.1	-9030477.0	-9030477.0	-9030477.0	24.721	25.333	49.946
-330.0	564.1	-8906449.0	-8906449.0	-8906449.0	24.214	25.911	49.875
-320.0	564.1	-8759863.0	-8759863.0	-8759863.0	23.788	26.396	49.816
-310.0	564.1	-8581991.0	-8581991.0	-8581991.0	23.444	26.789	49.767
-300.0	564.1	-8388633.0	-8388633.0	-8388633.0	23.178	27.092	49.730
-290.0	564.1	-8151094.0	-8151094.0	-8151094.0	22.989	27.307	49.704
-280.0	564.1	-7880011.0	-7880011.0	-7880011.0	22.876	27.436	49.688
-277.8	564.1	-7800075.0	-7800075.0	-7800075.0	22.862	27.452	49.686
-273.4	564.1	-7714181.0	-7714181.0	-7714181.0	22.843	27.473	49.684
-270.0	564.1	-7608773.0	-7608773.0	-7608773.0	22.839	27.478	49.683
-260.0	564.1	-7288764.0	-7288764.0	-7288764.0	22.876	27.436	49.688
-250.0	564.1	-6862094.0	-6862094.0	-6862094.0	22.989	27.307	49.704
-240.0	564.1	-6218656.0	-6218656.0	-6218656.0	23.178	27.092	49.730
-230.0	564.1	-5102061.0	-5102061.0	-5102061.0	23.444	26.789	49.767
-220.0	564.1	-3442358.0	-3442358.0	-3442358.0	23.789	26.396	49.816
-210.0	564.1	-1340632.0	-1340632.0	-1340632.0	24.214	25.911	49.875
-200.0	564.1	1224533.0	1224533.0	1224533.0	24.721	25.333	49.946
-190.0	564.1	4353339.0	4353339.0	4353339.0	25.314	24.658	50.028
-180.0	564.1	8179467.0	8179467.0	8179467.0	25.993	23.883	50.123

-170.0	564.1	12870825.0	12870825.0	12870825.0	26.762	23.008	50.231
-160.0	564.1	18643696.0	18643696.0	18643696.0	27.620	22.029	50.350
-150.0	564.1	25776912.0	25776912.0	25776912.0	28.569	20.948	50.483
-140.0	564.1	34629392.0	34629392.0	34629392.0	29.608	19.764	50.628
-130.0	564.1	45662688.0	45662688.0	45662688.0	30.732	18.483	50.785
-120.0	564.1	59461360.0	59461360.0	59461360.0	31.937	17.110	50.953
-110.0	564.1	76761136.0	76761136.0	76761136.0	33.213	15.656	51.131
-100.0	564.1	98462144.0	98462144.0	98462144.0	34.546	14.137	51.317
-90.0	564.1	125611712.0	125611712.0	125611712.0	35.916	12.576	51.508
-80.0	564.1	159318048.0	159318048.0	159318048.0	37.299	10.999	51.702
-70.0	564.1	200505376.0	200505376.0	200505376.0	38.665	9.443	51.892
-60.0	564.1	249661104.0	249661104.0	249661104.0	39.976	7.949	52.075
-50.0	564.1	305065216.0	305065216.0	305065216.0	41.191	6.564	52.245
-40.0	564.1	361635584.0	361635584.0	361635584.0	42.267	5.338	52.395
-30.0	564.1	409966080.0	409966080.0	409966080.0	43.160	4.320	52.520
-20.0	564.1	436080384.0	436080384.0	436080384.0	43.831	3.556	52.613
-10.0	564.1	426039552.0	426039552.0	426039552.0	44.247	3.082	52.671
-7.9	564.1	418727424.0	418727424.0	418727424.0	44.299	3.022	52.679
0.0	564.1	374782464.0	374782464.0	374782464.0	44.388	2.921	52.691
10.0	564.1	293739264.0	293739264.0	293739264.0	44.247	3.082	52.671
20.0	564.1	202832752.0	202832752.0	202832752.0	43.831	3.556	52.613
30.0	564.1	120465424.0	120465424.0	120465424.0	43.160	4.320	52.520
40.0	564.1	56096240.0	56096240.0	56096240.0	42.267	5.338	52.395
50.0	564.1	10708911.0	10708911.0	10708911.0	41.191	6.564	52.245
60.0	564.1	-19016128.0	-19016128.0	-19016128.0	39.976	7.949	52.075
70.0	564.1	-37354928.0	-37354928.0	-37354928.0	38.665	9.443	51.892
80.0	564.1	-47979280.0	-47979280.0	-47979280.0	37.299	10.999	51.702
90.0	564.1	-53587040.0	-53587040.0	-53587040.0	35.916	12.576	51.508
100.0	564.1	-56024208.0	-56024208.0	-56024208.0	34.546	14.137	51.317
110.0	564.1	-56503776.0	-56503776.0	-56503776.0	33.213	15.656	51.131
120.0	564.1	-55806512.0	-55806512.0	-55806512.0	31.937	17.110	50.953
130.0	564.1	-54430048.0	-54430048.0	-54430048.0	30.732	18.483	50.785
140.0	564.1	-52686608.0	-52686608.0	-52686608.0	29.608	19.764	50.628
150.0	564.1	-50765264.0	-50765264.0	-50765264.0	28.569	20.948	50.483
160.0	564.1	-48779344.0	-48779344.0	-48779344.0	27.620	22.029	50.350
170.0	564.1	-46814512.0	-46814512.0	-46814512.0	26.762	23.008	50.231
180.0	564.1	-44912752.0	-44912752.0	-44912752.0	25.993	23.883	50.123
190.0	564.1	-43095360.0	-43095360.0	-43095360.0	25.314	24.658	50.028

200.0	564.1	-41370096.0	-41370096.0	-41370096.0	24.721	25.333	49.946
210.0	564.1	-39704304.0	-39704304.0	-39704304.0	24.214	25.911	49.875
220.0	564.1	-37973472.0	-37973472.0	-37973472.0	23.789	26.396	49.816
230.0	564.1	-35949264.0	-35949264.0	-35949264.0	23.444	26.789	49.767
240.0	564.1	-33516192.0	-33516192.0	-33516192.0	23.178	27.092	49.730
250.0	564.1	-31117408.0	-31117408.0	-31117408.0	22.989	27.307	49.704
260.0	564.1	-29266384.0	-29266384.0	-29266384.0	22.876	27.436	49.688
270.0	564.1	-28153088.0	-28153088.0	-28153088.0	22.839	27.478	49.683
280.0	564.1	-27137568.0	-27137568.0	-27137568.0	22.876	27.436	49.688
290.0	564.1	-26124288.0	-26124288.0	-26124288.0	22.989	27.307	49.704
300.0	564.1	-25109072.0	-25109072.0	-25109072.0	23.178	27.092	49.730
310.0	564.1	-24088992.0	-24088992.0	-24088992.0	23.444	26.789	49.767
320.0	564.1	-23062368.0	-23062368.0	-23062368.0	23.788	26.396	49.816
330.0	564.1	-22029664.0	-22029664.0	-22029664.0	24.214	25.911	49.875
340.0	564.1	-20995408.0	-20995408.0	-20995408.0	24.721	25.333	49.946
350.0	564.1	-19968576.0	-19968576.0	-19968576.0	25.314	24.658	50.029
360.0	564.1	-18963264.0	-18963264.0	-18963264.0	25.993	23.883	50.123
370.0	564.1	-17994576.0	-17994576.0	-17994576.0	26.762	23.008	50.231
380.0	564.1	-17077344.0	-17077344.0	-17077344.0	27.620	22.029	50.350
390.0	564.1	-16219000.0	-16219000.0	-16219000.0	28.569	20.948	50.483
400.0	564.1	-15423043.0	-15423043.0	-15423043.0	29.608	19.764	50.628
410.0	564.1	-14691016.0	-14691016.0	-14691016.0	30.732	18.483	50.785
420.0	564.1	-14019017.0	-14019017.0	-14019017.0	31.937	17.110	50.953
430.0	564.1	-13399150.0	-13399150.0	-13399150.0	33.213	15.656	51.131
440.0	564.1	-12819410.0	-12819410.0	-12819410.0	34.546	14.137	51.317
450.0	564.1	-12260011.0	-12260011.0	-12260011.0	35.916	12.576	51.508
460.0	564.1	-11693709.0	-11693709.0	-11693709.0	37.299	10.999	51.702
470.0	564.1	-11092387.0	-11092387.0	-11092387.0	38.665	9.443	51.892
480.0	564.1	-10461035.0	-10461035.0	-10461035.0	39.976	7.949	52.075
490.0	564.1	-9754812.0	-9754812.0	-9754812.0	41.191	6.564	52.245
500.0	564.1	-8860437.0	-8860437.0	-8860437.0	42.267	5.338	52.395
510.0	564.1	-7973377.0	-7973377.0	-7973377.0	43.160	4.320	52.520
520.0	564.1	-7057017.0	-7057017.0	-7057017.0	43.831	3.556	52.613
530.0	564.1	-6119823.0	-6119823.0	-6119823.0	44.247	3.082	52.671
540.0	564.1	-5217056.0	-5217056.0	-5217056.0	44.388	2.921	52.691
550.0	564.1	-4458532.	-4458532.0	-4458532.0	44.247	3.082	52.671

SAMPLE FIRING OUTPUT

```
---------------------------------------------------------------------------
---------------------------------------------------------------------------

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

---------------------------------------------------------------------------
---------------------------------------------------------------------------

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

---------------------------------------------------------------------------

 >>>>> OPERATING MODE

         FIRING CYCLE

         SPECIFIED BURN RATE

            BURN DURATION    =   90.000 DEG CA
            WIEBE CONSTANT   =    5.000
            WIEBE EXPONENT   =    1.500

---------------------------------------------------------------------------

 >>>>> OPERATING CONDITIONS

         FUEL USED IS ISOOCTANE

         F/A EQUIVALENCE RATIO =     1.000

         SPARK TIMING          =   -30.00 DEG CA

         ENGINE SPEED          =  3000.0 RPM
```

```
>>>>> MANIFOLD CONDITIONS

          INTAKE MANIFOLD PRESSURE   =     0.9800 ATM
          EXHAUST MANIFOLD PRESSURE =     1.0200 ATM
          FRESH CHARGE TEMPERATURE   =   300.00   K
          EXHAUST GAS RECIRCULATION =     0.00   %
          EGR TEMPERATURE            =   300.00   K
          INTAKE CHARGE TEMPERATURE =   300.00   K
          ATMOSPHERIC PRESSURE       =     1.0000 ATM
          ATMOSPHERIC TEMPERATURE    =   300.00   K

>>>>> HEAT TRANSFER AND TURBULENCE PARAMETERS

          HEAT TRANSFER CONSTANT         =      0.0350
          HEAT TRANSFER EXPONENT         =      0.8000
          ROTOR TEMPERATURE              =    370.00    K
          SIDE WALL TEMPERATURE          =    370.00    K
          HOUSING WALL TEMPERATURE       =    370.00    K

>>>>> ENGINE DESIGN PARAMETERS

          ECCENTRICITY OF ROTOR   =     1.500 CM
          RADIUS OF ROTOR         =    10.500 CM
          DEPTH OF CHAMBER        =     7.000 CM
          COMPRESSION RATIO       =     9.407
          DISPLACED VOLUME        =   572.875 CC
```

```
          VOLUME OF ROTOR POCKET  =    35.000 CC

          INTAKE PORT OPENS      =  -530.0   DEG CA

          INTAKE PORT CLOSES     =  -180.0   DEG CA

          EXHAUST PORT OPENS     =   199.0   DEG CA

          EXHAUST PORT CLOSES    =   588.5   DEG CA
```

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

          LEAK AREA PER APEX     =     0.010000  CM*CM

          CREVICE VOLUME PER APEX=     0.875000  CC

          CREVICE GAS TEMPERATURE=   370.000000  K
```

```
>>>>> COMPUTATIONAL PARAMETERS

          MAXIMUM # OF ITERATIONS =      3

          OUTPUT AT ITERATION #   =      3

          TPRINT                  =     10.00
          TPRINX                  =      1.00
          XBZERO                  =      0.00030
          XESTOP                  =      0.00000
          XBSTOP                  =      0.99500
          CIINTG                  =      0.000100
          CCINTG                  =      0.000100
          CBINTG                  =      0.000050
          CEINTG                  =      0.000100
          AREROT                  =      0.000200
          REL                     =      0.000200
          ERMAX                   =      0.000000
          MAXERR                  =      0.030000
          MAXTRY                  =      2
```

