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A COMPREHENSIVE CYCLE ANALYSIS AND DIGITAL COMPUTER SIMULATION FOR SPARK-IGNITED ENGINES

Donald J. Patterson

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NOMENCLATURE

A	Area
ATC	After top center
a	Atoms of carbon per molecule of fuel
a	Activity
BDC	Bottom center piston position
BTC	Before top center
Bore	Engine bore
b	Atoms of hydrogen per molecule of fuel
C_p	Constant pressure heat capacity per mole
C_v	Constant volume heat capacity per mole
c	Mole ratio of nitrogen to oxygen in atmospheric air
c_p	Constant pressure heat capacity per unit mass
E	Activation energy
F	Exhaust residual mass fraction
F	A constant, $F = RT/V$
F_0	Moles of fuel inducted per engine power cycle
f	Fugacity
G	Gibbs free energy
G	Mass rate of flow per unit area
H	Enthalpy
h	Convective heat transfer coefficient
J	Conversion factor from heat to work units
K_c	Equilibrium constant based on concentrations
K_p	Equilibrium constant based on partial pressures

NOMENCLATURE (CONT'D)

K_1	Flame speed factor (Equation (4-24))
k	Heat capacity ratio
k	Thermal conductivity
L	Hydraulic radius
M	Molecular weight
mep	Indicated mean effective pressure
n	Polytropic exponent
n_i	Number of moles of component 'i'
P	Pressure
p_i	Partial pressure of component 'i'
Q	Amount of heat transferred
q	Rate of heat transfer
R	Universal gas constant
Rod	Engine connecting rod length
r	Compression ratio
rpm	Engine speed
S	Entropy
S_ℓ	Laminar flame speed
S_t	Turbulent flame speed
Stroke	Piston stroke
T	Temperature
TDC	Top center piston position
t	Time
U	Internal energy

NOMENCLATURE (CONT'D)

V	Volume
V_{bot}	Clearance volume plus swept volume
V_{top}	Clearance volume
v	Specific volume
W	Work
w	Average piston velocity
X	Square root of partial pressure of O_2
x	Air-fuel ratio, fraction chemically correct air
Y	Square root of partial pressure of H_2
Z	Square root of partial pressure of N_2
α	Thermal diffusivity, $\alpha = \rho\ c_p/k$
ΔH_c	Enthalpy of combustion
ΔH_f	Enthalpy of formation
η	Thermal efficiency
η_v	Volumetric efficiency
θ	Crank angle degrees, 0° = BDC piston position
θ	$\theta = T/T_0$
μ	Viscosity
ρ	Density
ϕ	Fuel-air ratio, fraction chemically correct fuel, $\phi = 1/x$

SUPERSCRIPTS

$'$	Designates a trial value
o	Ideal gas state

NOMENCLATURE (CONT'D)

SUBSCRIPTS

b	Burned
e	Exhaust manifold
f	Flame element
f	Fuel
i	Inlet manifold
P	Constant pressure
p	Piston
t	Total
u	Unburned
w	Wall
0	Reference state
298	298.16

I. INTRODUCTION

A. Purpose

The purpose of this investigation was to study the four stroke spark ignited internal combustion engine cycle from a fundamental point of view. The effects of mixture composition, combustion chamber geometry, flame propagation, and heat transfer were incorporated into an analytical model, suitable for programming on a digital computer, which approximates more closely than heretofore possible the actual performance of an engine. This work is primarily concerned with the development of such a model and the subsequent evaluation of the individual effects of the heat transfer and flame propagation phenomena on the thermal efficiency and indicated mean effective pressure of the hyphothetical engine. Experimentally determined performance data are compared with values calculated using the analytical model.

B. Previous Work

In 1876 Nicolas Otto constructed the first successful gas engine which employed compression prior to the combustion of the charge. This innovation, although suggested earlier by Beau de Rochas in 1862, produced an engine which was more efficient than any heretofore and marked the beginning of the modern four stroke cycle spark-ignited engine(1, 2). Although it was the introduction of the compression process which accounted for the improved efficiency, Otto himself did not seem to realize this and attributed the improvement in efficiency to a stratification of the charge. Only when thermodynamic analyses of the various gas engine cycles of the day were made were the relative merits of Otto's engine understood.

The earliest attempts to analytically study engines largely followed the fundamental work of Sadi Carnot. As in any mathematical simulation of a real physical process, an analytical model was developed which incorporated the salient features of the physical process which it approximated. In the case of Otto's engine, the processes which the working fluid underwent could be closely approximated by the constant volume cycle, now commonly called the Otto cycle. The Otto cycle is composed of four highly idealized processes (see Figure 1).

Process 1-2. Compression of the working fluid from volume V_1 to V_2. This occurs reversibly and adiabatically, therfore, isentropically.

Process 2-3. Constant volume heat addition. An amount of heat Q_1 is added to the working fluid thereby raising its temperature to T_3 and its pressure to P_3. This occurs when the piston is at the top center position.

Process 3-4. Expansion of the working fluid from V_2 to V_1. This expansion occurs isentropically.

Process 4-1. Constant volume heat rejection. An amount of heat Q_2 is transferred from the working fluid, lowering its temperature to T_1 and its pressure to P_1, thus completing the cycle.

The isentropic compression and expansion follow the path PV^k = a constant, where 'k' is the ratio of heat capacity of the working fluid at constant pressure to that at constant volume. The work of the cycle is $Q_1 - Q_2$ and its thermal efficiency is

$$\eta = \frac{Q_1 - Q_2}{Q_1} \tag{1-1}$$

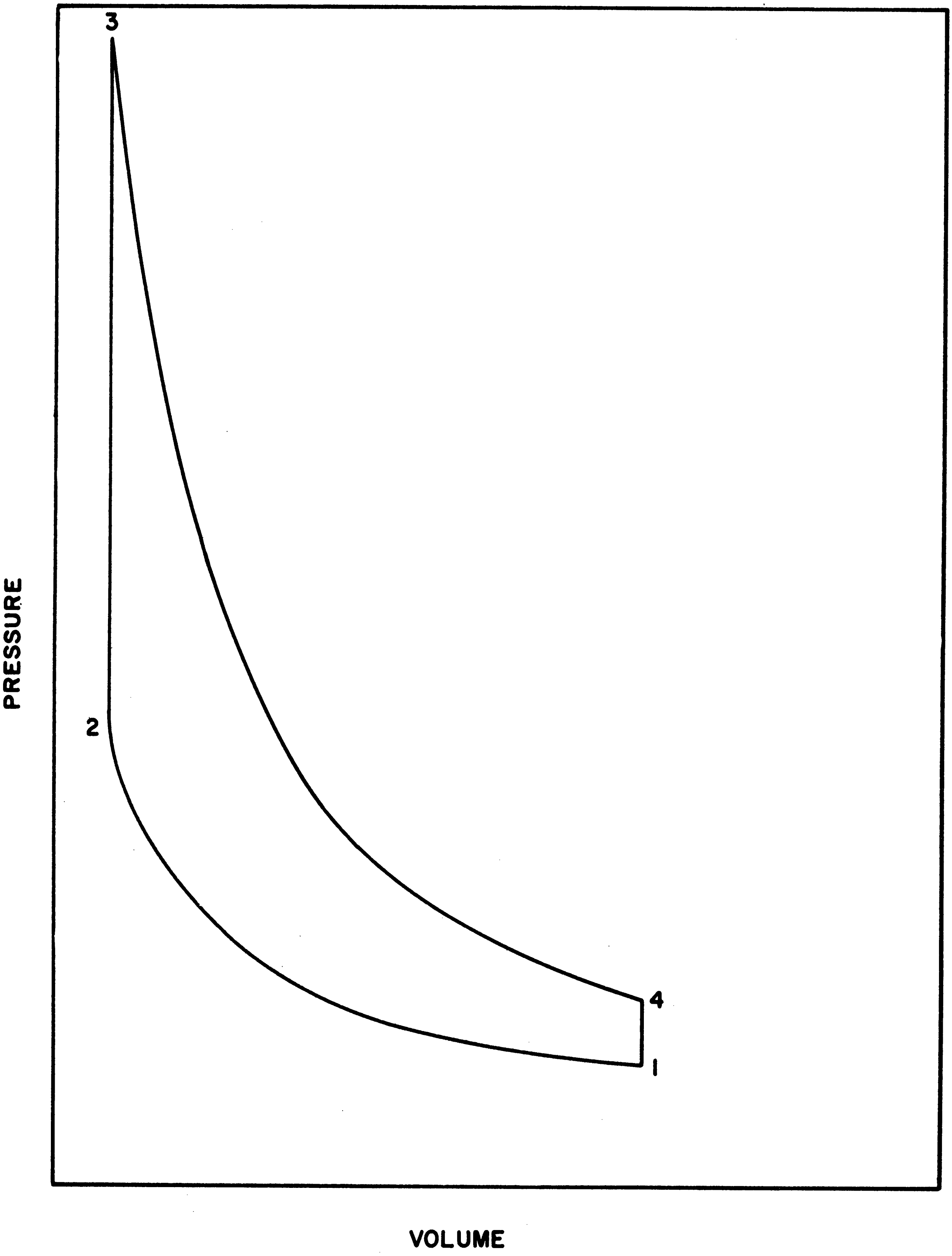


Figure 1. The Otto cycle.

For an Otto cycle engine of compression ratio 'r' this can be expressed as

$$\eta = 1 - (\frac{1}{r})^k \tag{1-2}$$

The mean effective pressure, defined as the quotient of the cycle work and the displacement is

$$\text{mep} = \frac{\eta \cdot Q_1}{V_1 - V_2} \cdot J \tag{1-3}$$

Thus, as a consequence of such an analysis, convenient mathematical expressions were developed for the efficiency and mean effective pressure of an engine operating on this idealized Otto cycle.

Because at this time knowledge about the properties of the working fluid was meager, it was decided to adopt as an analytical model for the Otto cycle, the constant volume cycle operating on an idealized fluid having the properties of air at standard conditions. In 1905 a committee of the Institution of Civil Engineers(3) recommended that the air cycle efficiency be officially adopted as the standard of comparison against which measured values from internal combustion engines might be compared. This decision was based on the result of tests which consistantly showed that at a given compression ratio measured efficiencies were from 50% to 70% of air cycle efficiencies. This report left little doubt concerning the value of compression in the internal combustion engine.

Shortly thereafter, Clerk(4), using heat capacities deduced by experimental methods(5), showed that in considering the actual heat capacity of the working fluid, the attainable thermal efficiencies were considerably lower than those predicted by the air cycle analysis. In 1908, Hopkinson(6) analyzed the Otto cycle engine using the heat capacity of the mixture calculated from the known values for the individual constituents. By this, he was able to quantitatively predict the influence of the fuel-air ratio on the thermal efficiency and mean effective pressure and thus confirm experimental evidence that leaner mixtures tended to give higher thermal efficiencies. His analysis took account of the exhaust residual.

Not until 1921, was an analysis of the constant volume cycle carried out which considered the actual composition of the working fluid including the effects of dissociation. At this time this became possible because accurate heat capacity data and sufficient information on the extent of dissociation of carbon, hydrogen, oxygen, and nitrogen systems at elevated temperatures were available. This analysis, by Tizard and Pye(7), assumed that during compression the working fluid was primarily composed of air, but that after combustion and during expansion, the working fluid consisted of O_2, N_2, CO_2, H_2O, CO, and H_2 in a state of chemical equilibrium. Because of the complexity of the analysis, no analytical expressions for thermal efficiency or mean effective pressure could be derived.

Whereas the effect of compression ratio on the performance of the Otto cycle engine was shown by the air cycle analysis, that of mixture composition was shown by Clerk's analysis, and that of fuel-air ratio was shown by Hopkinson's analysis, the effects of dissociation were introduced by Tizard and Pye. In doing so they answered three pressing problems of the day. First, because of dissociation effects, the highest combustion temperatures and mean effective pressures occur with mixtures 10 to 15 percent richer than stoiciometric. Second, for increasingly rich mixtures the mean effective pressure, which is a measure of the power output, is relatively constant and only decreases slowly as the fuel-air ratio is increased. Third, the thermal efficiency of the engine increases as the mixture is leaned out. This last effect is due to the fact that both heat capacity and dissociation increase with an increase in temperature.

Whereas the best measured thermal efficiencies are as low as 50 to 70 percent of the air cycle efficiency, they are 80 to 85 percent of those calculated by Tizard and Pye's method. Many people had been openly critical of the validity of the air cycle analysis, but now it was realized that at a given compression ratio, the efficiency calculated from the air cycle represented an optimum value which could be approached in practice only with very lean mixtures. This study was the first of many which analyzed the Otto cycle engine in this manner.

In 1924, Goodenough and Felbeck(8) presented a comprehensive discussion of the theory of chemical equilibrium and the effects of dissociation on the maximum temperatures and pressures attainable in combustion processes. Using the results of this analysis Goodenough and Baker(9), in 1927, presented a complete thermodynamic analysis of the Otto cycle together with the results of numerous calculations. Their analysis followed along the same lines as Tizard and Pye's, but in addition included the effects of the mixing of the exhaust residual with the fresh charge.

In 1935, Hershey, Eberhardt, and Hottel(10) presented thermodynamic charts from which the properties of the working fluid in the Otto cycle engine could be read. These eliminated the tedious calculations of Goodenough and Baker. The charts, based on spectroscopic heat capacity data, allowed for complex dissociation at high temperatures. The species included O_2, N_2, CO_2, H_2O, CO, H_2, OH, NO, O, and H in the products of combustion.

The charts have been widely used from the time of their introduction for the analysis of the Otto cycle engine and have been revised a number of times to allow for improvements in fundamental data (see bibliography of Reference 11). While the charts allow a considerable reduction in the mathematical difficulties of the Otto cycle analysis, they are not general, having been developed for a particular fuel and a selected number of fuel-air ratios. The analysis of the Otto cycle proposed by Hershey, Eberhardt, and Hottel was very similar to that proposed by Goodenough and Baker but considered the induction and exhaust processes in detail.

The Otto cycle is termed the fuel-air cycle when the actual properties of the working fluid are considered just as it was termed the air cycle when air was considered to be the working fluid. The fuel-air cycle is described in more detail in Chapter III.

In spite of the refinements of the fuel-air cycle analysis, measured thermal efficiencies were still between 80 and 90 percent of those calculated. This is because many important phenomena present in actual engines are disregarded in the simplicity of the Otto cycle engine. Two significant items neglected are the flame propagation and the heat transfer. However incorporating these effects into an analytical model poses extremely complex mathematical problems. Nevertheless some investigators have attempted to include one or another of these phenomena in their analysis.

Attempts to consider the effects of flame propagation (progressive burning of the charge), were first made in connection with thermodynamic studies of combustion in constant volume bombs. Among the earliest was an analysis by Nagel(12) in 1907. A similar analysis was made by

Rosecrans(13) in 1926 which made use of the equilibrium studies of Goodenough and Felbeck. Endres(14) was among the first to consider the effects of piston motion. Hershey, Eberhardt and Hottel(10) suggested a method by which the temperature gradients in a constant volume bomb could be calculated considering mixture composition, variable specific heats, and dissociation. In 1937, Hottel and Eberhardt(15) extended the work of Reference 10 and proposed a method for calculating the temperature gradients in an engine considering both piston motion and spark advance. Pressure volume diagrams were calculated for the combustion portion of the cycle assuming no heat was transfered to the cylinder walls.

Rassweiler and Withrow(16) and Rassweiler, Withrow, and Cornelius (17) suggested a method for treating the combined effects of flame propagation and piston motion in internal combustion engines in order to analyze combustion photographs. In 1940 Withrow and Cornelius(18) proposed a method for calculating the pressure rise in an internal combustion engine. They combined the analysis of the previous two references with the thermodynamic charts of Reference 10. Rabezanna, Kalmar, and Candelise(19) in 1939, proposed a method for the analysis of flame propagation and expansion during combustion which took into acount combustion chamber geometry, spark advance, and piston motion. Although this analysis considered the thermodynamics of the working fluid in an uncomplicated manner, pressure-time diagrams could be calculated from measured flame propagation rates by their method.

These analyses of flame propagation in internal combustion engines were hindered in two respects. First, fundamental information about the nature of the flame propagation in an internal combustion engine was not available. Second, the sheer magnitude of the calculations involved, assuming that flame propagation information were available, would have precluded any extensive analysis. All of these studies assumed that the engine operated under adiabatic conditions.

In 1940, David and Leah(20) presented charts of "attainable thermal efficiency" and fuel consumption for Otto cycle engines. These charts were computed from an analysis similar to that of Hershey, Eberhardt, and Hottel, but included a prescribed amount of heat transfer during the constant volume combustion and subsequent expansion.

A concise presentation of References 10 and 15 was published in 1948(11), the thermodynamic charts having been revised in light of more accurate thermodynamic data. However no new technique for internal combustion engine analysis was introduced. In 1950, Leah(21) illustrated a technique for approximating the thermal efficiencies the Otto cycle engine for any hydrocarbon fuel from charts. Edson(22) in 1961 presented the results of calculations on the fuel-air cycle model made on a digital computer. These convered a wide range of variables. A portion of the work done in the investigation being reported involves an analysis similar to that made by Edson and is reported in Chapter III.

The problem of considering the combined effects of mixture composition, variable specific heats, dissociation, flame propagation, and heat transfer simultaneously presented such a formidable mathematical obstacle that not until the widespread use of automatic computing machines was such an analysis contemplated. In 1960, Edson(23)proposed an analytical model for combustion in the internal combustion engine which was suitable for programming on a digital computer. His analysis included the effects of flame propagation and piston motion but did not include heat transfer. To date no computed results have been reported.

C. Scope of This Paper

The remainder of this paper describes the development and evaluation of a comprehensive cycle analysis and digital computer simulation for spark-ignited internal combustion engines. Chapter II describes a method which is used for the determination of the thermodynamic properties and composition of the working fluid. Chapter III presents the results of computations using a well known internal combustion engine cycle analysis but employing the methods of Chapter II to describe the working fluid.

Chapters IV and V discuss the nature of the flame propagation and heat transfer in the spark-ignited engine. Chapter VI describes an analytical model for engine cycle calculation which includes both heat transfer and flame propagation effects. Chapter VII presents results of computer calculation made using this analytical model. These are compared with experimental engine data.

II. THE THERMODYNAMIC PROPERTIES AND COMPOSITION OF THE WORKING FLUID IN A SPARK-IGNITED ENGINE

A. General

This chapter describes a method by which the thermodynamic properties and composition of the working fluid of an internal combustion engine can be calculated. The method presented is ultimately employed to describe the working fluid of the "analytical model" engine proposed in Chapter VI. It is also employed in the fuel-air engine cycle analysis discussed in Chapter III.

For the reaction between a hydrocarbon fuel and oxygen and nitrogen, the following equation can be written when stoiciometric proportions of oxygen and nitrogen, subsequently referred to as air, are present:

$$C_aH_b + (a+b/4)O_2 + c(a+b/4)N_2 = aCO_2 + b/2H_2O + c(a+b/4)N_2 \quad (2\text{-}1)$$

where 'c' is the mole ratio of nitrogen to oxygen in air and 'a' and 'b' are the number of carbon and hydrogen atoms in a molecule of fuel. When an excess of air is present, the following equation can be written:

$$C_aH_b + x(a+b/4)O_2 + cx(a+b/4)N_2 = aCO_2 + b/2H_2O + (x-1)(a+b/4)O_2 + cx(a+b/4)N_2 \quad (2\text{-}2)$$

where 'x' is the fraction of chemically correct air entering the reaction. When 'x' is less than one, that is for rich mixtures, no oxygen is present in the products but some CO and H_2 will be. These equations tend to over simplify the combustion process and many more chemical species will be present in the products due to dissociation.

While it is true that atmospheric air contains substances other than oxygen and nitrogen, only water vapor exists to any appreciable extent. In order to establish a reference base for all the calculations, dry air is assumed. Dry air at sea level has the following composition(24):

Basis: 100 moles dry air

O_2		20.99
N_2	78.03	
A	0.94	
CO_2	0.03	
H_2	0.01	79.01
		100.00

For the purposes of this work, the argon, carbon dioxide, and hydrogen normally found in air are lumped together with the nitrogen and are assumed to have the same thermodynamic properties as nitrogen. Thus air is assumed to be composed of 79.01 parts of nitrogen by volume to 20.99 of oxygen, their ratio 'c' being 3.764 to 1. The error in the value of the thermodynamic properties calculated on this basis is about 0.4% or less.

Furthermore, all substances including the fuel are treated as ideal gases and mixtures are assumed to follow Dalton's law of partial pressures. The error in the thermodynamic properties introduced by this assumption varies as it depends on the temperature and pressure. Because of the nature of the Otto cycle, the highest pressures always coincide with the highest temperatures and thus the deviation from ideal gas behavior tends to be small. Such deviations as may exist are greatest during the induction and compression processes. Reference 11 presents charts for corrections to ideal gas thermal functions calculated by the Beattie-Bridgman equation of state for octene-air mixtures. For such a hydrocarbon-air mixture which is compressed isentropically from room temperature and pressure, the ideal gas thermodynamic properties will be no more than about 0.5 percent greater than those of the real gas for the states encountered along this path.

B. Calculation of Ideal Gas Thermodynamic Properties

1. Empirical Heat Capacity Equations

In a carbon, hydrogen, oxygen, nitrogen system at high temperatures, dissociation produces many chemical species whose individual thermodynamic properties must be known in order to compute the gross properties of the working fluid which they comprise. These thermodynamic properties are normally presented in tabular form or may be calculated from equations approximating the tabular data. Since the analytical model for the internal combustion engine presented in this study is designed to be simulated mathematically on a digital computer, it was decided to calculate the thermodynamic properties from ideal gas empirical heat capacity equations. This obviates the use of a large amount of computer storage capacity for the tables.