```
>>>>> START OF INTAKE PROCESS

   CA        P         TEMP      MIN        MEX          VIV        VEV         X1        Q DOT        WORK      IMF   IFG
  (DEG)    (ATM)       (K)       (G)        (G)       (CM/SEC)   (CM/SEC)     (-)      (KJ/DEG)      (KJ)
--------------------------------------------------------------------------------------------------------------------------
 -530.0   1.0198     871.27   0.00000    0.00000        0.0                0.00000                0.000000
 -520.0   1.0092     851.10  -0.00125   -0.00336    -8820.2    -4728.4    0.01106    0.000029    0.000595     0     2
 -510.0   0.9847     830.53  -0.00376   -0.00917    -3571.3    -8531.4    0.02064    0.000028    0.001559     0     2
 -505.8   0.9798     823.76  -0.00408   -0.01147      702.7    -9076.9    0.02428    0.000028    0.002068     0     8
 -500.0   0.9755     815.63  -0.00316   -0.01376     3523.3    -9527.2    0.02893    0.000028    0.002868     0     2
 -492.9   0.9658     805.91  -0.00000   -0.01507     6222.7   -10493.0    0.03413    0.000028    0.003998     0     8
 -490.0   0.9516     775.32   0.00326   -0.01511     5103.4        0.0    0.08742    0.000026    0.004501     1     2
 -480.0   0.9371     635.90   0.02393   -0.01511     6217.7        0.0    0.35817    0.000020    0.006397     1     2
 -470.0   0.9397     547.43   0.04991   -0.01511     6037.6        0.0    0.53119    0.000015    0.008570     1     2
 -460.0   0.9432     490.67   0.07938   -0.01511     5778.4        0.0    0.64043    0.000011    0.011004     1     2
 -450.0   0.9474     452.71   0.11177   -0.01511     5451.3        0.0    0.71344    0.000009    0.013670     1     2
 -440.0   0.9510     426.05   0.14645   -0.01511     5152.4        0.0    0.76448    0.000006    0.016533     1     2
 -430.0   0.9543     406.65   0.18296   -0.01511     4861.0        0.0    0.80159    0.000004    0.019554     1     2
 -420.0   0.9579     392.15   0.22091   -0.01511     4518.3        0.0    0.82946    0.000003    0.022694     1     2
 -410.0   0.9615     381.09   0.25966   -0.01511     4142.8        0.0    0.85079    0.000001    0.025910     1     2
 -400.0   0.9619     372.43   0.29759   -0.01511     4091.8        0.0    0.86699    0.000000    0.029156     1     2
 -390.0   0.9626     365.62   0.33504   -0.01511     4019.5        0.0    0.87981   -0.000001    0.032381     1     2
 -380.0   0.9637     360.23   0.37159   -0.01511     3886.4        0.0    0.89011   -0.000002    0.035544     1     2
 -370.0   0.9656     356.02   0.40653   -0.01511     3665.1        0.0    0.89841   -0.000002    0.038604     1     2
 -360.0   0.9680     352.79   0.43892   -0.01511     3352.9        0.0    0.90486   -0.000003    0.041520     1     2
 -350.0   0.9696     350.32   0.46756   -0.01511     3119.8        0.0    0.90931   -0.000003    0.044252     1     2
 -340.0   0.9707     348.45   0.49241   -0.01511     2953.8        0.0    0.91193   -0.000004    0.046760     1     2
 -330.0   0.9719     347.05   0.51402   -0.01511     2750.0        0.0    0.91327   -0.000004    0.049010     1     2
 -320.0   0.9730     345.98   0.53241   -0.01511     2566.1        0.0    0.91392   -0.000004    0.050969     1     2
 -310.0   0.9743     345.21   0.54781   -0.01511     2319.2        0.0    0.91431   -0.000005    0.052612     1     2
 -300.0   0.9761     344.72   0.56019   -0.01511     1923.9        0.0    0.91453   -0.000005    0.053915     1     2
 -290.0   0.9776     344.46   0.56884   -0.01511     1497.6        0.0    0.91449   -0.000005    0.054860     1     2
 -280.0   0.9799     344.46   0.57409   -0.01511      234.6        0.0    0.91420   -0.000005    0.055433     1     2
 -277.3   0.9801     344.50   0.57452   -0.01511     -389.2        0.0    0.91403   -0.000005    0.055523     1     8
 -270.0   0.9804     344.66   0.57402   -0.01511     -625.9        0.0    0.91344   -0.000005    0.055626     0     2
 -260.0   0.9828     345.01   0.57133   -0.01511    -1753.5        0.0    0.91276   -0.000005    0.055433     0     2
 -250.0   0.9895     345.73   0.56695   -0.01511    -3191.0        0.0    0.91218   -0.000005    0.054855     0     2
 -240.0   1.0030     347.05   0.56212   -0.01511    -4907.7        0.0    0.91168   -0.000004    0.053891     0     2
 -230.0   1.0293     349.47   0.55949   -0.01511    -7020.5        0.0    0.91125   -0.000004    0.052534     0     2
 -220.0   1.0690     352.96   0.55879   -0.01511    -9104.5        0.0    0.91090   -0.000003    0.050764     0     2
 -210.0   1.1206     357.32   0.55862   -0.01511   -10950.4        0.0    0.91058   -0.000003    0.048558     0     2
 -200.0   1.1850     362.52   0.55859   -0.01511   -12549.1        0.0    0.91028   -0.000002    0.045889     0     2
 -190.0   1.2642     368.59   0.55858   -0.01511   -13904.5        0.0    0.90998   -0.000000    0.042725     0     2
 -180.0   1.3610     375.59   0.55858   -0.01511        0.0        0.0    0.90968    0.000001    0.039026     0     2
 -180.0   1.3610     375.59   0.55858   -0.01511        0.0        0.0    0.90968    0.000001    0.039026     0     2
--------------------------------------------------------------------------------------------------------------------------
```

```
>>>>> START OF COMPRESSION PROCESS

   CA        P        TEMP                                                        Q DOT       WORK         IFG
 (DEG)     (ATM)      (K)                                                       (KJ/DEG)      (KJ)

-180.0    1.3610     375.59                                                     0.000001    0.039026        2
-170.0    1.4790     383.60                                                     0.000003    0.034747        2
-160.0    1.6231     392.69                                                     0.000005    0.029834        2
-150.0    1.7994     402.96                                                     0.000008    0.024223        2
-140.0    2.0160     414.52                                                     0.000011    0.017840        2
-130.0    2.2835     427.49                                                     0.000015    0.010600        2
-120.0    2.6142     441.93                                                     0.000019    0.002412        2
-110.0    3.0252     457.96                                                     0.000025   -0.006820        2
-100.0    3.5418     475.75                                                     0.000032   -0.017197        2
 -90.0    4.1946     495.42                                                     0.000041   -0.028815        2
 -80.0    5.0235     517.19                                                     0.000052   -0.041751        2
 -70.0    6.0720     540.81                                                     0.000066   -0.056021        2
 -60.0    7.3831     565.81                                                     0.000084   -0.071517        2
 -50.0    8.9851     591.54                                                     0.000105   -0.087921        2
 -40.0   10.8563     616.84                                                     0.000130   -0.104577        2
 -30.0   12.8713     639.82                                                     0.000156   -0.120372        2
```

```
>>>>> START OF COMBUSTION AND EXPANSION PROCESSES

  CA       P                 TB        TU           XBURND          Q DOT         WORK         IFG
 (DEG)   (ATM)               (K)       (K)           (-)          (KJ/DEG)        (KJ)