Hougen, Watson, and Ragatz have tabulated a number of heat capacity equations in the appendix of their recent text(25) which includes most of the equations developed by Kobe and his associates(26). Either a single equation was used for a rather narrow temperature range (such as 273-1500°K) giving fairly accurate results, but not covering the higher temperatures, or a single equation for a larger temperature range (such as 273-3800°K) with a significant decrease in accuracy. Spencer(27) presents heat capacity equations calculated by the method of least squares for a number of hydrocarbons. Williams(28) presents heat capacity equations for a large number of substances. Two sets of constants are given for each substance, one set for the temperature range 500-3000°K, the other for the range 3000-6000°K. In these references the constants for the empirical heat capacity equations are presented as five or six digit numbers.

In order to achieve greater accuracy than the above equations afford in the desired temperature range, it was decided to develope highly accurate empirical heat capacity equations for the required substances. Two equations were developed for each compound, the first covering the range 298.16-1500°K and the second the range 1500-3500°K. Moreover, since a high speed computing machine capable of handling eight digit numbers was to be employed, the constants were calculated and used as eight digit numbers. The basic data used to develope the equations came from tables of ideal gas heat capacity at one atmosphere as a function of temperature. For the substances employed here, two sources were used, the American Petroleum Institute Report 44(29) and the National Bureau of Standards Circular 564(30). Using these data, empirical equations for the heat capacity as a function of temperature were developed by the method of least squares, the details of which are given in Appendix A. The equations for each substance are of the form:

$$C_p = a_0 + a_1T + a_2T^2 + a_3T^3 \qquad (2\text{-}3)$$

298.16-1500°K

$$C_p = b_0 + b_1T + b_2T^2 + b_3T^3 \qquad (2\text{-}4)$$

1500-3500°K

Table I gives the data source, the a's and b's, the maximum percent deviation, and the root mean square deviation for those substances which comprise the working fluid of an internal combustion engine. For these substances Table II lists the enthalpies of formation and absolute entropies at 298.16°K, the enthalpies and entropies at 1500°K, and the enthalpy and free energy of reaction at 1500°K, for selected reactions (all quantities at 1 atmosphere pressure). Table III gives selected values of heat capacity as a function of temperature, listing both the tabular and calculated value at each point. The heat capacity representation in the range 1500-3500°K proved to be very accurate. The maximum deviation for any of the substances considered was less than 0.1 percent of the tabular value. In this range, the use of such approximating equations will represent the tabular function within the stated uncertainty of the table. In the range from 298.16-1500°K, where the heat capacity function changes rapidly with temperature, the accuracy is less. The maximum percentage deviation is about 0.6 percent of the tabular value for some substances, less than 0.3 percent for most.

2. Computation of Thermodynamic Functions and Equilibrium Constants From Empirical Heat Capacity Equations

The computation of the ideal gas thermodynamic functions and equilibirum constants from the empirical heat capacity equations developed in the previous section is most conveniently made by arranging the constants for each substance (the a's and b's) and the necessary fundamental data in matrix form. The thermodynamic functions then can be calculated, as required, by a series of matrix multiplications. This procedure is outlined in Appendix C.

TABLE I

IDEAL GAS EMPIRICAL HEAT CAPACITY EQUATIONS

$C_p^o = a_0 + a_1T + a_2T^2 + a_3T^3$ cal/mole-°K
298.16-1500°K

Substance	Data Source	*a_0	a_1	a_2	a_3	Max. % Dev.	RMS Dev.
O_2	NBS-564	0.61907849E+01	0.29234242E-02	-0.70522172E-06	-0.80285969E-10	0.64	0.022
N_2	API-44	0.70507626E+01	-0.11515000E-02	0.30557188E-05	-0.11525971E-08	0.35	0.015
CO_2	NBS-564	0.51113583E+01	0.15430851E-01	-0.99580134E-05	0.24073171E-08	0.36	0.020
H_2O	NBS-564	0.77613959E+01	0.19662306E-04	0.31476535E-05	-0.10812777E-08	0.22	0.0092
CO	API-44	0.69101229E+01	-0.56810040E-03	0.26467764E-05	-0.10721376E-08	0.47	0.020
H_2	NBS-564	0.68529104E+01	0.16183303E-03	0.61791131E-07	0.14864846E-09	0.53	0.018
OH	API-44	0.76220243E+01	-0.24470010E-02	0.29835421E-05	-0.82731476E-09	0.30	0.0063
NO	API-44	0.70200658E+01	-0.36766843E-03	0.25451986E-05	-0.10864604E-09	0.68	0.029
O	API-44	0.55969158E+01	-0.16383585E-02	0.14788035E-05	-0.44240119E-09	0.31	0.0080
H	API-44	0.49680000E+01	0.000000000000	0.000000000000	0.000000000000	0.0	0.0
n-Heptane	API-44	-0.11854254E+01	0.16126768E+00	-0.86976233E-04	0.18208351E-07	0.30	0.084
n-Octane	API-44	-0.14126484E+01	0.18397817E+00	-0.99985303E-04	0.21072621E-07	0.30	0.092
1-Octene	API-44	-0.59674715E+00	0.17107204E+00	-0.94379942E-04	0.20222447E-07	0.21	0.086

$C_p^o = b_0 + b_1T + b_2T^2 + b_3T^3$ cal/mole-°K
1500-3500°K

Substance	Data Source	*b_0	b_1	b_2	b_3	Max. % Dev.	RMS Dev.
O_2	NBS-564	0.78906694E-01	0.51781745E-03	0.53216719E-07	-0.13820401E-10	0.028	0.0009
N_2	API-44	0.64837196E+01	0.19298323E-02	-0.54849168E-06	0.56397533E-10	0.056	0.0021
CO_2	NBS-564	0.10728501E+02	0.33912981E-02	-0.97734787E-06	0.10230199E-09	0.070	0.0044
H_2O	NBS-564	0.53120816E+01	0.58710071E-02	-0.14930128E-05	0.14120276E-09	0.026	0.0019
CO	API-44	0.67392679E+01	0.17599157E-02	-0.50255810E-06	0.51864546E-10	0.052	0.0021
H_2	NBS-564	0.52684432E+01	0.22852214E-02	-0.50854453E-06	0.48668136E-10	0.050	0.0019
OH	API-44	0.54319835E+01	0.23640016E-02	-0.57035617E-06	0.53582743E-10	0.018	0.0009
NO	API-44	0.71280200E+01	0.15047494E-02	-0.43395095E-06	0.46032279E-10	0.048	0.0019
O	API-44	0.50290719E+01	-0.34659544E-04	-0.42474464E-08	0.43342867E-11	0.001	0.0002
H	API-44	0.49680000E+01	0.000000000000	0.000000000000	0.000000000000	0.0	0.0

*Note 0.xx .... E$\pm$ xx = (0.xx ...)$\cdot$($10^{\pm xx}$)

TABLE II

*FUNDAMENTAL THERMODYNAMIC PROPERTIES

Substance	ΔH^o_{f298} cal/mole	S^o_{298} cal/mole-°K	$(H^o_{1500}-H^o_{298}) +\Delta H^o_{f298}$ cal/mole	S^o_{1500} cal/mole-°K	ΔH^o_{c298} kcal/mole
O_2	0	49.014[b]	9705.3[b]	61.6639[b]	--
N_2	0	45.767[a]	9181.3[a]	57.786[a]	--
CO_2	-94051.8[a]	51.070[b]	-79303.6[b]	69.812[b]	--
H_2O	-57797.9[a]	45.106[b]	-46303.6[b]	59.8567[b]	--
CO	-26415.7[a]	47.301[a]	-17130.3[a]	59.436[a]	--
H_2	0	31.208[b]	8673.6[b]	42.7206[b]	--
OH	10060.0[a]	43.888[a]	18863.3[a]	55.568[a]	--
NO	21600.0[a]	50.339[a]	31099.8[a]	62.760[a]	--
O	59159.0[a]	38.469[a]	65204.9[a]	46.641[a]	--
H	52089.0[a]	27.327[a]	58059.7[a]	35.419[a]	--
n-Heptane	44890.0[a]	102.24[a]	--	--	1075.85[a]
n-Octane	49820.0[a]	111.55[a]	--	--	1222.77[a]
1-Octene	19820.0[a]	110.55[a]	--	--	1194.97[a]

Reaction	ΔH^o_{1500} cal/mole	$(\Delta G^o/RT)_{1500}$
$CO_2 = CO + \frac{1}{2}O_2$	67026.0	12.192
$H_2O = H_2 + \frac{1}{2}O_2$	59830.0	13.180
$NO = \frac{1}{2}N_2 + \frac{1}{2}O_2$	-21656.0	-5.7379
$OH = \frac{1}{2}H_2 + \frac{1}{2}O_2$	-9673.8	-1.5465
$O = \frac{1}{2}O_2$	-60352.0	-12.292
$H = \frac{1}{2}H_2$	-53723.0	-10.948

* All quantities at 1 atmosphere pressure.

[a] Reference 29.

[b] Reference 30.

TABLE III

CALCULATED AND TABULAR VALUES OF IDEAL GAS HEAT CAPACITY, C_p^o

Units: cal/mole-°K

Temp (°K)	n-Octane	O_2	N_2	CO_2	H_2O	CO	H_2	OH	NO	O	H
298.16	45.11	6.998	6.949	8.891	8.018	6.948	6.911	7.136	7.108	5.228	4.968
	45.14	-----	6.960	-----	-----	6.965	-----	7.141	7.137	5.236	4.968
300.00	45.35	7.002	6.949	8.909	8.021	6.949	6.911	7.134	7.109	5.227	4.968
	45.35	7.024	6.961	8.895	8.027	6.965	6.895	7.139	7.134	5.234	4.968
500.00	68.21	7.466	7.095	10.638	8.423	7.154	6.968	7.041	7.337	5.092	4.968
	68.32	7.431	7.070	10.665	8.415	7.120	7.000	7.048	7.289	5.080	4.968
700.00	85.61	7.864	7.347	11.859	8.947	7.442	7.047	7.087	7.637	5.023	4.968
	85.66	7.884	7.351	11.845	8.954	7.451	7.037	7.087	7.657	5.028	4.968
900.00	98.54	8.192	7.649	12.688	9.540	7.761	7.157	7.233	7.959	4.998	4.968
	98.43	8.212	7.671	12.667	9.546	7.787	7.142	7.234	7.990	5.005	4.968
1100.00	108.0	8.446	7.947	13.240	10.153	8.061	7.304	7.439	8.249	4.995	4.968
	108.0	8.439	7.947	13.243	10.151	8.058	7.305	7.440	8.243	4.994	4.968
1300.00	115.1	8.623	8.186	13.631	10.731	8.289	7.494	7.665	8.457	4.994	4.968
	115.2	8.605	8.165	13.656	10.723	8.265	7.516	7.663	8.426	4.986	4.968
1500.00	120.7	8.718	8.309	13.977	11.224	8.395	7.736	7.872	8.528	4.974	4.968
	120.6	8.739	8.330	13.952	11.233	8.419	7.720	7.875	8.560	4.982	4.968
1500.00	-----	8.740	8.335	13.962	11.236	8.423	7.716	7.876	8.564	4.982	4.968
	-----	8.739	8.330	13.952	11.233	8.419	7.720	7.875	8.560	4.982	4.968
2000.00	-----	9.029	8.601	14.420	12.212	8.664	8.194	8.307	8.770	4.977	4.968
	-----	9.029	8.602	14.423	12.213	8.665	8.195	8.308	8.771	4.977	4.968
2500.00	-----	9.302	8.761	14.697	12.865	8.808	8.564	8.614	8.897	4.984	4.968
	-----	9.301	8.759	14.691	12.862	8.806	8.565	8.614	8.895	4.983	4.968
3000.00	-----	9.550	8.860	14.868	13.300	8.896	8.861	8.838	8.980	5.004	4.968
	-----	9.551	8.861	14.872	13.303	8.898	8.859	8.838	8.981	5.004	4.968
3500.00	-----	9.762	8.937	15.012	13.625	8.966	9.124	9.016	9.052	5.042	4.968
		9.762	8.934	15.005	------	8.963	9.123	9.015	9.049	5.041	4.968

Underlined entry is tabular value.