-30.0   12.8716            2373.61   639.27        0.00030        0.000156    -0.120372        2
-29.0   13.0745            2353.29   641.38        0.00037        0.000168    -0.121846        2
-28.0   13.2872            2349.54   643.57        0.00067        0.000176    -0.123295        2
-27.0   13.5147            2353.19   645.89        0.00131        0.000188    -0.124719        2
-26.0   13.7606            2357.54   648.37        0.00238        0.000203    -0.126116        2
-25.0   14.0283            2361.65   651.04        0.00393        0.000221    -0.127488        2
-24.0   14.3206            2365.70   653.93        0.00602        0.000241    -0.128833        2
-23.0   14.6400            2369.88   657.04        0.00870        0.000264    -0.130154        2
-22.0   14.9886            2374.30   660.38        0.01201        0.000289    -0.131448        2
-21.0   15.3683            2378.99   663.97        0.01599        0.000317    -0.132717        2
-20.0   15.7807            2383.97   667.79        0.02067        0.000347    -0.133959        2
-19.0   16.2269            2389.24   671.83        0.02607        0.000379    -0.135174        2
-18.0   16.7077            2394.78   676.11        0.03224        0.000415    -0.136362        2
-17.0   17.2237            2400.56   680.58        0.03917        0.000452    -0.137520        2
-16.0   17.7750            2406.55   685.25        0.04690        0.000492    -0.138647        2
-15.0   18.3612            2412.72   690.08        0.05542        0.000536    -0.139741        2
-14.0   18.9819            2419.03   695.06        0.06476        0.000581    -0.140800        2
-13.0   19.6361            2425.43   700.17        0.07490        0.000630    -0.141820        2
-12.0   20.3221            2431.88   705.37        0.08586        0.000682    -0.142797        2
-11.0   21.0386            2438.35   710.65        0.09762        0.000736    -0.143728        2
-10.0   21.7831            2444.77   715.97        0.11018        0.000794    -0.144609        2
 -9.0   22.5533            2451.13   721.31        0.12352        0.000854    -0.145435        2
 -8.0   23.3467            2457.37   726.64        0.13762        0.000917    -0.146200        2
 -7.0   24.1600            2463.47   731.94        0.15247        0.000983    -0.146898        2
 -6.0   24.9900            2469.38   737.19        0.16804        0.001052    -0.147525        2
 -5.0   25.8336            2475.10   742.36        0.18430        0.001123    -0.148074        2
 -4.0   26.6866            2480.57   747.43        0.20121        0.001196    -0.148538        2
 -3.0   27.5456            2485.79   752.38        0.21875        0.001272    -0.148910        2
 -2.0   28.4066            2490.73   757.20        0.23687        0.001349    -0.149135        2
 -1.0   29.2656            2495.37   761.86        0.25553        0.001429    -0.149354        2
  0.0   30.1188            2499.69   766.35        0.27470        0.001509    -0.149412        2
  1.0   30.9622            2503.69   770.66        0.29431        0.001591    -0.149352        2
  2.0   31.7919            2507.35   774.77        0.31432        0.001674    -0.149167        2
  3.0   32.6040            2510.66   778.68        0.33469        0.001757    -0.148850        2
  4.0   33.3951            2513.62   782.38        0.35536        0.001840    -0.148396        2
  5.0   34.1616            2516.22   785.85        0.37627        0.001923    -0.147799        2
  6.0   34.9000            2518.46   789.09        0.39738        0.002006    -0.147053        2
  7.0   35.6074            2520.33   792.10        0.41862        0.002088    -0.146153        2
  8.0   36.2808            2521.84   794.87        0.43995        0.002168    -0.145095        2
  9.0   36.9177            2522.98   797.40        0.46131        0.002247    -0.143874        2
```

10.0	37.5156	2523.75	799.68	0.48264	0.002324	-0.142488	2
11.0	38.0726	2524.16	801.72	0.50390	0.002398	-0.140932	2
12.0	38.5867	2524.20	803.51	0.52502	0.002470	-0.139205	2
13.0	39.0566	2523.89	805.06	0.54597	0.002540	-0.137304	2
14.0	39.4810	2523.23	806.36	0.56668	0.002605	-0.135230	2
15.0	39.8590	2522.22	807.43	0.58712	0.002668	-0.132980	2
16.0	40.1900	2520.86	808.25	0.60725	0.002727	-0.130555	2
17.0	40.4736	2519.16	808.84	0.62701	0.002782	-0.127956	2
18.0	40.7097	2517.13	809.19	0.64637	0.002833	-0.125184	2
19.0	40.8984	2514.78	809.31	0.66529	0.002880	-0.122240	2
20.0	41.0403	2512.10	809.21	0.68374	0.002922	-0.119127	2
21.0	41.1359	2509.10	808.89	0.70169	0.002960	-0.115849	2
22.0	41.1860	2505.80	808.36	0.71911	0.002994	-0.112407	2
23.0	41.1917	2502.20	807.61	0.73599	0.003023	-0.108807	2
24.0	41.1542	2498.30	806.66	0.75229	0.003047	-0.105052	2
25.0	41.0749	2494.11	805.52	0.76800	0.003067	-0.101147	2
26.0	40.9552	2489.64	804.18	0.78311	0.003082	-0.097097	2
27.0	40.7969	2484.90	802.65	0.79761	0.003093	-0.092908	2
28.0	40.6015	2479.89	800.94	0.81149	0.003099	-0.088584	2
29.0	40.3710	2474.62	799.06	0.82474	0.003102	-0.084133	2
30.0	40.1073	2469.09	797.01	0.83737	0.003100	-0.079559	2
31.0	39.8122	2463.33	794.80	0.84938	0.003094	-0.074870	2
32.0	39.4877	2457.32	792.43	0.86077	0.003084	-0.070072	2
33.0	39.1359	2451.09	789.92	0.87154	0.003070	-0.065170	2
34.0	38.7588	2444.64	787.26	0.88172	0.003053	-0.060172	2
35.0	38.3584	2437.97	784.46	0.89130	0.003033	-0.055084	2
36.0	37.9366	2431.09	781.54	0.90030	0.003009	-0.049913	2
37.0	37.4975	2424.12	779.24	0.90875	0.002983	-0.044665	2
38.0	37.0389	2416.86	776.07	0.91664	0.002954	-0.039346	2
39.0	36.5647	2409.41	772.75	0.92401	0.002922	-0.033963	2
40.0	36.0766	2401.78	769.27	0.93088	0.002888	-0.028523	2
40.3	35.9453	2399.73	768.32	0.93261	0.002879	-0.027073	8
41.0	35.5764	2393.98	765.60	0.93725	0.002852	-0.023030	2
42.0	35.0655	2386.00	761.69	0.94316	0.002814	-0.017492	2
43.0	34.5469	2377.87	757.49	0.94861	0.002775	-0.011914	2
44.0	34.0194	2369.55	752.92	0.95365	0.002734	-0.006302	2
45.0	33.4847	2361.04	747.91	0.95828	0.002691	-0.000660	2
46.0	32.9468	2352.42	742.50	0.96254	0.002647	0.005005	2
47.0	32.4051	2343.65	736.65	0.96643	0.002602	0.010689	2
48.0	31.8626	2334.78	730.38	0.96999	0.002557	0.016385	2
49.0	31.3188	2325.78	723.60	0.97323	0.002511	0.022091	2
50.0	30.7761	2316.69	716.34	0.97618	0.002465	0.027801	2
51.0	30.2346	2307.50	708.54	0.97885	0.002418	0.033512	2
52.0	29.6961	2298.24	700.19	0.98127	0.002372	0.039219	2
53.0	29.1607	2288.90	691.22	0.98346	0.002326	0.044919	2
54.0	28.6296	2279.51	681.65	0.98542	0.002279	0.050608	2
55.0	28.1033	2270.06	671.41	0.98719	0.002234	0.056284	2
56.0	27.5825	2260.56	660.48	0.98877	0.002188	0.061942	2
57.0	27.0678	2251.04	648.84	0.99018	0.002143	0.067581	2
58.0	26.5597	2241.48	636.46	0.99145	0.002099	0.073197	2
59.0	26.0585	2231.91	623.32	0.99257	0.002055	0.078787	2

60.0	25.5648	2222.33	609.40	0.99356	0.002012	0.084351	2
61.0	25.0786	2212.74	594.71	0.99444	0.001970	0.089885	2
62.0	24.5988	2203.11	579.14	0.99515	0.001928	0.095388	2
63.0	24.1236	2193.41	563.00	0.99561	0.001886	0.100857	2
64.0	23.6575	2183.75	547.00	0.99601	0.001846	0.106290	2
65.0	23.2005	2174.12	531.27	0.99636	0.001806	0.111686	2
66.0	22.7528	2164.53	515.96	0.99667	0.001767	0.117043	2
67.0	22.3142	2154.98	501.19	0.99693	0.001729	0.122360	2
68.0	21.8847	2145.48	487.19	0.99717	0.001693	0.127637	2
69.0	21.4642	2136.04	474.02	0.99737	0.001657	0.132872	2
70.0	21.0528	2126.64	461.72	0.99754	0.001622	0.138065	2
71.0	20.6503	2117.31	450.36	0.99769	0.001589	0.143215	2
72.0	20.2566	2108.04	439.97	0.99782	0.001556	0.148320	2
73.0	19.8717	2098.82	430.53	0.99793	0.001524	0.153382	2
74.0	19.4953	2089.67	422.03	0.99803	0.001493	0.158398	2
75.0	19.1268	2080.57	414.43	0.99808	0.001463	0.163369	2
76.0	18.7668	2071.54	407.74	0.99813	0.001434	0.168294	2
77.0	18.4151	2062.59	401.85	0.99817	0.001406	0.173173	2
78.0	18.0715	2053.70	396.67	0.99820	0.001378	0.178005	2
79.0	17.7359	2044.88	392.12	0.99823	0.001352	0.182791	2
80.0	17.4081	2036.14	388.11	0.99825	0.001326	0.187530	2
81.0	17.0879	2027.47	384.58	0.99827	0.001301	0.192221	2
82.0	16.7752	2018.88	381.46	0.99829	0.001277	0.196867	2
83.0	16.4699	2010.36	378.70	0.99830	0.001253	0.201465	2
84.0	16.1718	2001.92	376.24	0.99832	0.001230	0.206016	2
85.0	15.8806	1993.55	374.05	0.99833	0.001208	0.210520	2
86.0	15.5963	1985.26	372.08	0.99833	0.001187	0.214977	2
87.0	15.3187	1977.04	370.30	0.99834	0.001166	0.219387	2
88.0	15.0476	1968.90	368.68	0.99835	0.001145	0.223751	2
89.0	14.7829	1960.83	367.21	0.99835	0.001126	0.228068	2
90.0	14.5244	1952.84	365.86	0.99835	0.001107	0.232339	2
91.0	14.2720	1944.93	364.61	0.99836	0.001088	0.236564	2
92.0	14.0256	1937.08	363.45	0.99836	0.001070	0.240743	2
93.0	13.7849	1929.32	362.36	0.99836	0.001053	0.244876	2
94.0	13.5498	1921.63	361.34	0.99836	0.001036	0.248963	2
95.0	13.3203	1914.01	360.37	0.99836	0.001019	0.253006	2
96.0	13.0962	1906.46	359.44	0.99837	0.001003	0.257003	2
97.0	12.8772	1898.99	358.55	0.99837	0.000987	0.260956	2
98.0	12.6634	1891.60	357.69	0.99837	0.000972	0.264864	2
99.0	12.4546	1884.27	356.86	0.99837	0.000957	0.268728	2
100.0	12.2506	1877.02	356.05	0.99837	0.000943	0.272549	2
101.0	12.0514	1869.85	355.26	0.99837	0.000929	0.276326	2
102.0	11.8568	1862.74	354.48	0.99837	0.000916	0.280060	2
103.0	11.6666	1855.70	353.71	0.99837	0.000902	0.283751	2
104.0	11.4809	1848.74	352.94	0.99837	0.000889	0.287399	2
105.0	11.2994	1841.84	352.18	0.99837	0.000877	0.291006	2
106.0	11.1221	1835.02	351.42	0.99837	0.000865	0.294571	2
107.0	10.9489	1828.27	350.66	0.99837	0.000853	0.298094	2
108.0	10.7796	1821.58	349.90	0.99837	0.000841	0.301577	2
109.0	10.6142	1814.96	349.13	0.99837	0.000830	0.305019	2
110.0	10.4525	1808.41	348.35	0.99837	0.000819	0.308420	2
111.0	10.2945	1801.93	347.57	0.99837	0.000808	0.311782	2
112.0	10.1401	1795.52	346.77	0.99837	0.000798	0.315104	2
113.0	9.9891	1789.17	345.97	0.99837	0.000787	0.318387	2
114.0	9.8416	1782.88	345.15	0.99837	0.000777	0.321631	2

115.0	9.6973	1776.67	344.31	0.99837	0.000768	0.324837	2
116.0	9.5563	1770.51	343.46	0.99837	0.000758	0.328004	2
117.0	9.4184	1764.42	342.60	0.99837	0.000749	0.331134	2
118.0	9.2836	1758.40	341.71	0.99837	0.000740	0.334227	2
119.0	9.1518	1752.43	340.81	0.99837	0.000731	0.337282	2
120.0	9.0228	1746.53	339.88	0.99837	0.000722	0.340301	2
121.0	8.8967	1740.70	338.94	0.99837	0.000714	0.343284	2
122.0	8.7734	1734.92	337.97	0.99837	0.000706	0.346230	2
122.5	8.7123	1732.03	337.46	0.99837	0.000702	0.347701	8
123.0	8.6528	1729.20	336.96	0.99837	0.000698	0.349142	2
124.0	8.5348	1723.55	335.98	0.99837	0.000690	0.352018	2
125.0	8.4194	1717.95	335.01	0.99837	0.000682	0.354859	2
126.0	8.3066	1712.42	334.07	0.99837	0.000675	0.357666	2
127.0	8.1961	1706.94	333.14	0.99837	0.000667	0.360439	2
128.0	8.0880	1701.52	332.23	0.99837	0.000660	0.363178	2
129.0	7.9823	1696.15	331.33	0.99837	0.000653	0.365883	2
130.0	7.8788	1690.85	330.44	0.99837	0.000646	0.368556	2
131.0	7.7775	1685.60	329.57	0.99837	0.000640	0.371196	2
132.0	7.6784	1680.41	328.72	0.99837	0.000633	0.373803	2
133.0	7.5814	1675.27	327.88	0.99837	0.000627	0.376379	2
134.0	7.4865	1670.19	327.05	0.99837	0.000620	0.378923	2
135.0	7.3935	1665.16	326.24	0.99837	0.000614	0.381435	2
136.0	7.3025	1660.18	325.44	0.99837	0.000608	0.383916	2
137.0	7.2134	1655.26	324.66	0.99837	0.000602	0.386367	2
138.0	7.1262	1650.39	323.89	0.99837	0.000597	0.388787	2
139.0	7.0408	1645.58	323.13	0.99837	0.000591	0.391177	2
140.0	6.9572	1640.81	322.39	0.99837	0.000585	0.393537	2
141.0	6.8753	1636.10	321.65	0.99837	0.000580	0.395868	2
142.0	6.7951	1631.44	320.94	0.99837	0.000575	0.398170	2
143.0	6.7165	1626.83	320.23	0.99837	0.000569	0.400443	2
144.0	6.6396	1622.26	319.53	0.99837	0.000564	0.402687	2
145.0	6.5642	1617.75	318.85	0.99837	0.000559	0.404902	2
146.0	6.4904	1613.29	318.18	0.99837	0.000555	0.407090	2
147.0	6.4181	1608.87	317.53	0.99837	0.000550	0.409250	2
148.0	6.3472	1604.51	316.88	0.99837	0.000545	0.411383	2
149.0	6.2778	1600.19	316.25	0.99837	0.000540	0.413488	2
150.0	6.2098	1595.92	315.62	0.99837	0.000536	0.415567	2
151.0	6.1432	1591.69	315.01	0.99837	0.000531	0.417619	2
152.0	6.0779	1587.52	314.41	0.99837	0.000527	0.419644	2
153.0	6.0139	1583.38	313.82	0.99837	0.000523	0.421644	2
154.0	5.9512	1579.30	313.24	0.99837	0.000519	0.423618	2
155.0	5.8898	1575.25	312.68	0.99837	0.000515	0.425566	2
156.0	5.8296	1571.26	312.12	0.99837	0.000511	0.427488	2
157.0	5.7705	1567.30	311.57	0.99837	0.000507	0.429386	2
158.0	5.7127	1563.39	311.04	0.99837	0.000503	0.431259	2
159.0	5.6560	1559.53	310.51	0.99837	0.000499	0.433107	2
160.0	5.6004	1555.71	310.00	0.99837	0.000495	0.434931	2
161.0	5.5459	1551.93	309.49	0.99837	0.000492	0.436731	2
162.0	5.4925	1548.19	309.00	0.99837	0.000488	0.438507	2
163.0	5.4402	1544.49	308.51	0.99837	0.000485	0.440259	2
164.0	5.3888	1540.84	308.04	0.99837	0.000481	0.441988	2

165.0	5.3385	1537.22	307.57	0.99837	0.000478	0.443694	2
166.0	5.2892	1533.65	307.12	0.99837	0.000474	0.445376	2
167.0	5.2408	1530.12	306.67	0.99837	0.000471	0.447036	2
168.0	5.1934	1526.62	306.23	0.99837	0.000468	0.448673	2
169.0	5.1468	1523.17	305.80	0.99837	0.000465	0.450288	2
170.0	5.1012	1519.76	305.38	0.99837	0.000462	0.451881	2
171.0	5.0565	1516.38	304.97	0.99837	0.000459	0.453452	2
172.0	5.0127	1513.04	304.57	0.99837	0.000456	0.455001	2
173.0	4.9697	1509.75	304.18	0.99837	0.000453	0.456529	2
174.0	4.9275	1506.49	303.79	0.99837	0.000450	0.458035	2
175.0	4.8862	1503.26	303.42	0.99837	0.000447	0.459520	2
176.0	4.8456	1500.08	303.05	0.99837	0.000444	0.460984	2
177.0	4.8059	1496.93	302.69	0.99837	0.000442	0.462427	2
178.0	4.7669	1493.82	302.34	0.99837	0.000439	0.463850	2
179.0	4.7286	1490.74	302.00	0.99837	0.000436	0.465252	2
180.0	4.6911	1487.70	301.67	0.99837	0.000434	0.466634	2
181.0	4.6543	1484.69	301.34	0.99837	0.000431	0.467996	2
182.0	4.6183	1481.73	301.02	0.99837	0.000429	0.469338	2
183.0	4.5829	1478.79	300.71	0.99837	0.000426	0.470661	2
184.0	4.5482	1475.89	300.41	0.99837	0.000424	0.471963	2
185.0	4.5142	1473.03	300.12	0.99837	0.000421	0.473247	2
186.0	4.4808	1470.20	299.83	0.99837	0.000419	0.474511	2
187.0	4.4481	1467.40	299.55	0.99837	0.000417	0.475756	2
188.0	4.4160	1464.64	299.28	0.99837	0.000415	0.476982	2
189.0	4.3846	1461.91	299.02	0.99837	0.000412	0.478189	2
190.0	4.3537	1459.21	298.76	0.99837	0.000410	0.479378	2
191.0	4.3235	1456.55	298.52	0.99837	0.000408	0.480548	2
192.0	4.2938	1453.92	298.27	0.99837	0.000406	0.481699	2
193.0	4.2648	1451.32	298.04	0.99837	0.000404	0.482833	2
194.0	4.2363	1448.75	297.81	0.99837	0.000402	0.483948	2
195.0	4.2083	1446.22	297.59	0.99837	0.000400	0.485046	2
196.0	4.1809	1443.71	297.38	0.99837	0.000398	0.486126	2
197.0	4.1540	1441.24	297.18	0.99837	0.000396	0.487188	2
198.0	4.1277	1438.80	296.98	0.99837	0.000394	0.488233	2
199.0	4.1019	1436.39	296.79	0.99837	0.000392	0.489260	2

```
>>>>> START OF EXHAUST PROCESS

  CA       P       TEMP          MEX              VEV           Q DOT       WORK       IFG
 (DEG)   (ATM)     (K)           (G)             (M/SEC)       (KJ/DEG)    (KJ)
-----------------------------------------------------------------------------------------------
 199.0   4.1019   1436.39      -0.01511            0.0        0.000392    0.489260      2
 200.0   4.0758   1434.07      -0.01499        27739.8        0.000306    0.490270      2
 210.0   3.7284   1403.59      -0.00078        27452.6        0.000287    0.499344      2
 220.0   3.2678   1361.34       0.03378        27049.3        0.000257    0.506420      2
 230.0   2.7555   1309.09       0.08299        26541.7        0.000221    0.511520      2
 240.0   2.2441   1248.89       0.14070        25944.4        0.000183    0.514875      2
 250.0   1.8197   1189.71       0.19421        25337.1        0.000151    0.516845      2
 260.0   1.5002   1136.80       0.23840        23776.6        0.000125    0.517824      2
 270.0   1.2704   1092.13       0.27298        20207.8        0.000106    0.518102      2
 280.0   1.1213   1058.25       0.29744        14498.3        0.000093    0.517873      2
 290.0   1.0446   1037.36       0.31182         7638.1        0.000086    0.517244      2
 300.0   1.0246   1028.32       0.31819         3371.7        0.000083    0.516247      2
 310.0   1.0257   1023.65       0.32245         3725.8        0.000082    0.514877      2
 320.0   1.0290   1019.10       0.32774         4653.2        0.000081    0.513143      2
 330.0   1.0331   1014.29       0.33428         5574.3        0.000079    0.511065      2
 340.0   1.0379   1009.15       0.34203         6471.9        0.000078    0.508667      2
 350.0   1.0438   1003.33       0.35106         7403.6        0.000076    0.505976      2
 360.0   1.0514    996.33       0.36147         8397.8        0.000074    0.503022      2
 370.0   1.0601    988.00       0.37337         9369.2        0.000072    0.499838      2
 380.0   1.0686    978.75       0.38672        10183.1        0.000069    0.496462      2
 390.0   1.0754    969.23       0.40124        10737.5        0.000067    0.492941      2
 400.0   1.0791    960.00       0.41655        10998.6        0.000064    0.489329      2
 410.0   1.0795    951.35       0.43221        10986.1        0.000061    0.485685      2
 420.0   1.0771    943.25       0.44780        10742.4        0.000058    0.482069      2
 430.0   1.0727    935.61       0.46299        10320.7        0.000055    0.478539      2
 440.0   1.0669    928.27       0.47751         9757.0        0.000052    0.475145      2
 450.0   1.0607    921.18       0.49117         9108.3        0.000050    0.471937      2
 460.0   1.0546    914.27       0.50381         8418.5        0.000047    0.468955      2
 470.0   1.0477    907.18       0.51535         7557.5        0.000045    0.466239      2
 480.0   1.0408    899.96       0.52565         6569.2        0.000043    0.463820      2
 490.0   1.0343    892.56       0.53461         5459.6        0.000041    0.461727      2
 500.0   1.0305    885.33       0.54212         4679.7        0.000040    0.459984      2
 510.0   1.0262    877.62       0.54820         3602.5        0.000038    0.458610      2
 520.0   1.0231    869.84       0.55273         2549.5        0.000037    0.457618      2
 530.0   1.0210    862.14       0.55566         1403.8        0.000037    0.457019      2
 540.0   1.0203    854.92       0.55695          821.9        0.000036    0.456818      2
 550.0   1.0190    847.97       0.55660        -1428.8        0.000036    0.457019      2
-----------------------------------------------------------------------------------------------
```

```
>-------------+-------------<
>                           <
>    CALCULATION RESULTS    <
>                           <
>-------------+-------------<

-->  VOLUMETRIC EFFICIENCY; (%)
     BASED ON: INTAKE / ATM            ---->    75.9    74.4

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

-->  GROSS INDICATED MEAN EFFECTIVE
     PRESSURE; (KPA) : IMEP            ---->   807.

-->  GROSS INDICATED SPECIFIC FUEL
     CONSUMPTION; (G/IKW-HR) : ISFC    ---->   270.