Tables IV and V list the calculated values of enthalpy and entropy alongside their corresponding tabular values as a function of temperature. The values of enthalpy are calculated from the following expression:

$$H^o_T - H^o_0 = H^o_T - H^o_{T_0} + (H^o_{T_0} - H^o_0)$$

where

$$H^o_T - H^o_{T_0} = \int_{T_0}^{T} C^o_p dT$$

The entropy is calculated from

$$S^o_T = S^o_T - S^o_{T_0} + (S^o_{T_0})$$

where

$$S^o_T - S^o_{T_0} = \int_{T_0}^{T} \frac{C^o_p}{T} dT$$

The quantities $(H^o_{T_0} - H^o_0)$ and $(S^o_{T_0})$ are the tabular values at the reference temperature 'T_0'. For the substances reported here they are from the data sources indicated in Table I and are doubly underlined in Tables IV and V. The low temperature range reference temperature is 298.16°K for the substances from API 44 and 300°K for those from NBS 564. The high temperature range reference temperature is 1500°K in every case. In general, the calculated values of enthalpy and entropy deviate less, percentagewise, from their tabulated values than do the calculated values of the heat capacity from tabular values. Such calculations for mixtures are always more accurate than the least accurate component.

TABLE IV

CALCULATED AND TABULAR VALUES OF IDEAL GAS ENTHALPY, $H^o - H^o_0$

Units: cal/mole

Temp (°K)	n-Octane	O_2	N_2	CO_2	H_2O	CO	H_2	OH	NO	O	H
298.16	8608.0	2074.8	2072.3	2238.3	2366.8	2072.6	2023.8	2106.2	2194.2	1607.4	1481.2
	8608.0	------	2072.3	------	------	2072.6	------	2106.2	2194.2	1607.4	1481.2
300.00	8691.0	2087.6	2085.1	2254.7	2381.5	2085.4	2036.5	2119.3	2207.3	1617.0	1490.3
	8691.0	2087.6	2085.1	2254.7	2381.5	2085.6	2036.5	2119.2	2206.8	1617.0	1490.4
500.00	20147.0	3535.5	3487.2	4218.9	4023.5	3493.8	3424.2	3534.2	3650.2	2647.6	2483.9
	20130.0	3528.9	3485.0	4223.6	4021.0	3490.0	3429.5	3535.0	3644.0	2645.4	2484.0
700.00	35612.0	5069.7	4930.1	6476.1	5758.8	4952.4	4825.3	4945.0	5146.9	3658.2	3477.5
	35581.0	5062.1	4925.3	6482.0	5756.7	4945.5	4831.8	4946.9	5136.6	3655.5	3477.6
900.00	54093.0	6676.5	6429.3	8936.4	7606.8	6472.6	6245.1	6375.7	6706.5	4659.7	4471.1
	54081.0	6673.8	6428.0	8938.2	7606.1	6471.0	6248.4	6377.4	6700.5	4658.7	4471.2
1100.00	74799.0	8341.6	7989.5	11532.9	9576.2	8055.6	7690.5	7842.3	8328.2	5658.8	5464.7
	74767.0	8340.3	7991.5	11532.2	9576.1	8056.4	7692.9	7844.1	8323.7	5658.4	5464.7
1300.00	97142.0	10049.9	9604.3	14221.8	11665.6	9692.2	9169.5	9352.8	10000.7	6657.9	6458.3
	97162.0	10045.4	9604.7	14224.6	11664.4	9690.2	9174.2	9354.8	9991.8	6656.4	6458.3
1500.00	120736.0	11785.4	11256.1	16982.4	13862.9	11363.0	10691.7	10907.2	11701.9	7655.2	7451.9
	120750.0	11780.0	11253.6	16986.5	13861.1	11358.0	10697.4	10909.5	11694.0	7653.3	7451.9
1500.00	--------	11780.0	11253.6	16986.5	13861.1	11358.0	10697.4	10909.5	11694.0	7653.3	7451.9
	--------	11780.0	11253.6	16986.5	13861.1	11358.0	10697.4	10909.5	11694.0	7653.3	7451.9
2000.00	--------	16222.7	15492.7	24091.1	19738.8	15635.0	14680.3	14961.0	16032.0	10142.8	9935.9
	--------	16223.2	15494.8	24093.1	19739.2	15636.0	14795.0	14960.0	16030.0	10142.8	9936.0
2500.00	--------	20806.2	19836.7	31376.3	26019.1	20006.0	18873.3	19196.0	20451.0	12632.6	12419.9
	--------	20806.4	19839.0	31377.2	26019.1	20008.0	18873.3	19193.0	20450.0	12632.5	12420.0
3000.00	--------	25520.4	24243.7	38770.4	32567.1	24434.0	23231.8	23562.0	24921.0	15128.8	14903.9
	--------	25520.8	24245.4	38770.4	32567.2	24435.0	23231.7	23559.0	24924.0	15128.7	14904.0
3500.00	--------	30350.1	28693.0	46240.0	39301.0	28899.0	27728.8	28026.0	29429.0	17639.3	17387.9
	--------	30350.8	28697.0	46241.3	-------	28900.0	27728.9	28025.0	29428.0	17639.3	17388.0

Underlined entry is tabular value.

TABLE V

CALCULATED AND TABULAR VALUES OF IDEAL GAS ENTROPY, S^o, AT 1 ATMOSPHERE PRESSURE

Units: cal/mole-°K

Temp (°K)	n-Octane	O_2	N_2	CO_2	H_2O	CO	H_2	OH	NO	O	H
298.16	111.55	49.014	45.767	51.070	45.106	47.301	31.208	43.888	50.339	38.469	27.393
	111.55	------	45.767	------	------	47.301	------	43.888	50.339	38.469	27.393
300.00	111.83	49.057	45.810	51.125	45.150	47.344	31.251	43.932	50.383	38.501	27.423
	111.84	49.057	45.809	51.125	45.154	47.343	31.251	43.932	50.384	38.501	27.423
500.00	140.59	52.745	49.388	56.104	49.340	50.937	34.793	47.548	54.063	41.136	29.961
	140.56	52.729	49.385	56.116	49.333	50.927	34.808	47.553	54.048	41.131	29.961
700.00	166.45	55.322	51.813	59.890	52.255	53.388	37.150	49.921	56.578	42.837	31.633
	166.37	55.304	51.805	59.904	52.248	53.373	37.166	49.927	56.557	42.831	31.633
900.00	189.60	57.340	53.695	62.977	54.574	55.296	38.933	51.718	58.537	44.096	32.881
	189.53	57.328	53.692	62.986	54.568	55.287	38.945	51.723	58.520	44.091	32.881
1100.00	210.34	59.010	55.260	65.581	56.548	56.884	40.383	53.189	60.163	45.098	33.878
	210.28	58.999	55.259	65.587	56.543	56.878	40.394	53.194	60.150	45.094	33.878
1300.00	228.99	60.436	56.608	67.826	58.292	58.250	41.618	54.450	61.559	45.933	34.708
	228.98	60.423	56.606	67.835	58.286	58.243	41.630	54.457	61.544	45.928	34.708
1500.00	245.86	61.678	57.790	69.801	59.863	59.445	42.707	55.562	62.776	46.646	35.419
	245.84	61.664	57.786	69.812	59.857	59.436	42.720	55.568	62.760	46.641	35.419
1500.00	------	61.664	57.786	69.812	59.857	59.436	42.720	55.568	62.760	46.641	35.419
	------	61.664	57.786	69.812	59.857	59.436	42.720	55.568	62.760	46.641	35.419
2000.00	------	64.218	60.223	73.897	63.232	61.895	45.008	57.896	65.254	48.074	36.848
	------	64.218	60.225	73.896	63.232	61.896	45.008	57.894	65.252	48.074	36.848
2500.00	------	66.262	62.161	77.147	66.032	63.845	46.878	59.785	67.226	49.185	37.957
	------	66.263	62.164	77.147	66.032	63.845	46.878	59.781	67.225	49.185	37.957
3000.00	------	67.981	63.768	79.842	68.418	65.459	48.467	61.376	68.856	50.095	38.862
	------	67.981	63.769	79.841	68.419	65.459	48.466	61.374	68.857	50.095	38.863
3500.00	------	69.469	65.139	82.145	70.494	66.836	49.852	62.752	70.245	50.869	39.628
	------	69.470	65.140	82.144	------	66.835	49.852	62.751	70.247	50.869	39.629

Underlined entry is tabular value.

Table VI lists values of the equilibrium constants, calculated from Equation (C-5) (see Appendix C) for the principle dissociation reactions in the high temperature products of a hydrocarbon-air reaction. A derivation of the expression for the equilibrium constant as a function of temperature is presented in Appendix B. The calculated values of the equilibirum constants usuallly deviate less, percentagewise, from their tabulated values than does the maximum percentage deviation exhibited by the heat capacity function of any of the reaction constituents. However, since the calculation for the equilibrium constant involves differences of thermodynamic functions, the percent deviation tends to get larger as the absolute magnitude of the equilibrium constant diminishes. Because the heat capacity data were taken from several references no strickly comparable tabular values are available.

In Tables III, IV, and V, a double entry is made at 1500°K. This is the break point between the two temperature ranges. The first entry is calculated from the heat capacity equations for the lower range whereas the second is calculated from those for the higher range. Any discontinuity at 1500°K could be removed by adding appropriate constants to the fundamental data at the beginning of each temperature range. However, as no particular advantage could be seen in doing this, it was not done.

Appendix C also indicates the proceedure used to calculate

$(\frac{\partial H}{\partial T})_P$ and $(\frac{\partial S}{\partial T})_P$.

TABLE VI

CALCULATED VALUES OF Log_{10} OF THE EQUILIBRIUM CONSTANT, K_p

Temp (°K)	Reaction					
	$CO_2 = CO + 1/2O_2$	$H_2O = H_2 + 1/2O_2$	$OH = 1/2O_2 + 1/2H_2$	$NO = 1/2N_2 + 1/2O_2$	$H = 1/2H_2$	$O = 1/2O_2$
1500.00	-5.294	-5.721	0.6711	2.491	4.755	5.338
2000.00	-2.863	-3.535	0.3214	1.703	2.790	3.135
2500.00	-1.418	-2.218	0.1150	1.230	1.601	1.808
3000.00	-0.4642	-1.337	-0.0203	0.9155	0.8029	0.9205
3500.00	0.2112	-0.7061	-0.1145	0.6921	0.2302	0.2856

C. The Composition of the Products of Combustion

1. Assumption of Chemical Equilibrium

Having developed a scheme by which the thermodynamic properties of a system can be calculated when the chemical composition of that system is known, it is now necessary to investigate the nature of high temperature combustion in order to establish not only what chemical species exist, but also the amount of each. The conditions under which combustion occurs are always idealized for the purpose of calculation and assumptions of homogeneity, steady state, and absence of wall effects are made which then allow the subject to be treated by the methods of steady state thermodynamics. Throughout this work such assumptions were made in determining the composition of the products of combustion.

Combustion in an internal combustion engine occurs under conditions which are often far from ideal. Consequently results based on such calculations generally tend to over estimate the performance of the engine. Thus it is necessary to investigate the above mentioned assumptions in order to predict, at least qualitatively, in so far as possible, what effects deviations from these idealizations might have upon the chemical composition of the working fluid and ultimately upon the performance of the engine.

Homogeneity

It is a long established fact that the mixture in an internal combustion engine is not entirely homogeneous(34). Aside from wall effects, which will be discussed later, the the inhomogeneity arises during the induction of the fresh charge. During this process a mixture of air and both gaseous and liquid fuel in the form of droplets is inducted and mixed with residual exhaust gas. Whether or not efficient mixing occurs depends largely on the design of the carburator, manifold, and inlet valve as well as the engine speed. In any event the charge during compression is composed more or less of pockets rich in exhaust gas interspersed within regions of charge, some of which are richer and other leaner than the measured fuel-air ratio. When combustion occurs, the products are hetrogeneous, reflecting the fact that the initial mixture was not homogeneous. Thus, for example, if a stoiciometric mixture of fuel and air were burned, one might expect to find evidence of products resulting from both rich and lean combustion. That is, carbon dioxide and hydrogen as well as oxygen would be present in concentrations in excess of expected equilibrium amounts. David and Leah(20) have an interesting discussion of inhomogeneities caused by improper mixing. The effect of these inhomogeneities, assuming the difficulties of ignition and flame propagation can be overcome, is to cause incomplete combustion of the charge unless the mixture is quite lean. Pockets of unburned or partially burned gas may exist in the combustion chamber. Thus one would expect to find somewhat lower thermal efficiencies and mean effective pressures whenever mixing is not complete.

Additional inhomogeneity resulting from the flame propagation process is manifest as a continuous stratification of the burned products. For a discussion of this phenomenon see Brown(35) or Hershey, Eberhardt, and Hottel(10). This subject will be treated more extensively in the discussion of the theoretical model for the internal combustion engine in Chapter VI.

Steady State

The assumption of steady state is tantamount to the assumption of chemical equilibrium. The implication is that the system, comprising the products of combustion has been allowed to remain in a given state of temperature and volume long enough to reach a homogeneous condition. That is all chemical reactions have proceeded to such an extent that the rate of the forward reaction is just equalled by the rate of the reverse reaction. At this point, the free energy of the system is at its minimum value and no spontaneous change can occur within an isolated system. Thus, because this in an equilibrium state, the composition can be completely determined by the methods of classical thermodynamics. However, if the time available for combustion is short, true equilibrium may not be attained.

The time during which the system is maintained at constant conditions is termed the residence time. In an internal combustion engine the residence time, strictly speaking, is zero. The system volume and temperature are constantly changing. Fortunately this change is usually relatively slow compared to the time required to achieve equilibrium. This is especially true during combustion as compared to expansion.

To estimate the order of magnitude of the residence time in an internal combustion engine during combustion, one might consider the time required for one degree of crank revolution. During this period, changes in temperature and pressure are not large. For an engine operating at 2000 rpm this time is about 10^{-4} seconds. While it is difficult, if not impossible at this time to quantatively predict the time interval necessary to reach near equilibrium conditions in a system as complex as the working fluid of an internal combustion engine, it is known that at the temperatures and pressures existant during combustion the relaxation times for many of the chemical species present are from 10^{-6} to 10^{-8} seconds or less(36, 37). Thus one might expect that during combustion the chemical composition of the products could be calculated from equilibrium thermodynamics with very little error.

However during expansion, when temperatures and pressures are lower and many recombination reactions are taking place, equilibrium is not always maintained. This condition is termed equilibirum lag. The reactions lag and give rise to compositions which would be considered in equilibrium if the temperature were higher. Not all reactions lag the same amount and for a complex system as in the internal combustion engine, an exact analysis on this basis would be difficult to make and apply. Nevertheless a simple analysis is illustrative of the more complex system behavior.

Reference 37 describes a method whereby a pseudo temperature can be found for simple reactions which is suitable for the calculation of non-equilibrium compositions. In the case of recombination reactions requiring a three body collision between molecules A, B, and a third body M the following reaction can be written,

$$A + B + M \underset{K_b}{\overset{K_f}{\rightleftharpoons}} AB+M$$

where K_f and K_b denote the forward and reverse reaction rates respectively.

The equilibrium constant K_c for this reaction is,

$$K_c = \frac{(AB)}{(A)(B)} = \frac{K_f}{K_b}$$

where the parentheses denote concentrations in moles per unit volume. The resultant expression for the pseudo temperature is (37),

$$T' = T + \frac{[1 + (C_V T/\Delta U)]\ [-\partial T/\partial t]}{K_f(M)\ [(A) + (B) + 1/K_c']}$$

where

T' = the pseudo temperature

C_v = the heat capacity at constant volume for the system

$-\Delta U$ = the heat of reaction at constant volume

$\frac{\partial T}{\partial t}$ = the reciprocal of the residence time per degree

K_c' = the equilibrium constant at T'

During the expansion stroke of an internal combustion engine, $-\partial T/\partial t$ is of the order of 10^5 to 10^6 °K per second (see Appendix D). Reference 37 suggests the following values for common recombination reactions: $-\Delta U$ from 50 to 150 kcal/mole and K_f about 10^{11} $(\text{moles/liter})^{-2}/\text{sec}$. The quantity $(1 + C_V T/\Delta U)$ will be between 0 and 1 and consequently T' will be nearly equal to T unless the concentrations of A and B are very small in which case further recombinations will have only small effects.

It must be remembered that the above numerical values will change as the state of the system changes and in particular the rate of recombination will become lower as the pressure and temperature of the system are reduced. Moreover other types of reactions occur which under certain circumstances may be quite slow. The decomposition of NO into N_2

and O_2 is an example of such a reaction. Concentration of NO considerably in excess of equilibrium amounts have been observed in the exhaust of both rocket and internal combustion engines. In the analysis of the expansion process in rocket engines where $-\partial T/\partial t$ is 10^7 or 10^8 (46), chemical equilibrium is normally assumed. Thus the assumption of chemical equilibrium during expansion for internal combustion engine calculations is at least as good as it is for rocket engine calculations.

The effect of assuming chemical equilibrium during expansion is to increase the thermal efficiency and indicated mean effective pressure of the engine cycle. This is because the recombination of the radicals releases energy which can be used to do work.

There is a temperature, however, below which the rate of reaction is so slow that for all practical purposes no further reaction occurs and the equilibrium is effectively frozen. This temperature varies with the particular reaction. Gaydon(36) recommends 1500°K for the reaction

$$CO = 1/2CO_2 + 1/2C_{solid}$$

and Hottel(11) suggests 1600°K for the water gas reaction. Some early studies of Lovell and Boyd(38) suggest 1600-1700°K as the temperature at which the equilibrium freezes in the exhaust of an internal combustion engine. However, 1500°K is used throughout this work as the temperature below which no further changes occur in composition.

Wall Effects

The presence of a wall can effectively quench a combustion reaction. This phenomenona occurs because the walls absorbe heat or chain carriers, one or both of which must be transferred ahead of the flame to the unburned gas in sufficient quantity to continue the propagation of the flame. Thus in the region near a wall, unreacted or partially reacted quantities of mixture may be found. In an engine this region appears as a layer a few thousands of an inch thick around the inside of the combustion chamber. Daniel(39) presents photographs which illustrate the presents of this layer. It is commonly thought that quenching is a major cause of partially reacted products, such as CH_4, in the exhaust.

Because this dead space is a region of partially reacted or unreacted mixture, its effect is to reduce the thermal efficiency and mean effective pressure of an internal combustion engine.

Summary

In summary, inhomogeneities in the original mixture and quenching at the wall result in incomplete combustion of the charge. Even if the charge were completely homogeneous and were all burned, the rate of reaction may be so slow for some reactions that a state of chemical equilibrium is not attained in the products, especially during the expansion part of the cycle. Nevertheless to circumvent the inherent difficulties of treating these deviations from ideality, complete homogeneity and chemical equilibrium will be assumed to exist for the purposes of calculating the composition of the working fluid above 1500°K in the analytical model of the internal combustion engine. Below 1500°K, the composition will be assumed frozen at that composition which existed at 1500°K. These assumptions will always produce calculated thermal efficiencies and mean effective pressures which are higher than those found if the exact composition of the working fluid were used.

2. The Chemical Composition at Equilibrium

a. General

The products of a hydrocarbon-air reaction consist of a number of atoms and molecules whose individual amounts vary with changes in pressure and temperature according to the laws of chemical kinetics, subject to the condition that the mass of each basic atomic specie remains constant. When the condition of chemical equilibrium is imposed on the system, the amount of each constituent can be found by purely thermodynamic consideration. For the range of pressures and temperatures encountered in the internal combustion engine, 10 gaseous species must be considered in the products:

Reactants	Products	Specie No.
Fuel-C_aH_b	--	1
Air $-O_2$	O_2	2
$-N_2$	N_2	3
	CO_2	4
	H_2O	5
	CO	6
	H_2	7
	OH	8
	NO	9
	O	10
	H	11

Additional species may be considered such as N, NO_2, C, or CH_4. However their amounts, calculated from equilibrium considerations, will be extremely small and their contribution to the overall thermodynamic properties of the system will be negligible.

In order to establish the amount of each of the 10 constituents 10 equations are required. Since some of these equations are non-linear, an explicit solution can not be obtained and resort must be made to a trial and error solution. Many solution techniques have been developed for such equations. Some are specifically directed at the solution of equations for the combustion of a hydrocarbon fuel with air and some are quite general in scope and are capable of treating systems of arbitrary reactants with solid, liquid or gaseous products. Hershey, Eberhardt, and Hottel(10) as well as Goodenough and Felbeck(8) employed the former, or specific type of solution, to their combustion equations. Vickland(40) analyzed a number of methods, both general and specific, finally adopting a combination of them which was suitable for a computer solution. Huff and Co-workers(41) proposed a method for treating arbitrary reactants and solid, liquid, or gaseous products which has been widely used for combustion calculations. Brinkly(37) proposed still a different method for treating a general system. This method was used by Edson(22). A summary and comparison of the most widely used general methods is presented in Zeleznik(42). In comparing the rate of convergence for the general methods considered, it was found in Reference 42 that no significant advantage was obtained using any one general method in preference to another.