-->  GROSS INDICATED THERMAL
     EFFICIENCY; (%)                   ---->    30.0

-->  NET INDICATED THERMAL
     EFFICIENCY; (%)                   ---->    29.7

-->  (HEAT TRANSFER PER CYCLE)/
     (MASS OF FUEL TIMES LHV); (%)     ---->    21.2

-->  IGNITION DELAY (0 - 10%)
     (CRANK ANGLE) / (MS)              ---->    19.19    1.07

-->  BURN DURATION (10 - 90%)
     (CRANK ANGLE) / (MS)              ---->    46.78    2.60

-->  MEAN EXHAUST
     TEMPERATURE; (K)                  ---->  1124.4
```

```
MASS IN CYLINDER AT TIVO =  0.02858 G

MASS IN CYLINDER AT TIVC =  0.66149 G

MASS OF FUEL INDUCTED    =  0.03467 G

RESIDUAL FRACTION        =  0.09032
```

```
HEATI   =    0.001518 KJ  (TIPO    -    -270)
WORKI   =    0.055626 KJ

HEATC   =    0.006440 KJ  (-270    - TSPARK)
WORKC   =   -0.175998 KJ

HEATCE  =    0.308159 KJ  (TIPC    -     +270
WORKCE  =    0.462476 KJ

HEATE   =    0.017150 KJ  (+270    -    TIPO)
WORKE   =   -0.061083 KJ
```

```
TOTAL ENTHALPY IN / CYCLE    =  0.09030 KJ

TOTAL ENTHALPY OUT / CYCLE   = -0.88656 KJ

TOTAL HEAT LOSS / CYCLE      =  0.32683 KJ

TOTAL WORK OUTPUT / CYCLE    =  0.45702 KJ

HEAT LOSS TO CREVICE/CYCLE   =  0.11964 KJ

"LOST" FUEL ENERGY           =  0.09587 KJ

NET ENERGY GAIN / CYCLE      =  0.02250 KJ

(ENERGY GAIN)/(ENTHALPY IN) = 24.91203 %

(ENERGY GAIN)/(MFUEL*LHV)    =  1.46151 %
```

LEAKAGE AND CREVICE VOLUME DATA

CA (DEG)	CHAMBER MASS (G)	LEAD CREVICE MASS (G)	LAG CREVICE MASS (G)	LEAD LEAKAGE MASS (G)	LAG LEAKAGE MASS (G)	LEAD CREVICE COMPOSITION ( )	LAG CREVICE COMPOSITION ( )
-520.0	0.0314	0.000000	0.000000	-0.000177	-0.000496	0.000000	0.000000
-510.0	0.0353	0.000000	0.000000	-0.000379	-0.000956	0.000000	0.000000
-505.8	0.0376	0.000000	0.000000	-0.000471	-0.001136	0.000000	0.000000
-500.0	0.0412	0.000000	0.000000	-0.000605	-0.001368	0.000000	0.000000
-492.9	0.0461	0.000000	0.000000	-0.000782	-0.001626	0.000000	0.000000
-490.0	0.0495	0.000000	0.000000	-0.000859	-0.001722	0.000000	0.000000
-480.0	0.0708	0.000000	0.000000	-0.001150	-0.002016	0.000000	0.000000
-470.0	0.0973	0.000000	0.000000	-0.001485	-0.002253	0.000000	0.000000
-460.0	0.1274	0.000000	0.000000	-0.001875	-0.002447	0.000000	0.000000
-450.0	0.1604	0.000000	0.000000	-0.002335	-0.002599	0.000000	0.000000
-440.0	0.1957	0.000000	0.000000	-0.002883	-0.002715	0.000000	0.000000
-430.0	0.2330	0.000000	0.000000	-0.003542	-0.002798	0.000000	0.000000
-420.0	0.2718	0.000000	0.000000	-0.004342	-0.002864	0.000000	0.000000
-410.0	0.3116	0.000000	0.000000	-0.005315	-0.002925	0.000000	0.000000
-400.0	0.3508	0.000000	0.000000	-0.006496	-0.002986	0.000000	0.000000
-390.0	0.3897	0.000000	0.000000	-0.007910	-0.003049	0.000000	0.000000
-380.0	0.4280	0.000000	0.000000	-0.009596	-0.003113	0.000000	0.000000
-370.0	0.4652	0.000000	0.000000	-0.011802	-0.003179	0.000000	0.000000
-360.0	0.5007	0.000000	0.000000	-0.014881	-0.003247	0.000000	0.000000
-350.0	0.5335	0.000000	0.000000	-0.018924	-0.003317	0.000000	0.000000
-340.0	0.5631	0.000000	0.000000	-0.023625	-0.003391	0.000000	0.000000
-330.0	0.5896	0.000000	0.000000	-0.028464	-0.003467	0.000000	0.000000
-320.0	0.6126	0.000000	0.000000	-0.032988	-0.003544	0.000000	0.000000
-310.0	0.6321	0.000000	0.000000	-0.036943	-0.003623	0.000000	0.000000
-300.0	0.6479	0.000000	0.000000	-0.040268	-0.003700	0.000000	0.000000
-290.0	0.6593	0.000000	0.000000	-0.043014	-0.003776	0.000000	0.000000
-280.0	0.6669	0.000000	0.000000	-0.045280	-0.003849	0.000000	0.000000
-277.3	0.6679	0.000000	0.000000	-0.045823	-0.003868	0.000000	0.000000
-270.0	0.6688	0.000000	0.000000	-0.047160	-0.003919	0.000000	0.000000
-260.0	0.6677	0.000000	0.000000	-0.048738	-0.003985	0.000000	0.000000
-250.0	0.6648	0.000000	0.000000	-0.050076	-0.004046	0.000000	0.000000
-240.0	0.6611	0.000000	0.000000	-0.051224	-0.004100	0.000000	0.000000
-230.0	0.6595	0.000000	0.000000	-0.052220	-0.004136	0.000000	0.000000
-220.0	0.6597	0.000000	0.000892	-0.053095	-0.004112	0.000000	0.234322
-210.0	0.6602	0.000000	0.000939	-0.053872	-0.004049	0.000000	0.308123
-200.0	0.6607	0.000000	0.000998	-0.054568	-0.003962	0.000000	0.390065
-190.0	0.6611	0.000000	0.001069	-0.055199	-0.003852	0.000000	0.471789
-180.0	0.6615	0.000000	0.001156	-0.055776	-0.003720	0.000000	0.548449

-170.0	0.6618	0.000000	0.001261	-0.056309	-0.003566	0.000000	0.617016
-160.0	0.6620	0.000000	0.001389	-0.056805	-0.003389	0.000000	0.676261
-150.0	0.6621	0.000000	0.001544	-0.057266	-0.003188	0.000000	0.725959
-140.0	0.6621	0.000000	0.001734	-0.057677	-0.002963	0.000000	0.766591
-130.0	0.6619	0.000000	0.001968	-0.058001	-0.002709	0.000000	0.799286
-120.0	0.6612	0.002215	0.002256	-0.058032	-0.002419	0.503044	0.825299
-110.0	0.6599	0.002577	0.002614	-0.057732	-0.002086	0.599186	0.845764
-100.0	0.6582	0.003031	0.003063	-0.057346	-0.001697	0.678318	0.861720
-90.0	0.6562	0.003602	0.003630	-0.056891	-0.001239	0.739108	0.873995
-80.0	0.6537	0.004326	0.004350	-0.056347	-0.000694	0.785179	0.883308
-70.0	0.6506	0.005239	0.005260	-0.055691	-0.000037	0.819510	0.890255
-60.0	0.6467	0.006379	0.006398	-0.054896	0.000759	0.844633	0.895342
-50.0	0.6420	0.007771	0.007787	-0.053928	0.001728	0.862677	0.898998
-40.0	0.6364	0.009396	0.009411	-0.052752	0.002905	0.875363	0.901569
-30.0	0.6301	0.011146	0.011158	-0.051344	0.004314	0.884063	0.903332
-29.0	0.6294	0.011322	0.011335	-0.051190	0.004468	0.884754	0.904023
-28.0	0.6287	0.011507	0.011520	-0.051033	0.004624	0.885431	0.904700
-27.0	0.6280	0.011704	0.011717	-0.050874	0.004784	0.886094	0.905363
-26.0	0.6273	0.011918	0.011931	-0.050712	0.004946	0.886734	0.906003
-25.0	0.6265	0.012150	0.012164	-0.050547	0.005111	0.887340	0.906608
-24.0	0.6256	0.012404	0.012417	-0.050379	0.005279	0.887893	0.907162
-23.0	0.6248	0.012681	0.012695	-0.050207	0.005451	0.888374	0.907642
-22.0	0.6238	0.012983	0.012997	-0.050031	0.005627	0.888757	0.908026
-21.0	0.6228	0.013312	0.013327	-0.049851	0.005808	0.889015	0.908283
-20.0	0.6217	0.013669	0.013685	-0.049666	0.005993	0.889118	0.908386
-19.0	0.6205	0.014056	0.014071	-0.049476	0.006183	0.889033	0.908301
-18.0	0.6193	0.014472	0.014488	-0.049280	0.006378	0.888728	0.907996
-17.0	0.6180	0.014918	0.014935	-0.049079	0.006580	0.888171	0.907439
-16.0	0.6166	0.015395	0.015412	-0.048871	0.006788	0.887331	0.906599
-15.0	0.6152	0.015902	0.015920	-0.048656	0.007002	0.886178	0.905447
-14.0	0.6137	0.016438	0.016456	-0.048434	0.007224	0.884687	0.903956
-13.0	0.6121	0.017003	0.017022	-0.048205	0.007454	0.882834	0.902104
-12.0	0.6104	0.017595	0.017614	-0.047968	0.007691	0.880601	0.899871
-11.0	0.6087	0.018212	0.018232	-0.047722	0.007937	0.877972	0.897242
-10.0	0.6069	0.018853	0.018874	-0.047468	0.008191	0.874938	0.894209
-9.0	0.6050	0.019516	0.019538	-0.047205	0.008454	0.871493	0.890764
-8.0	0.6031	0.020198	0.020221	-0.046933	0.008727	0.867633	0.886906
-7.0	0.6011	0.020897	0.020920	-0.046651	0.009009	0.863366	0.882639
-6.0	0.5991	0.021609	0.021633	-0.046359	0.009301	0.858696	0.877969
-5.0	0.5971	0.022332	0.022356	-0.046057	0.009602	0.853632	0.872907
-4.0	0.5950	0.023062	0.023087	-0.045746	0.009914	0.848192	0.867467
-3.0	0.5928	0.023796	0.023823	-0.045424	0.010236	0.842390	0.861667
-2.0	0.5907	0.024531	0.024559	-0.045092	0.010568	0.836249	0.855528
-1.0	0.5885	0.025264	0.025292	-0.044750	0.010910	0.829791	0.849071
0.0	0.5863	0.025990	0.026019	-0.044398	0.011263	0.823040	0.842321
1.0	0.5842	0.026707	0.026737	-0.044036	0.011625	0.816023	0.835306
2.0	0.5820	0.027412	0.027442	-0.043664	0.011997	0.808768	0.828052
3.0	0.5798	0.028100	0.028131	-0.043282	0.012379	0.801304	0.820590
4.0	0.5777	0.028769	0.028801	-0.042891	0.012770	0.793661	0.812949
5.0	0.5755	0.029416	0.029449	-0.042491	0.013171	0.785870	0.805160
6.0	0.5735	0.030039	0.030072	-0.042081	0.013580	0.777963	0.797255
7.0	0.5714	0.030634	0.030667	-0.041664	0.013998	0.769970	0.789264
8.0	0.5694	0.031199	0.031233	-0.041238	0.014424	0.761923	0.781219
9.0	0.5674	0.031732	0.031767	-0.040805	0.014858	0.753852	0.773151

10.0	0.5655	0.032231	0.032266	-0.040364	0.015298	0.745788	0.765089
11.0	0.5637	0.032694	0.032730	-0.039917	0.015746	0.737760	0.757064
12.0	0.5619	0.033121	0.033157	-0.039463	0.016200	0.729798	0.749104
13.0	0.5601	0.033509	0.033546	-0.039004	0.016660	0.721928	0.741237
14.0	0.5585	0.033858	0.033895	-0.038539	0.017124	0.714178	0.733489
15.0	0.5569	0.034168	0.034205	-0.038070	0.017594	0.706572	0.725887
16.0	0.5554	0.034437	0.034475	-0.037596	0.018067	0.699136	0.718454
17.0	0.5539	0.034665	0.034704	-0.037119	0.018545	0.691892	0.711212
18.0	0.5526	0.034854	0.034892	-0.036639	0.019025	0.684860	0.704184
19.0	0.5513	0.035002	0.035040	-0.036157	0.019507	0.678060	0.697387
20.0	0.5501	0.035110	0.035149	-0.035673	0.019992	0.671511	0.690841
21.0	0.5489	0.035179	0.035218	-0.035187	0.020478	0.665228	0.684562
22.0	0.5479	0.035210	0.035249	-0.034701	0.020964	0.659226	0.678564
23.0	0.5469	0.035204	0.035242	-0.034214	0.021451	0.653518	0.672860
24.0	0.5460	0.035161	0.035200	-0.033728	0.021938	0.648115	0.667461
25.0	0.5452	0.035083	0.035122	-0.033242	0.022423	0.643028	0.662377
26.0	0.5444	0.034971	0.035010	-0.032758	0.022908	0.638262	0.657615
27.0	0.5437	0.034827	0.034866	-0.032275	0.023391	0.633826	0.653183
28.0	0.5431	0.034653	0.034691	-0.031794	0.023872	0.629723	0.649085
29.0	0.5425	0.034449	0.034486	-0.031316	0.024350	0.625958	0.645323
30.0	0.5420	0.034217	0.034254	-0.030841	0.024825	0.622530	0.641900
31.0	0.5416	0.033959	0.033996	-0.030370	0.025297	0.619442	0.638816
32.0	0.5412	0.033677	0.033714	-0.029902	0.025765	0.616691	0.636069
33.0	0.5409	0.033373	0.033409	-0.029438	0.026230	0.614275	0.633658
34.0	0.5406	0.033047	0.033083	-0.028978	0.026690	0.612192	0.631579
35.0	0.5404	0.032702	0.032738	-0.028523	0.027145	0.610435	0.629827
36.0	0.5402	0.032340	0.032376	-0.028073	0.027595	0.609001	0.628397
37.0	0.5400	0.031964	0.031999	-0.027628	0.028040	0.607881	0.627282
38.0	0.5399	0.031571	0.031606	-0.027188	0.028480	0.607060	0.626465
39.0	0.5399	0.031166	0.031201	-0.026754	0.028915	0.606509	0.625919
40.0	0.5399	0.030750	0.030784	-0.026325	0.029344	0.606192	0.625606
40.3	0.5399	0.030638	0.030671	-0.026212	0.029456	0.606141	0.625556
41.0	0.5399	0.030323	0.030356	-0.025902	0.029767	0.606057	0.625474
42.0	0.5399	0.029888	0.029920	-0.025485	0.030184	0.606032	0.625451
43.0	0.5400	0.029446	0.029478	-0.025075	0.030594	0.606046	0.625465
44.0	0.5401	0.028996	0.029028	-0.024670	0.030999	0.606075	0.625494
45.0	0.5402	0.028540	0.028572	-0.024272	0.031398	0.606074	0.625492
46.0	0.5403	0.028082	0.028113	-0.023880	0.031790	0.606053	0.625471
47.0	0.5405	0.027620	0.027650	-0.023494	0.032176	0.606048	0.625467
48.0	0.5406	0.027158	0.027188	-0.023115	0.032555	0.606057	0.625476
49.0	0.5408	0.026694	0.026724	-0.022742	0.032928	0.606061	0.625480
50.0	0.5410	0.026232	0.026261	-0.022376	0.033294	0.606059	0.625478
51.0	0.5412	0.025770	0.025798	-0.022016	0.033655	0.606059	0.625477
52.0	0.5414	0.025311	0.025339	-0.021662	0.034008	0.606059	0.625477
53.0	0.5416	0.024855	0.024882	-0.021315	0.034356	0.606059	0.625477
54.0	0.5419	0.024402	0.024429	-0.020974	0.034697	0.606059	0.625477
55.0	0.5421	0.023954	0.023980	-0.020640	0.035032	0.606059	0.625477
56.0	0.5423	0.023510	0.023536	-0.020311	0.035360	0.606059	0.625477
57.0	0.5425	0.023071	0.023096	-0.019989	0.035683	0.606059	0.625477
58.0	0.5428	0.022638	0.022663	-0.019672	0.035999	0.606059	0.625477
59.0	0.5430	0.022211	0.022235	-0.019362	0.036310	0.606059	0.625477

60.0	0.5432	0.021790	0.021814	-0.019057	0.036615	0.606059	0.625477
61.0	0.5435	0.021375	0.021399	-0.018758	0.036914	0.606059	0.625477
62.0	0.5437	0.020967	0.020990	-0.018465	0.037207	0.606059	0.625477
63.0	0.5439	0.020561	0.020584	-0.018178	0.037494	0.606059	0.625477
64.0	0.5442	0.020164	0.020186	-0.017896	0.037777	0.606059	0.625477
65.0	0.5444	0.019775	0.019796	-0.017619	0.038053	0.606059	0.625477
66.0	0.5446	0.019393	0.019414	-0.017348	0.038324	0.606059	0.625477
67.0	0.5448	0.019019	0.019040	-0.017082	0.038590	0.606059	0.625477
68.0	0.5450	0.018653	0.018674	-0.016822	0.038851	0.606059	0.625477
69.0	0.5453	0.018295	0.018315	-0.016566	0.039107	0.606059	0.625477
70.0	0.5455	0.017944	0.017964	-0.016315	0.039358	0.606059	0.625477
71.0	0.5456	0.017601	0.017620	-0.016069	0.039604	0.606059	0.625477
72.0	0.5458	0.017266	0.017285	-0.015828	0.039846	0.606059	0.625477
73.0	0.5460	0.016937	0.016956	-0.015591	0.040082	0.606059	0.625477
74.0	0.5462	0.016617	0.016635	-0.015359	0.040315	0.606059	0.625477
75.0	0.5464	0.016303	0.016320	-0.015131	0.040543	0.606059	0.625477
76.0	0.5465	0.015996	0.016013	-0.014907	0.040766	0.606059	0.625477
77.0	0.5467	0.015696	0.015713	-0.014688	0.040986	0.606059	0.625477
78.0	0.5469	0.015403	0.015420	-0.014473	0.041201	0.606059	0.625477
79.0	0.5470	0.015117	0.015134	-0.014261	0.041413	0.606059	0.625477
80.0	0.5471	0.014838	0.014854	-0.014054	0.041620	0.606059	0.625477
81.0	0.5473	0.014565	0.014581	-0.013851	0.041824	0.606059	0.625477
82.0	0.5474	0.014298	0.014314	-0.013651	0.042024	0.606059	0.625477
83.0	0.5475	0.014038	0.014053	-0.013455	0.042220	0.606059	0.625477
84.0	0.5477	0.013784	0.013799	-0.013262	0.042412	0.606059	0.625477
85.0	0.5478	0.013536	0.013551	-0.013073	0.042602	0.606059	0.625477
86.0	0.5479	0.013293	0.013308	-0.012887	0.042787	0.606059	0.625477
87.0	0.5480	0.013057	0.013071	-0.012705	0.042970	0.606059	0.625477
88.0	0.5481	0.012826	0.012840	-0.012526	0.043149	0.606059	0.625477
89.0	0.5482	0.012600	0.012614	-0.012350	0.043325	0.606059	0.625477
90.0	0.5483	0.012380	0.012393	-0.012177	0.043498	0.606059	0.625477
91.0	0.5484	0.012165	0.012178	-0.012007	0.043668	0.606059	0.625477
92.0	0.5485	0.011955	0.011968	-0.011840	0.043835	0.606059	0.625477
93.0	0.5486	0.011749	0.011762	-0.011676	0.043999	0.606059	0.625477
94.0	0.5486	0.011549	0.011562	-0.011515	0.044161	0.606059	0.625477
95.0	0.5487	0.011353	0.011366	-0.011356	0.044319	0.606059	0.625477
96.0	0.5488	0.011162	0.011175	-0.011200	0.044475	0.606059	0.625477
97.0	0.5489	0.010976	0.010988	-0.011047	0.044628	0.606059	0.625477
98.0	0.5489	0.010794	0.010805	-0.010896	0.044779	0.606059	0.625477
99.0	0.5490	0.010616	0.010627	-0.010748	0.044928	0.606059	0.625477

100.0	0.5490	0.010442	0.010453	-0.010602	0.045073	0.606059	0.625477
101.0	0.5491	0.010272	0.010283	-0.010459	0.045217	0.606059	0.625477
102.0	0.5491	0.010106	0.010117	-0.010318	0.045358	0.606059	0.625477
103.0	0.5492	0.009944	0.009955	-0.010179	0.045497	0.606059	0.625477
104.0	0.5492	0.009786	0.009796	-0.010043	0.045633	0.606059	0.625477
105.0	0.5493	0.009631	0.009642	-0.009908	0.045768	0.606059	0.625477
106.0	0.5493	0.009480	0.009490	-0.009776	0.045900	0.606059	0.625477
107.0	0.5493	0.009332	0.009342	-0.009646	0.046030	0.606059	0.625477
108.0	0.5494	0.009188	0.009198	-0.009517	0.046159	0.606059	0.625477
109.0	0.5494	0.009047	0.009057	-0.009391	0.046285	0.606059	0.625477
110.0	0.5494	0.008909	0.008919	-0.009267	0.046409	0.606059	0.625477
111.0	0.5495	0.008774	0.008784	-0.009145	0.046532	0.606059	0.625477
112.0	0.5495	0.008643	0.008652	-0.009024	0.046652	0.606059	0.625477
113.0	0.5495	0.008514	0.008523	-0.008905	0.046771	0.606059	0.625477
114.0	0.5495	0.008388	0.008398	-0.008788	0.046888	0.606059	0.625477
115.0	0.5495	0.008265	0.008274	-0.008673	0.047004	0.606059	0.625477
116.0	0.5495	0.008145	0.008154	-0.008559	0.047117	0.606059	0.625477
117.0	0.5496	0.008028	0.008036	-0.008447	0.047229	0.606059	0.625477
118.0	0.5496	0.007913	0.007921	-0.008337	0.047340	0.606059	0.625477
119.0	0.5496	0.007800	0.007809	-0.008228	0.047448	0.606059	0.625477
120.0	0.5496	0.007691	0.007699	-0.008121	0.047556	0.606059	0.625477
121.0	0.5496	0.007583	0.007591	-0.008015	0.047661	0.606059	0.625477
122.0	0.5496	0.007478	0.007486	-0.007911	0.047766	0.606059	0.625477
122.5	0.5496	0.007426	0.007434	-0.007859	0.047818	0.606070	0.625488
123.0	0.5496	0.007375	0.007383	-0.007808	0.047869	0.606091	0.625508
124.0	0.5496	0.007275	0.007283	-0.007707	0.047970	0.606008	0.625433

125.0	0.5496	0.007176	0.007184	-0.007607	0.048070	0.605888	0.625315
126.0	0.5496	0.007080	0.007088	-0.007508	0.048169	0.605668	0.625103
127.0	0.5496	0.006986	0.006993	-0.007411	0.048266	0.605392	0.624831
128.0	0.5496	0.006893	0.006901	-0.007315	0.048362	0.605047	0.624492
129.0	0.5496	0.006803	0.006811	-0.007220	0.048457	0.604634	0.624084
130.0	0.5495	0.006715	0.006722	-0.007126	0.048551	0.604153	0.623609
131.0	0.5495	0.006628	0.006635	-0.007034	0.048643	0.603606	0.623067
132.0	0.5495	0.006543	0.006551	-0.006943	0.048734	0.602992	0.622459
133.0	0.5495	0.006461	0.006468	-0.006853	0.048825	0.602312	0.621784
134.0	0.5495	0.006379	0.006386	-0.006764	0.048913	0.601566	0.621044
135.0	0.5495	0.006300	0.006307	-0.006676	0.049001	0.600755	0.620238
136.0	0.5495	0.006222	0.006229	-0.006589	0.049088	0.599879	0.619368
137.0	0.5494	0.006146	0.006153	-0.006504	0.049174	0.598939	0.618433
138.0	0.5494	0.006071	0.006078	-0.006419	0.049258	0.597935	0.617434
139.0	0.5494	0.005998	0.006005	-0.006336	0.049342	0.596868	0.616373
140.0	0.5494	0.005926	0.005933	-0.006253	0.049425	0.595738	0.615248
141.0	0.5493	0.005856	0.005863	-0.006171	0.049506	0.594546	0.614062
142.0	0.5493	0.005788	0.005794	-0.006091	0.049587	0.593292	0.612814
143.0	0.5493	0.005720	0.005726	-0.006011	0.049667	0.591978	0.611505
144.0	0.5493	0.005654	0.005660	-0.005932	0.049745	0.590604	0.610136
145.0	0.5492	0.005590	0.005596	-0.005855	0.049823	0.589170	0.608708
146.0	0.5492	0.005526	0.005532	-0.005778	0.049900	0.587677	0.607220
147.0	0.5492	0.005464	0.005470	-0.005701	0.049976	0.586127	0.605675
148.0	0.5492	0.005403	0.005409	-0.005626	0.050052	0.584519	0.604072
149.0	0.5491	0.005344	0.005350	-0.005552	0.050126	0.582854	0.602412

150.0	0.5491	0.005285	0.005291	-0.005478	0.050200	0.581133	0.600697
151.0	0.5491	0.005228	0.005234	-0.005405	0.050273	0.579357	0.598926
152.0	0.5490	0.005172	0.005178	-0.005333	0.050345	0.577527	0.597101
153.0	0.5490	0.005117	0.005123	-0.005262	0.050416	0.575643	0.595222
154.0	0.5490	0.005063	0.005069	-0.005191	0.050487	0.573706	0.593291
155.0	0.5489	0.005010	0.005016	-0.005121	0.050557	0.571717	0.591307
156.0	0.5489	0.004959	0.004964	-0.005052	0.050626	0.569677	0.589272
157.0	0.5488	0.004908	0.004913	-0.004984	0.050694	0.567586	0.587187
158.0	0.5488	0.004858	0.004863	-0.004916	0.050762	0.565446	0.585052
159.0	0.5488	0.004809	0.004815	-0.004849	0.050829	0.563257	0.582868
160.0	0.5487	0.004761	0.004767	-0.004783	0.050895	0.561020	0.580636
161.0	0.5487	0.004714	0.004720	-0.004717	0.050961	0.558737	0.578358
162.0	0.5487	0.004668	0.004674	-0.004652	0.051026	0.556407	0.576033
163.0	0.5486	0.004623	0.004628	-0.004588	0.051091	0.554031	0.573663
164.0	0.5486	0.004579	0.004584	-0.004524	0.051154	0.551612	0.571248
165.0	0.5485	0.004536	0.004541	-0.004461	0.051218	0.549149	0.568790
166.0	0.5485	0.004493	0.004498	-0.004398	0.051280	0.546643	0.566289
167.0	0.5485	0.004451	0.004456	-0.004336	0.051342	0.544095	0.563746
168.0	0.5484	0.004410	0.004415	-0.004275	0.051404	0.541507	0.561163
169.0	0.5484	0.004370	0.004375	-0.004214	0.051465	0.538878	0.558539
170.0	0.5483	0.004331	0.004336	-0.004153	0.051525	0.536210	0.555877
171.0	0.5483	0.004292	0.004297	-0.004094	0.051585	0.533505	0.553176
172.0	0.5482	0.004254	0.004259	-0.004034	0.051644	0.530762	0.550438
173.0	0.5482	0.004217	0.004222	-0.003975	0.051703	0.527982	0.547663
174.0	0.5481	0.004181	0.004185	-0.003917	0.051762	0.525168	0.544853
175.0	0.5481	0.004145	0.004150	-0.003859	0.051819	0.522318	0.542008
176.0	0.5481	0.004110	0.004115	-0.003802	0.051877	0.519435	0.539130
177.0	0.5480	0.004076	0.004080	-0.003745	0.051934	0.516519	0.536219
178.0	0.5480	0.004042	0.004046	-0.003689	0.051990	0.513572	0.533276
179.0	0.5479	0.004009	0.004013	-0.003633	0.052046	0.510593	0.530303
180.0	0.5479	0.003976	0.003981	-0.003577	0.052101	0.507585	0.527299
181.0	0.5478	0.003944	0.003949	-0.003522	0.052156	0.504547	0.524266
182.0	0.5478	0.003913	0.003918	-0.003468	0.052211	0.501482	0.521205
183.0	0.5477	0.003883	0.003887	-0.003414	0.052265	0.498388	0.518116
184.0	0.5477	0.003852	0.003857	-0.003360	0.052319	0.495269	0.515001
185.0	0.5476	0.003823	0.003827	-0.003307	0.052372	0.492124	0.511861
186.0	0.5476	0.003794	0.003798	-0.003254	0.052425	0.488954	0.508696
187.0	0.5475	0.003766	0.003770	-0.003201	0.052478	0.485761	0.505507
188.0	0.5475	0.003738	0.003742	-0.003149	0.052530	0.482545	0.502295
189.0	0.5474	0.003711	0.003715	-0.003097	0.052582	0.479307	0.499061
190.0	0.5474	0.003684	0.003688	-0.003046	0.052633	0.476048	0.495807
191.0	0.5473	0.003658	0.003662	-0.002995	0.052684	0.472768	0.492532
192.0	0.5473	0.003632	0.003636	-0.002944	0.052735	0.469470	0.489237
193.0	0.5472	0.003606	0.003610	-0.002894	0.052785	0.466152	0.485924
194.0	0.5472	0.003582	0.003586	-0.002844	0.052835	0.462817	0.482594
195.0	0.5471	0.003557	0.003561	-0.002794	0.052885	0.459466	0.479246
196.0	0.5471	0.003534	0.003537	-0.002745	0.052934	0.456098	0.475883
197.0	0.5470	0.003510	0.003514	-0.002696	0.052983	0.452715	0.472504
198.0	0.5470	0.003487	0.003491	-0.002647	0.053032	0.449318	0.469111
199.0	0.5469	0.003465	0.003469	-0.002599	0.053080	0.445908	0.465705

200.0	0.5467	0.003442	0.003446	-0.002551	0.053129	0.442556	0.462208
210.0	0.5322	0.003145	0.003148	-0.002091	0.053589	0.420906	0.439635
220.0	0.4976	0.002756	0.002759	-0.001679	0.054000	0.416944	0.435533
230.0	0.4486	0.002324	0.002326	-0.001325	0.054324	0.416944	0.435533
240.0	0.3912	0.001893	0.000000	-0.001031	0.054356	0.416944	0.000000
250.0	0.3381	0.001535	0.000000	-0.000794	0.054057	0.416944	0.000000
260.0	0.2944	0.001265	0.000000	-0.000601	0.053670	0.416944	0.000000
270.0	0.2603	0.001071	0.000000	-0.000448	0.053214	0.416944	0.000000
280.0	0.2364	0.000946	0.000000	-0.000332	0.052671	0.416739	0.000000
290.0	0.2227	0.000880	0.000000	-0.000249	0.052015	0.408153	0.000000
300.0	0.2170	0.000863	0.000000	-0.000183	0.051220	0.386253	0.000000
310.0	0.2137	0.000862	0.000000	-0.000122	0.050252	0.360034	0.000000
320.0	0.2095	0.000864	0.000000	-0.000061	0.049076	0.335242	0.000000
330.0	0.2043	0.000866	0.000000	0.000002	0.047667	0.311968	0.000000
340.0	0.1982	0.000869	0.000000	0.000066	0.045989	0.290260	0.000000
350.0	0.1913	0.000873	0.000000	0.000132	0.043792	0.270183	0.000000
360.0	0.1838	0.000879	0.000000	0.000200	0.040721	0.251882	0.000000
370.0	0.1759	0.000885	0.000000	0.000271	0.036687	0.235688	0.000000
380.0	0.1672	0.000891	0.000000	0.000344	0.031997	0.221917	0.000000
390.0	0.1574	0.000897	0.000000	0.000420	0.027166	0.210741	0.000000
400.0	0.1465	0.000899	0.000000	0.000498	0.022650	0.202029	0.000000
410.0	0.1347	0.000899	0.000000	0.000576	0.018701	0.195487	0.000000
420.0	0.1224	0.000897	0.000000	0.000653	0.015382	0.190746	0.000000
430.0	0.1099	0.000893	0.000000	0.000728	0.012639	0.187452	0.000000
440.0	0.0975	0.000888	0.000000	0.000801	0.010378	0.185315	0.000000
450.0	0.0857	0.000883	0.000000	0.000870	0.008500	0.184063	0.000000
460.0	0.0746	0.000878	0.000000	0.000937	0.006926	0.183537	0.000000
470.0	0.0643	0.000872	0.000000	0.000998	0.005590	0.183593	0.000000
480.0	0.0551	0.000866	0.000000	0.001052	0.004444	0.184061	0.000000
490.0	0.0471	0.000861	0.000000	0.001089	0.003450	0.184627	0.000000
500.0	0.0405	0.000000	0.000000	0.001063	0.002576	0.000000	0.000000
510.0	0.0353	0.000000	0.000000	0.001000	0.001801	0.000000	0.000000
520.0	0.0315	0.000000	0.000000	0.000913	0.001106	0.000000	0.000000
530.0	0.0293	0.000000	0.000000	0.000802	0.000477	0.000000	0.000000
540.0	0.0287	0.000000	0.000000	0.000671	-0.000099	0.000000	0.000000
550.0	0.0298	0.000000	0.000000	0.000517	-0.000631	0.000000	0.000000

HEAT TRANSFER DATA

CA (DEG)	VELHTX (CM/SEC)	HTPARO (kW/M**2)	HTPASI (KW/M**2)	HTPAHO (KW/M**2)	Q% ROTOR (%)	Q% SIDE (%)	Q% HOUSING (%)
-520.0	824.7	15979107.0	15979107.0	15979107.0	43.831	3.556	52.613
-510.0	824.7	15218337.0	15218337.0	15218337.0	43.160	4.320	52.520
-505.8	824.7	15009003.0	15009003.0	15009003.0	42.810	4.720	52.471
-500.0	824.7	14775061.0	14775061.0	14775061.0	42.267	5.338	52.395
-492.9	824.7	14440517.0	14440517.0	14440517.0	41.519	6.190	52.291
-490.0	824.7	13599877.0	13599877.0	13599877.0	41.191	6.564	52.245
-480.0	824.7	9980390.0	9980390.0	9980390.0	39.976	7.949	52.075
-470.0	824.7	7309748.0	7309748.0	7309748.0	38.665	9.443	51.892
-460.0	824.7	5320346.0	5320346.0	5320346.0	37.299	10.999	51.702
-450.0	824.7	3835557.0	3835557.0	3835557.0	35.916	12.576	51.508
-440.0	824.7	2700186.0	2700186.0	2700186.0	34.546	14.137	51.317
-430.0	824.7	1818480.0	1818480.0	1818480.0	33.213	15.656	51.131
-420.0	824.7	1125338.0	1125338.0	1125338.0	31.937	17.110	50.953
-410.0	824.7	574305.7	574305.7	574305.7	30.732	18.483	50.785
-400.0	824.7	127642.1	127642.1	127642.1	29.608	19.764	50.628
-390.0	824.7	-232376.7	-232376.7	-232376.7	28.569	20.948	50.483
-380.0	824.7	-522968.9	-522968.9	-522968.9	27.620	22.029	50.350
-370.0	824.7	-754987.0	-754987.0	-754987.0	26.762	23.008	50.231
-360.0	824.7	-936047.4	-936047.4	-936047.4	25.993	23.883	50.123
-350.0	824.7	-1075939.0	-1075939.0	-1075939.0	25.314	24.658	50.029
-340.0	824.7	-1182815.0	-1182815.0	-1182815.0	24.721	25.333	49.946
-330.0	824.7	-1263735.0	-1263735.0	-1263735.0	24.214	25.911	49.875
-320.0	824.7	-1325647.0	-1325647.0	-1325647.0	23.788	26.396	49.816
-310.0	824.7	-1371296.0	-1371296.0	-1371296.0	23.444	26.789	49.767
-300.0	824.7	-1401694.0	-1401694.0	-1401694.0	23.178	27.092	49.730
-290.0	824.7	-1418573.0	-1418573.0	-1418573.0	22.989	27.307	49.704
-280.0	824.7	-1421271.0	-1421271.0	-1421271.0	22.876	27.436	49.688
-277.3	824.7	-1419089.0	-1419089.0	-1419089.0	22.859	27.456	49.686
-270.0	824.7	-1410017.0	-1410017.0	-1410017.0	22.839	27.478	49.683
-260.0	824.7	-1392293.0	-1392293.0	-1392293.0	22.876	27.436	49.688
-250.0	824.7	-1357968.0	-1357968.0	-1357968.0	22.989	27.307	49.704
-240.0	824.7	-1295586.0	-1295586.0	-1295586.0	23.178	27.092	49.730
-230.0	824.7	-1178865.0	-1178865.0	-1178865.0	23.444	26.789	49.767
-220.0	824.7	-1002928.9	-1002928.9	-1002928.9	23.789	26.396	49.816
-210.0	824.7	-770007.9	-770007.9	-770007.9	24.214	25.911	49.875
-200.0	824.7	-471504.7	-471504.7	-471504.7	24.721	25.333	49.946
-190.0	824.7	-92780.1	-92780.1	-92780.1	25.314	24.658	50.029
-180.0	824.7	386404.4	386404.4	386404.4	25.993	23.883	50.123

-170.0	824.7	992982.4	992982.4	992982.4	26.762	23.008	50.231
-160.0	824.7	1762636.0	1762636.0	1762636.0	27.620	22.029	50.350
-150.0	824.7	2742778.0	2742778.0	2742778.0	28.569	20.948	50.483
-140.0	824.7	3996364.0	3996364.0	3996364.0	29.608	19.764	50.628
-130.0	824.7	5607554.0	5607554.0	5607554.0	30.732	18.483	50.785
-120.0	824.7	7680330.0	7680330.0	7680330.0	31.937	17.110	50.953
-110.0	824.7	10353726.0	10353726.0	10353726.0	33.213	15.656	51.131
-100.0	824.7	13833265.0	13833265.0	13833265.0	34.546	14.137	51.317
-90.0	824.7	18374720.0	18374720.0	18374720.0	35.916	12.576	51.508
-80.0	824.7	24332560.0	24332560.0	24332560.0	37.299	10.999	51.702
-70.0	824.7	32066320.0	32066320.0	32066320.0	38.665	9.443	51.892
-60.0	824.7	41925712.0	41925712.0	41925712.0	39.976	7.949	52.075
-50.0	824.7	54154512.0	54154512.0	54154512.0	41.191	6.564	52.245
-40.0	824.7	68577840.0	68577840.0	68577840.0	42.267	5.338	52.395
-30.0	824.7	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
-30.0	824.7	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
-29.0	824.4	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
-28.0	824.3	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
-27.0	824.5	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
-26.0	825.0	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
-25.0	825.8	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
-24.0	827.0	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
-23.0	828.6	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
-22.0	830.7	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
-21.0	833.2	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
-20.0	836.2	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
-19.0	839.7	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
-18.0	843.7	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
-17.0	848.2	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
-16.0	853.3	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
-15.0	858.8	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
-14.0	864.8	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
-13.0	871.3	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
-12.0	878.3	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
-11.0	885.7	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
-10.0	893.6	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
-9.0	901.9	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
-8.0	910.6	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
-7.0	919.7	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
-6.0	929.1	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
-5.0	938.8	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
-4.0	948.8	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
-3.0	959.1	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
-2.0	969.6	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
-1.0	980.2	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
0.0	991.1	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
1.0	1002.0	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
2.0	1013.1	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
3.0	1024.2	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
4.0	1035.4	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
5.0	1046.6	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
6.0	1057.7	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
7.0	1068.8	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
8.0	1079.8	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
9.0	1090.7	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520