In spite of the availability of numerous methods for computing equilibirum compositions, many of which provide for the simultaneous computation of the adiabatic flame temperature, it was felt that a much more efficient solution might be obtained if a computational method were used which was not general but was explicitly developed to solve only those equations which arise in the combustion of a hydrocarbon fuel with air. Such a system would contain carbon, hydrogen, oxygen, and nitrogen, and be comprised of the 10 listed species.

The computation scheme which is illustrated in the following section is based on the work of Ritter von Stein(43). An adaptation of this method for the combustion of a hydrocarbon fuel and air is presented by Schmidt(44).

b. Computation of Homogeneous Gas Equilibrium

A number of assumptions have been made or implied so far concerning the nature of the products of combustion. The following assumptions are essential to the computation of the gas composition:

1) The products are in a state of chemical equilibrium.
2) All the products are gaseous and can be treated as perfect gases.
3) The system comprising the products of combustion is homogeneous and is maintained at constant temperature and volume.
4) The fuel is a pure hydrocarbon of the form C_aH_b.
5) Air is a mixture of O_2 and N_2.
6) Only 10 species exist in the products.
7) The mass of each basic atomic specie is known and remains constant.

The 10 equations necessary to determine the amount of each of the 10 constituents are determined from a consideration of the following:

1) The conservation of mass.
2) The law of mass action, governing chemical equilibrium.
3) The temperature and volume of the system.

The Conservation of Mass

The reactants are supposed to consist entirely of fuel, C_aH_b, and air, O_2 and N_2, and contain N_c mole atoms of carbon, N_h mole atoms of hydrogen, N_O mole atoms of oxygen, and N_n mole atoms of nitrogen. Four mass balance equations can then be written between the number of mole atoms of each basic specie in the products and that in the reactants.

To determine the number of mole atoms of carbon in the products the following equation can be written:

$$\text{mole atoms of carbon in products} = n_{CO_2} + n_{CO}$$

where n is the number of moles of a particular specie. Re-arranging this equation in terms of partial pressures yields:

$$\text{mole atoms of carbon in products} = V/RT(p_{CO_2} + p_{CO})$$

where T and V are the temperature and volume of the system. Since the mole atoms of carbon in the products must be equal those in the reactants

$$N_c = V/RT(p_{CO_2} + p_{CO})$$

Derived in a similar manner the four mass balance equations are:

$$F \cdot N_c = CO_2 + CO \tag{2-5}$$

$$F \cdot N_h = 2H_2O + 2H_2 + OH + H \tag{2-6}$$

$$F \cdot N_O = 2CO_2 + H_2O + 2O_2 + OH + NO + CO + O \tag{2-7}$$

$$F \cdot N_n = 2N_2 + NO \tag{2-8}$$

where F = RT/V and the formula names have been substituted for the partial pressures. The quantities on the right side of the equations are the "atom pressures" referred to by Ritter von Stein.

The Law of Mass Action

The following reactions are considered to occur among the products:

$CO_2 = CO + 1/2O_2$

$H_2O = 1/2H_2 + 1/2O_2$

$OH = 1/2H_2 + 1/2O_2$

$NO = 1/2N_2 + 1/2O_2$

$O = 1/2O_2$

$H = 1/2H_2$

By assuming the products to be perfect gases, the expressions for the equilibrium constants of these reactions can be written in terms of the partial pressures of the constituents. Letting $O_2 = X^2$, $H_2 = Y^2$, and $N_2 = Z^2$, they are

$$K_1 = \frac{CO \cdot X}{CO_2} \qquad (2\text{-}9)$$

$$K_2 = \frac{Y^2 \cdot X}{H_2O} \qquad (2\text{-}10)$$

$$K_3 = \frac{Y \cdot X}{OH} \qquad (2\text{-}11)$$

$$K_4 = \frac{Z \cdot X}{NO} \qquad (2\text{-}12)$$

$$K_5 = \frac{X}{O} \qquad (2\text{-}13)$$

$$K_6 = \frac{Y}{H} \qquad (2\text{-}14)$$

These six equations together with the 4 mass balance equations must then be solved together for the 10 unknown partial pressures. The equilibrium constants can be calculated by the method of Appendix C, Section 5.

Solution

By re-arranging and substituting equations 2-9 through 2-14 into equations 2-5 through 2-8, the number of equations to be solved is reduced to four.

$$F \cdot N_c = CO(1 + \frac{X}{K_1}) \tag{2-15}$$

$$F \cdot N_h = 2(Y^2 + \frac{Y^2X}{K_2}) + \frac{YX}{K_3} + \frac{Y}{K_6} \tag{2-16}$$

$$F \cdot N_0 = 2(\frac{CO \cdot X}{K_1}) + \frac{Y^2X}{K_2} + 2X^2 + \frac{YX}{K_3} + \frac{ZX}{K_4} + CO + \frac{X}{K_5} \tag{2-17}$$

$$F \cdot N_n = 2Z^2 + \frac{ZX}{K_4} \tag{2-18}$$

Solving Equation (2-18) for the positive value of Z,

$$Z = -\frac{X}{4K_4} + \sqrt{(\frac{X}{4K_4})^2 + \frac{F \cdot N_n}{2}} \tag{2-19}$$

and Equation (2-16) for the positive value of Y,

$$Y = \frac{-(\frac{X}{K_3} + \frac{1}{K_6}) + \sqrt{(\frac{X}{K_3} + \frac{1}{K_6})^2 + 8\,[1 + \frac{X}{K_2}] \cdot F \cdot N_h}}{4(1 + \frac{X}{K_2})} \tag{2-20}$$

If Equation (2-15) is then substituted into Equation (2-17),

$$F \cdot N_0 = \frac{\frac{X \cdot F \cdot N_c}{K_1}}{1 + \frac{X}{K_1}} + \frac{Y^2X}{K_2} + 2X^2 + \frac{YX}{K_3} + \frac{ZX}{K_4} + F \cdot N_c + \frac{X}{K_5} \tag{2-21}$$

In light of Equations (2-19) and (2-20), Y and Z are functions of X only. Then Equation (2-21) is only a function of X, since the equilibrium constants are only a function of temperature. It then remains to obtain the positive value of X which satisfies Equation (2-21). A method for doing this is presented in Appendix E along with an estimate of the rate of convergence of the method.

The quantity X having been determined, Y and Z can be calculated from Equations (2-19) and (2-20). The partial pressures can be calculated from Equations (2-9) through (2-15) re-arranged as follows:

$$O_2 = X^2 \tag{2-22}$$

$$N_2 = Y^2 \tag{2-23}$$

$$CO_2 = \frac{F \cdot N_c}{K_1/X+1} \tag{2-24}$$

$$H_2O = \frac{XY^2}{K_2} \tag{2-25}$$

$$CO = \frac{CO_2 \cdot K_1}{X} \tag{2-26}$$

$$H_2 = Y^2 \tag{2-27}$$

$$OH = \frac{XY}{K_3} \tag{2-28}$$

$$NO = \frac{XZ}{K_4} \tag{2-29}$$

$$O = \frac{X}{K_5} \tag{2-30}$$

$$H = \frac{Y}{K_6} \tag{2-31}$$

The number of moles of each constituent is the partial pressure divided by the factor 'F'.

Figures 2a through 2j show calculated mole fractions of the various constituents in the products as a function of the temperature and pressure of the system for a stoiciometric mixture of octane and air. These curves are in good agreement with those of Reference 40.

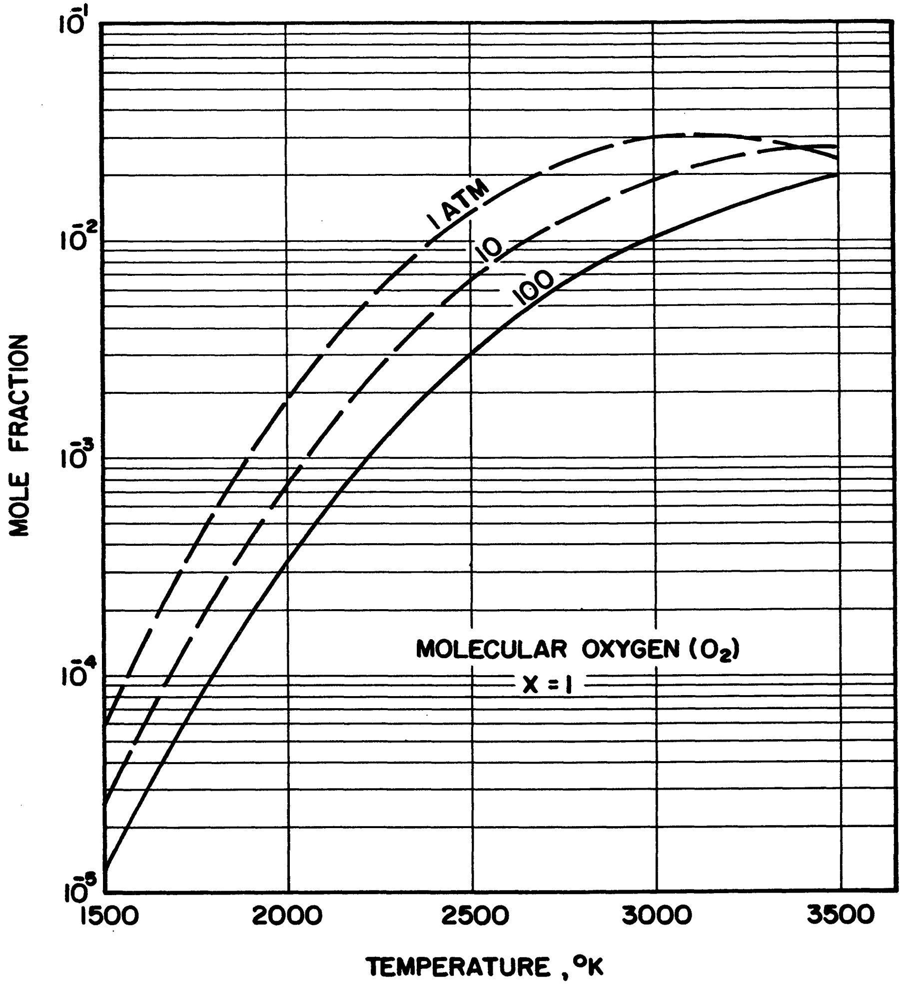


Figure 2a. Mole fraction vs temperature, O_2.