```
10.0    1101.5   84162576.0   84162576.0   84162576.0      43.160      4.320      52.520
11.0    1112.1   84162576.0   84162576.0   84162576.0      43.160      4.320      52.520
12.0    1122.6   84162576.0   84162576.0   84162576.0      43.160      4.320      52.520
13.0    1132.8   84162576.0   84162576.0   84162576.0      43.160      4.320      52.520
14.0    1142.8   84162576.0   84162576.0   84162576.0      43.160      4.320      52.520
15.0    1152.6   84162576.0   84162576.0   84162576.0      43.160      4.320      52.520
16.0    1162.2   84162576.0   84162576.0   84162576.0      43.160      4.320      52.520
17.0    1171.5   84162576.0   84162576.0   84162576.0      43.160      4.320      52.520
18.0    1180.4   84162576.0   84162576.0   84162576.0      43.160      4.320      52.520
19.0    1189.1   84162576.0   84162576.0   84162576.0      43.160      4.320      52.520
20.0    1197.5   84162576.0   84162576.0   84162576.0      43.160      4.320      52.520
21.0    1205.6   84162576.0   84162576.0   84162576.0      43.160      4.320      52.520
22.0    1213.4   84162576.0   84162576.0   84162576.0      43.160      4.320      52.520
23.0    1220.8   84162576.0   84162576.0   84162576.0      43.160      4.320      52.520
24.0    1227.9   84162576.0   84162576.0   84162576.0      43.160      4.320      52.520
25.0    1234.7   84162576.0   84162576.0   84162576.0      43.160      4.320      52.520
26.0    1241.1   84162576.0   84162576.0   84162576.0      43.160      4.320      52.520
27.0    1247.2   84162576.0   84162576.0   84162576.0      43.160      4.320      52.520
28.0    1252.9   84162576.0   84162576.0   84162576.0      43.160      4.320      52.520
29.0    1258.3   84162576.0   84162576.0   84162576.0      43.160      4.320      52.520
30.0    1263.3   84162576.0   84162576.0   84162576.0      43.160      4.320      52.520
31.0    1268.0   84162576.0   84162576.0   84162576.0      43.160      4.320      52.520
32.0    1272.4   84162576.0   84162576.0   84162576.0      43.160      4.320      52.520
33.0    1276.4   84162576.0   84162576.0   84162576.0      43.160      4.320      52.520
34.0    1280.2   84162576.0   84162576.0   84162576.0      43.160      4.320      52.520
35.0    1283.6   84162576.0   84162576.0   84162576.0      43.160      4.320      52.520
36.0    1286.7   84162576.0   84162576.0   84162576.0      43.160      4.320      52.520
37.0    1289.5   84162576.0   84162576.0   84162576.0      43.160      4.320      52.520
38.0    1292.0   84162576.0   84162576.0   84162576.0      43.160      4.320      52.520
39.0    1294.2   84162576.0   84162576.0   84162576.0      43.160      4.320      52.520
40.0    1296.2   84162576.0   84162576.0   84162576.0      43.160      4.320      52.520
40.3    1296.6   84162576.0   84162576.0   84162576.0      43.160      4.320      52.520
41.0    1297.8   84162576.0   84162576.0   84162576.0      43.160      4.320      52.520
42.0    1299.3   84162576.0   84162576.0   84162576.0      43.160      4.320      52.520
43.0    1300.5   84162576.0   84162576.0   84162576.0      43.160      4.320      52.520
44.0    1301.4   84162576.0   84162576.0   84162576.0      43.160      4.320      52.520
45.0    1302.1   84162576.0   84162576.0   84162576.0      43.160      4.320      52.520
46.0    1302.6   84162576.0   84162576.0   84162576.0      43.160      4.320      52.520
47.0    1302.8   84162576.0   84162576.0   84162576.0      43.160      4.320      52.520
48.0    1302.9   84162576.0   84162576.0   84162576.0      43.160      4.320      52.520
49.0    1302.9   84162576.0   84162576.0   84162576.0      43.160      4.320      52.520
50.0    1302.6   84162576.0   84162576.0   84162576.0      43.160      4.320      52.520
51.0    1302.2   84162576.0   84162576.0   84162576.0      43.160      4.320      52.520
52.0    1301.7   84162576.0   84162576.0   84162576.0      43.160      4.320      52.520
53.0    1301.0   84162576.0   84162576.0   84162576.0      43.160      4.320      52.520
54.0    1300.2   84162576.0   84162576.0   84162576.0      43.160      4.320      52.520
55.0    1299.3   84162576.0   84162576.0   84162576.0      43.160      4.320      52.520
56.0    1298.3   84162576.0   84162576.0   84162576.0      43.160      4.320      52.520
57.0    1297.2   84162576.0   84162576.0   84162576.0      43.160      4.320      52.520
58.0    1296.0   84162576.0   84162576.0   84162576.0      43.160      4.320      52.520
59.0    1294.7   84162576.0   84162576.0   84162576.0      43.160      4.320      52.520
```

60.0	1293.4	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
61.0	1292.0	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
62.0	1290.5	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
63.0	1288.9	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
64.0	1287.2	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
65.0	1285.5	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
66.0	1283.8	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
67.0	1282.1	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
68.0	1280.3	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
69.0	1278.6	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
70.0	1276.8	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
71.0	1275.1	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
72.0	1273.3	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
73.0	1271.5	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
74.0	1269.7	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
75.0	1268.0	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
76.0	1266.2	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
77.0	1264.4	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
78.0	1262.6	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
79.0	1260.8	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
80.0	1259.1	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
81.0	1257.3	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
82.0	1255.5	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
83.0	1253.8	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
84.0	1252.1	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
85.0	1250.3	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
86.0	1248.6	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
87.0	1246.9	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
88.0	1245.2	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
89.0	1243.5	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
90.0	1241.9	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
91.0	1240.2	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
92.0	1238.6	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
93.0	1236.9	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
94.0	1235.3	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
95.0	1233.7	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
96.0	1232.1	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
97.0	1230.5	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
98.0	1228.9	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
99.0	1227.3	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520

100.0	1225.8	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
101.0	1224.2	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
102.0	1222.7	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
103.0	1221.2	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
104.0	1219.6	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
105.0	1218.1	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
106.0	1216.7	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
107.0	1215.2	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
108.0	1213.7	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
109.0	1212.3	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
110.0	1210.8	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
111.0	1209.4	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
112.0	1208.0	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
113.0	1206.6	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
114.0	1205.2	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
115.0	1203.8	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
116.0	1202.5	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
117.0	1201.1	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
118.0	1199.8	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
119.0	1198.4	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
120.0	1197.1	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
121.0	1195.8	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
122.0	1194.5	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
122.5	1193.9	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
123.0	1193.2	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
124.0	1192.0	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
125.0	1190.7	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
126.0	1189.5	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
127.0	1188.2	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
128.0	1187.0	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
129.0	1185.8	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
130.0	1184.6	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
131.0	1183.4	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
132.0	1182.2	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
133.0	1181.1	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
134.0	1179.9	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
135.0	1178.8	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
136.0	1177.6	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
137.0	1176.5	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
138.0	1175.4	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
139.0	1174.3	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
140.0	1173.2	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
141.0	1172.1	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
142.0	1171.0	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
143.0	1170.0	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
144.0	1168.9	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
145.0	1167.9	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
146.0	1166.8	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
147.0	1165.8	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
148.0	1164.8	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520
149.0	1163.8	84162576.0	84162576.0	84162576.0	43.160	4.320	52.520

```
150.0    1162.8   84162576.0   84162576.0   84162576.0        43.160      4.320      52.520
151.0    1161.8   84162576.0   84162576.0   84162576.0        43.160      4.320      52.520
152.0    1160.9   84162576.0   84162576.0   84162576.0        43.160      4.320      52.520
153.0    1159.9   84162576.0   84162576.0   84162576.0        43.160      4.320      52.520
154.0    1158.9   84162576.0   84162576.0   84162576.0        43.160      4.320      52.520
155.0    1158.0   84162576.0   84162576.0   84162576.0        43.160      4.320      52.520
156.0    1157.1   84162576.0   84162576.0   84162576.0        43.160      4.320      52.520
157.0    1156.1   84162576.0   84162576.0   84162576.0        43.160      4.320      52.520
158.0    1155.2   84162576.0   84162576.0   84162576.0        43.160      4.320      52.520
159.0    1154.3   84162576.0   84162576.0   84162576.0        43.160      4.320      52.520
160.0    1153.4   84162576.0   84162576.0   84162576.0        43.160      4.320      52.520
161.0    1152.5   84162576.0   84162576.0   84162576.0        43.160      4.320      52.520
162.0    1151.7   84162576.0   84162576.0   84162576.0        43.160      4.320      52.520
163.0    1150.8   84162576.0   84162576.0   84162576.0        43.160      4.320      52.520
164.0    1149.9   84162576.0   84162576.0   84162576.0        43.160      4.320      52.520
165.0    1149.1   84162576.0   84162576.0   84162576.0        43.160      4.320      52.520
166.0    1148.2   84162576.0   84162576.0   84162576.0        43.160      4.320      52.520
167.0    1147.4   84162576.0   84162576.0   84162576.0        43.160      4.320      52.520
168.0    1146.6   84162576.0   84162576.0   84162576.0        43.160      4.320      52.520
169.0    1145.7   84162576.0   84162576.0   84162576.0        43.160      4.320      52.520
170.0    1144.9   84162576.0   84162576.0   84162576.0        43.160      4.320      52.520
171.0    1144.1   84162576.0   84162576.0   84162576.0        43.160      4.320      52.520
172.0    1143.3   84162576.0   84162576.0   84162576.0        43.160      4.320      52.520
173.0    1142.5   84162576.0   84162576.0   84162576.0        43.160      4.320      52.520
174.0    1141.8   84162576.0   84162576.0   84162576.0        43.160      4.320      52.520
175.0    1141.0   84162576.0   84162576.0   84162576.0        43.160      4.320      52.520
176.0    1140.2   84162576.0   84162576.0   84162576.0        43.160      4.320      52.520
177.0    1139.5   84162576.0   84162576.0   84162576.0        43.160      4.320      52.520
178.0    1138.7   84162576.0   84162576.0   84162576.0        43.160      4.320      52.520
179.0    1138.0   84162576.0   84162576.0   84162576.0        43.160      4.320      52.520
180.0    1137.2   84162576.0   84162576.0   84162576.0        43.160      4.320      52.520
181.0    1136.5   84162576.0   84162576.0   84162576.0        43.160      4.320      52.520
182.0    1135.8   84162576.0   84162576.0   84162576.0        43.160      4.320      52.520
183.0    1135.1   84162576.0   84162576.0   84162576.0        43.160      4.320      52.520
184.0    1134.4   84162576.0   84162576.0   84162576.0        43.160      4.320      52.520
185.0    1133.7   84162576.0   84162576.0   84162576.0        43.160      4.320      52.520
186.0    1133.0   84162576.0   84162576.0   84162576.0        43.160      4.320      52.520
187.0    1132.3   84162576.0   84162576.0   84162576.0        43.160      4.320      52.520
188.0    1131.6   84162576.0   84162576.0   84162576.0        43.160      4.320      52.520
189.0    1131.0   84162576.0   84162576.0   84162576.0        43.160      4.320      52.520
190.0    1130.3   84162576.0   84162576.0   84162576.0        43.160      4.320      52.520
191.0    1129.7   84162576.0   84162576.0   84162576.0        43.160      4.320      52.520
192.0    1129.0   84162576.0   84162576.0   84162576.0        43.160      4.320      52.520
193.0    1128.4   84162576.0   84162576.0   84162576.0        43.160      4.320      52.520
194.0    1127.7   84162576.0   84162576.0   84162576.0        43.160      4.320      52.520
195.0    1127.1   84162576.0   84162576.0   84162576.0        43.160      4.320      52.520
196.0    1126.5   84162576.0   84162576.0   84162576.0        43.160      4.320      52.520
197.0    1125.9   84162576.0   84162576.0   84162576.0        43.160      4.320      52.520
198.0    1125.3   84162576.0   84162576.0   84162576.0        43.160      4.320      52.520
199.0    1124.7   84162576.0   84162576.0   84162576.0        43.160      4.320      52.520
```

200.0	824.7	94743088.0	94743088.0	94743088.0	24.721	25.333	49.946
210.0	824.7	86922304.0	86922304.0	86922304.0	24.214	25.911	49.875
220.0	824.7	76551712.0	76551712.0	76551712.0	23.788	26.396	49.816
230.0	824.7	64925184.0	64925184.0	64925184.0	23.444	26.789	49.767
240.0	824.7	53187584.0	53187584.0	53187584.0	23.178	27.092	49.730
250.0	824.7	43313024.0	43313024.0	43313024.0	22.989	27.307	49.704
260.0	824.7	35775392.0	35775392.0	35775392.0	22.876	27.436	49.688
270.0	824.7	30287088.0	30287088.0	30287088.0	22.839	27.478	49.683
280.0	824.7	26669328.0	26669328.0	26669328.0	22.876	27.436	49.688
290.0	824.7	24758288.0	24758288.0	24758288.0	22.989	27.307	49.704
300.0	824.7	24188000.0	24188000.0	24188000.0	23.178	27.092	49.730
310.0	824.7	24108656.0	24108656.0	24108656.0	23.444	26.789	49.767
320.0	824.7	24072784.0	24072784.0	24072784.0	23.788	26.396	49.816
330.0	824.7	24045152.0	24045152.0	24045152.0	24.214	25.911	49.875
340.0	824.7	24022608.0	24022608.0	24022608.0	24.721	25.333	49.946
350.0	824.7	24004288.0	24004288.0	24004288.0	25.314	24.658	50.029
360.0	824.7	23986336.0	23986336.0	23986336.0	25.993	23.883	50.123
370.0	824.7	23956560.0	23956560.0	23956560.0	26.762	23.008	50.231
380.0	824.7	23897984.0	23897984.0	23897984.0	27.620	22.029	50.350
390.0	824.7	23795440.0	23795440.0	23795440.0	28.569	20.948	50.483
400.0	824.7	23642640.0	23642640.0	23642640.0	29.608	19.764	50.628
410.0	824.7	23443472.0	23443472.0	23443472.0	30.732	18.483	50.785
420.0	824.7	23206464.0	23206464.0	23206464.0	31.937	17.110	50.953
430.0	824.7	22944304.0	22944304.0	22944304.0	33.213	15.656	51.131
440.0	824.7	22666560.0	22666560.0	22666560.0	34.546	14.137	51.317
450.0	824.7	22387040.0	22387040.0	22387040.0	35.916	12.576	51.508
460.0	824.7	22114080.0	22114080.0	22114080.0	37.299	10.999	51.702
470.0	824.7	21823904.0	21823904.0	21823904.0	38.665	9.443	51.892
480.0	824.7	21530160.0	21530160.0	21530160.0	39.976	7.949	52.075
490.0	824.7	21238768.0	21238768.0	21238768.0	41.191	6.564	52.245
500.0	824.7	20995952.0	20995952.0	20995952.0	42.267	5.338	52.395
510.0	824.7	20732416.0	20732416.0	20732416.0	43.160	4.320	52.520
520.0	824.7	20485440.0	20485440.0	20485440.0	43.831	3.556	52.613
530.0	824.7	20254048.0	20254048.0	20254048.0	44.247	3.082	52.671
540.0	824.7	20058160.0	20058160.0	20058160.0	44.388	2.921	52.691
550.0	824.7	19856864.0	19856864.0	19856864.0	44.247	3.082	52.671