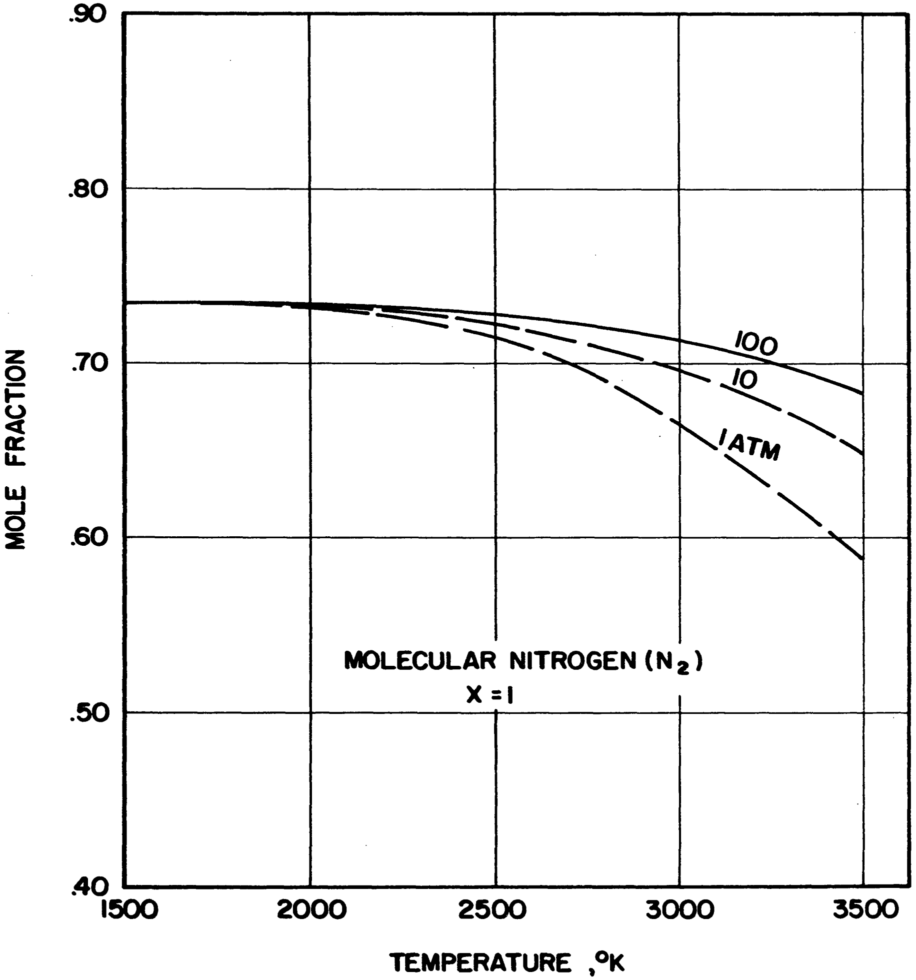


Figure 2b. Mole fraction vs temperature, N_2.

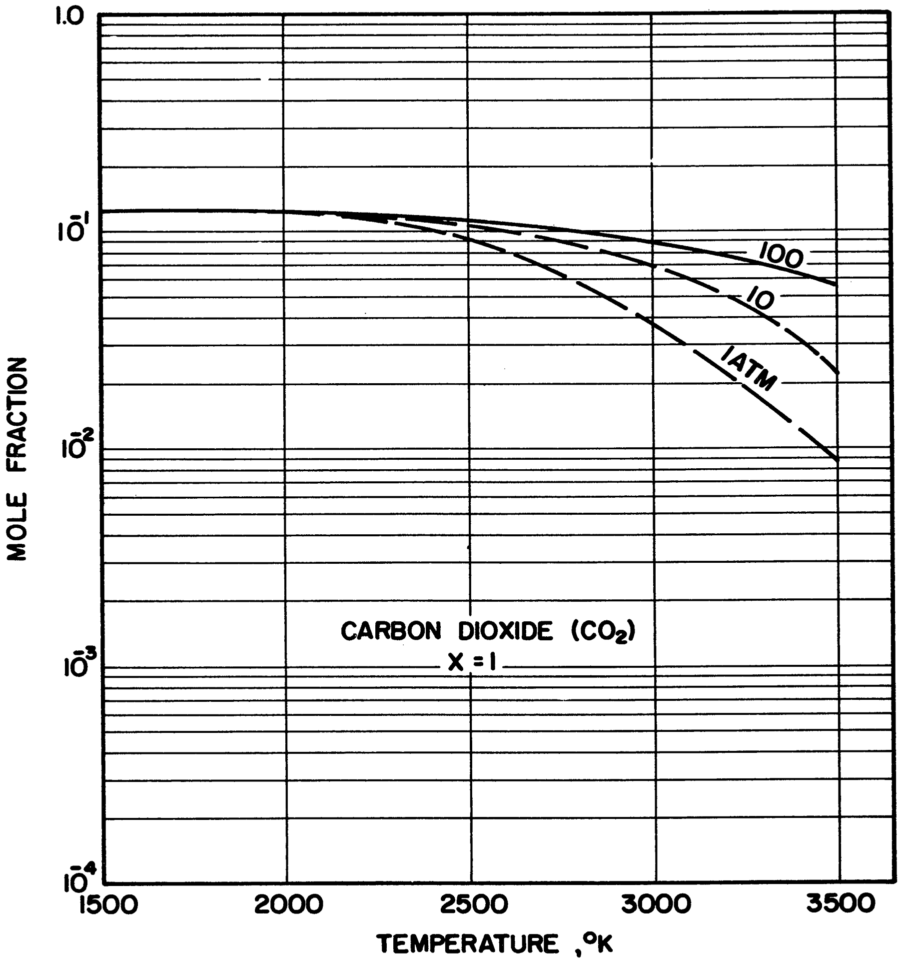


Figure 2c. Mole fraction vs temperature, CO_2.

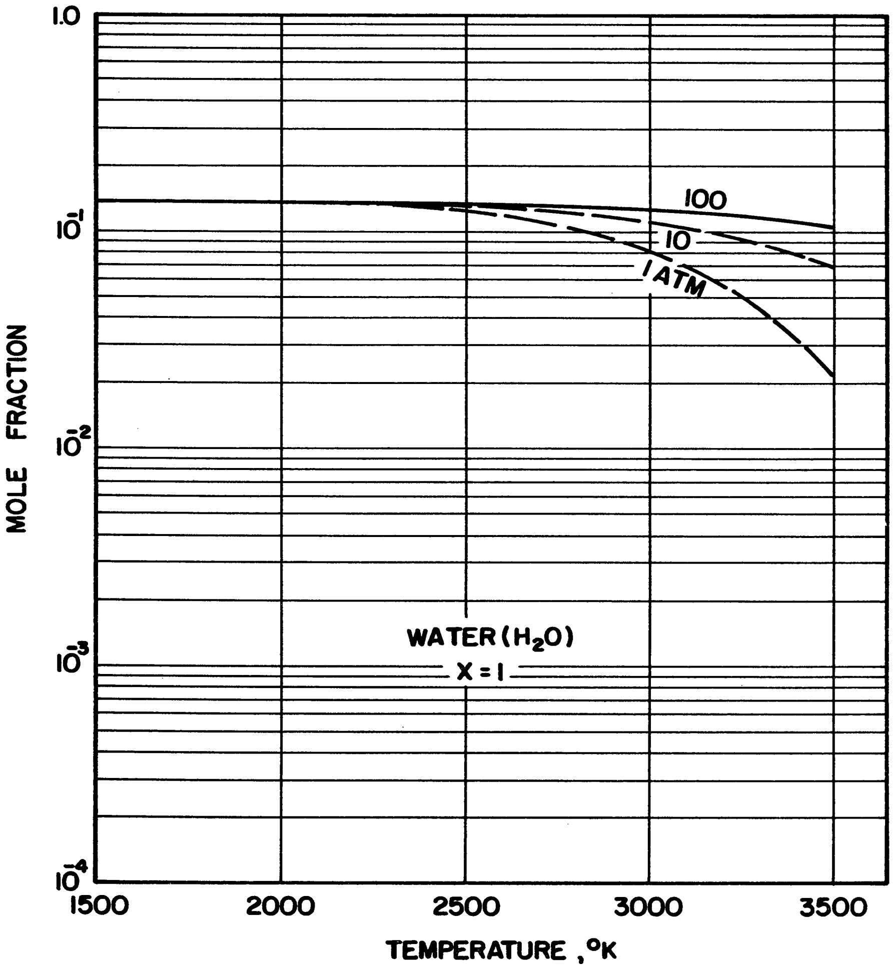


Figure 2d. Mole fraction vs temperature, H_2O.

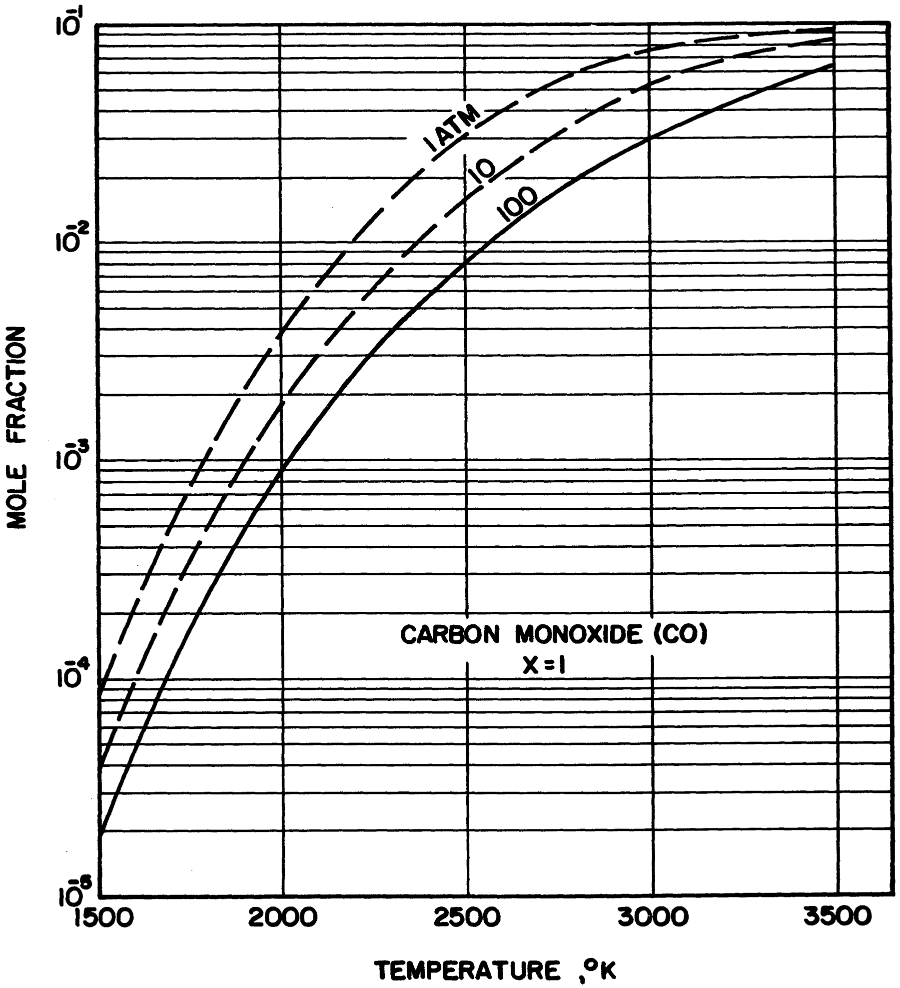


Figure 2e. Mole fraction vs temperature, CO.

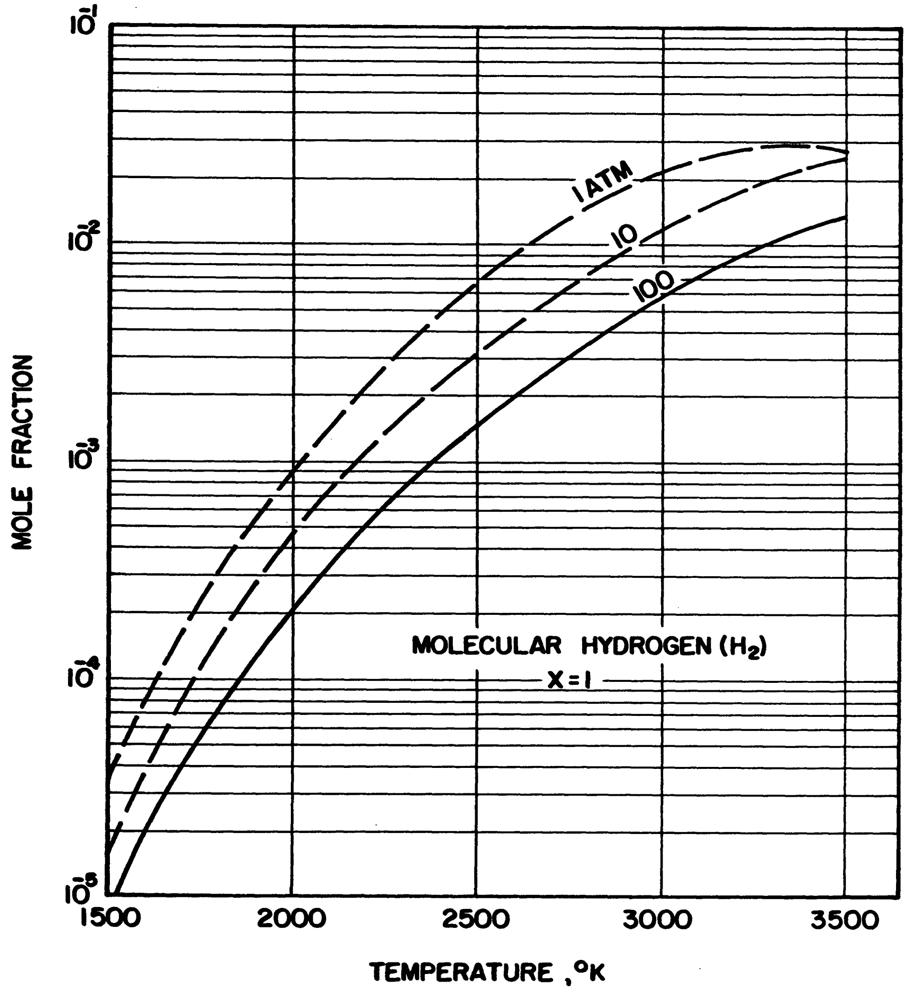


Figure 2f. Mole fraction vs temperature, H_2.

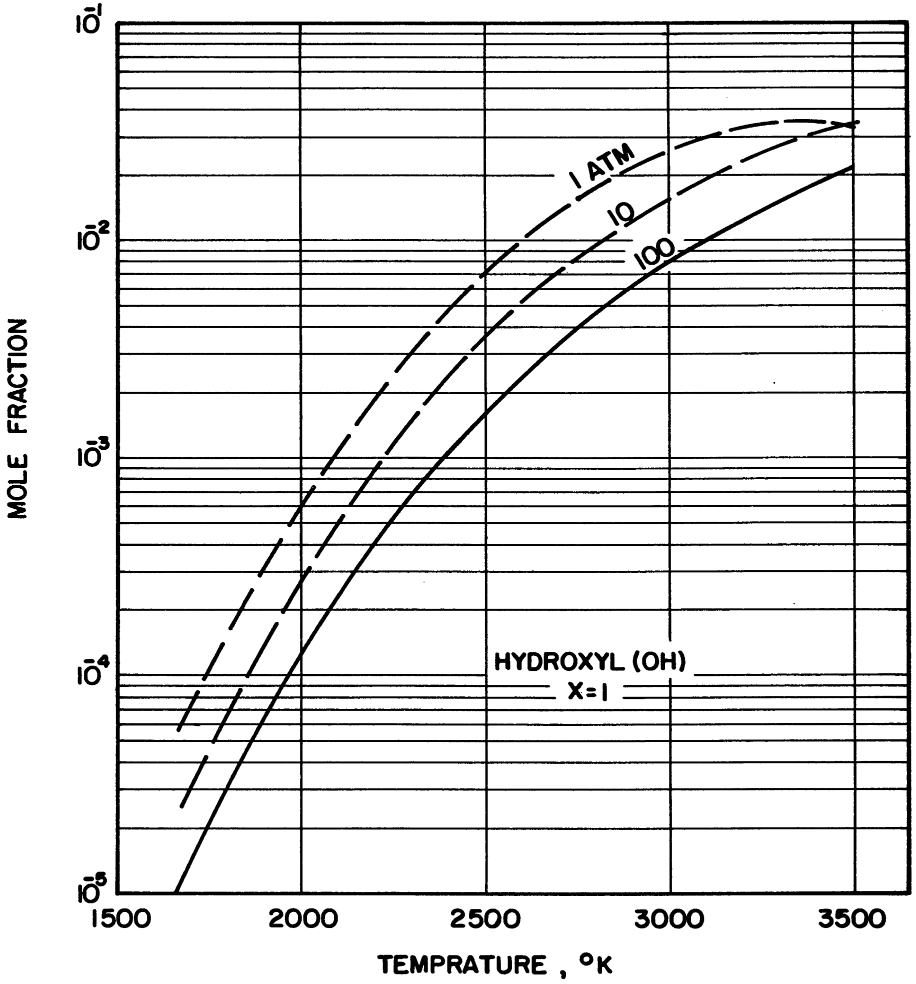


Figure 2g. Mole fraction vs temperature, OH.

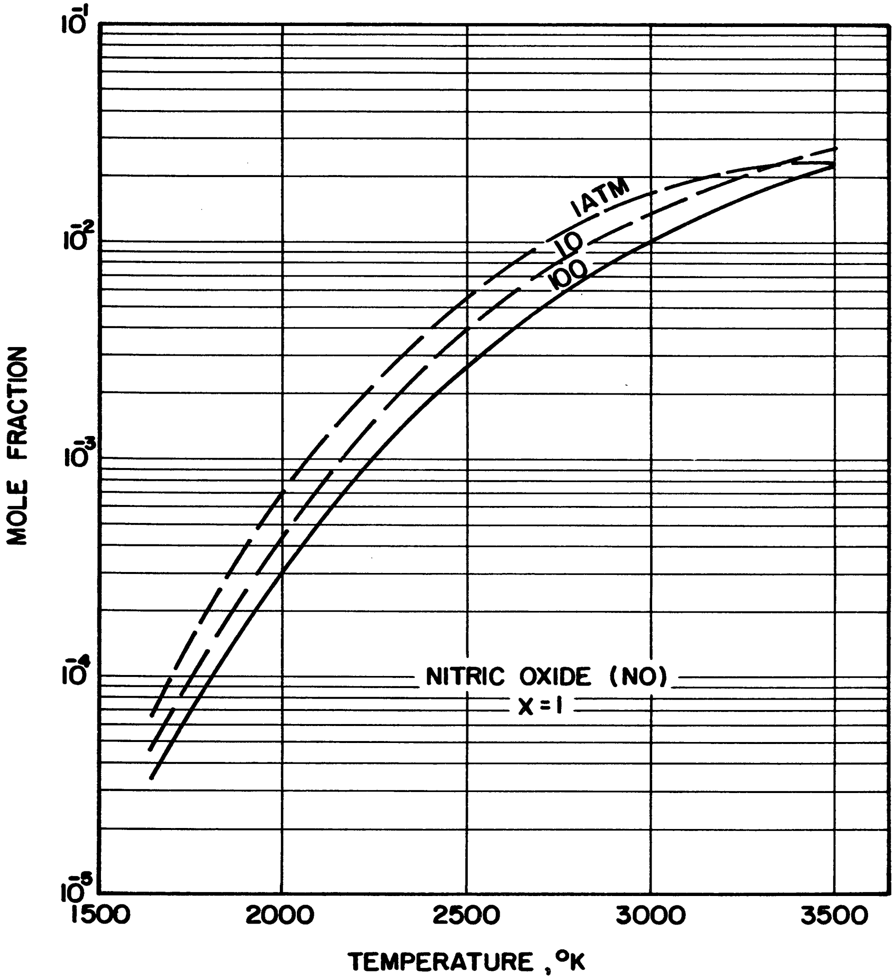


Figure 2h. Mole fraction vs temperature, NO.

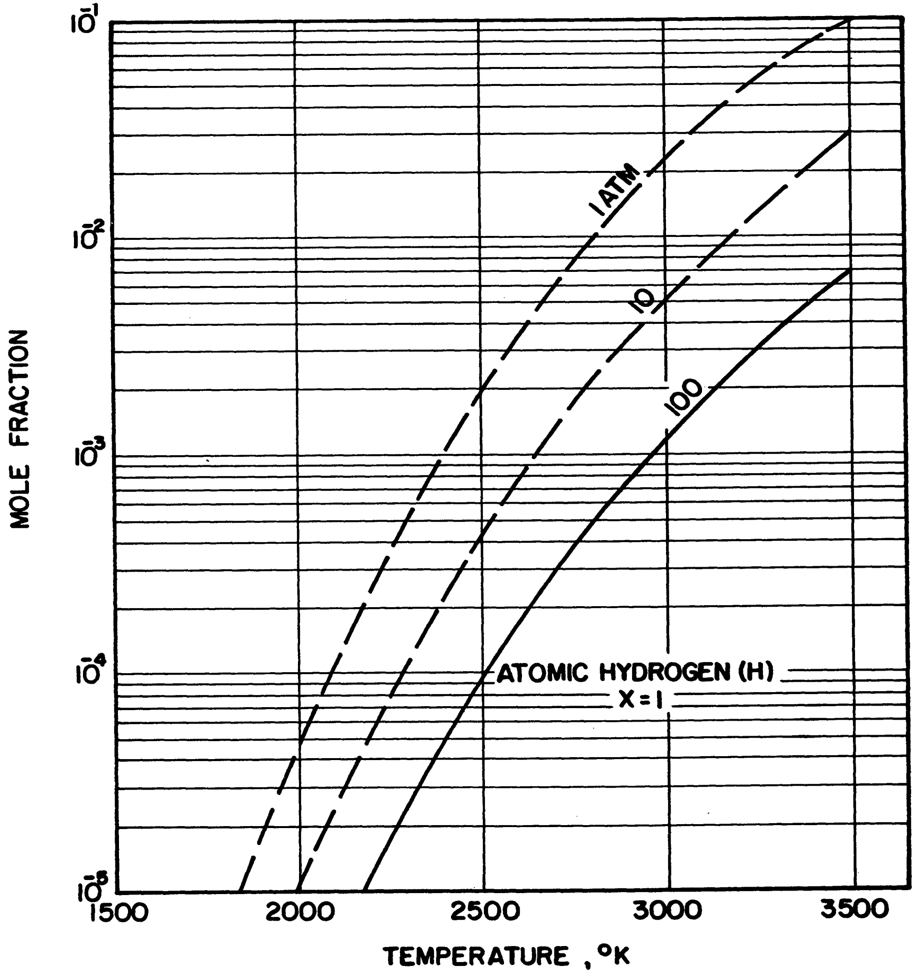


Figure 2i. Mole fraction vs temperature, H.

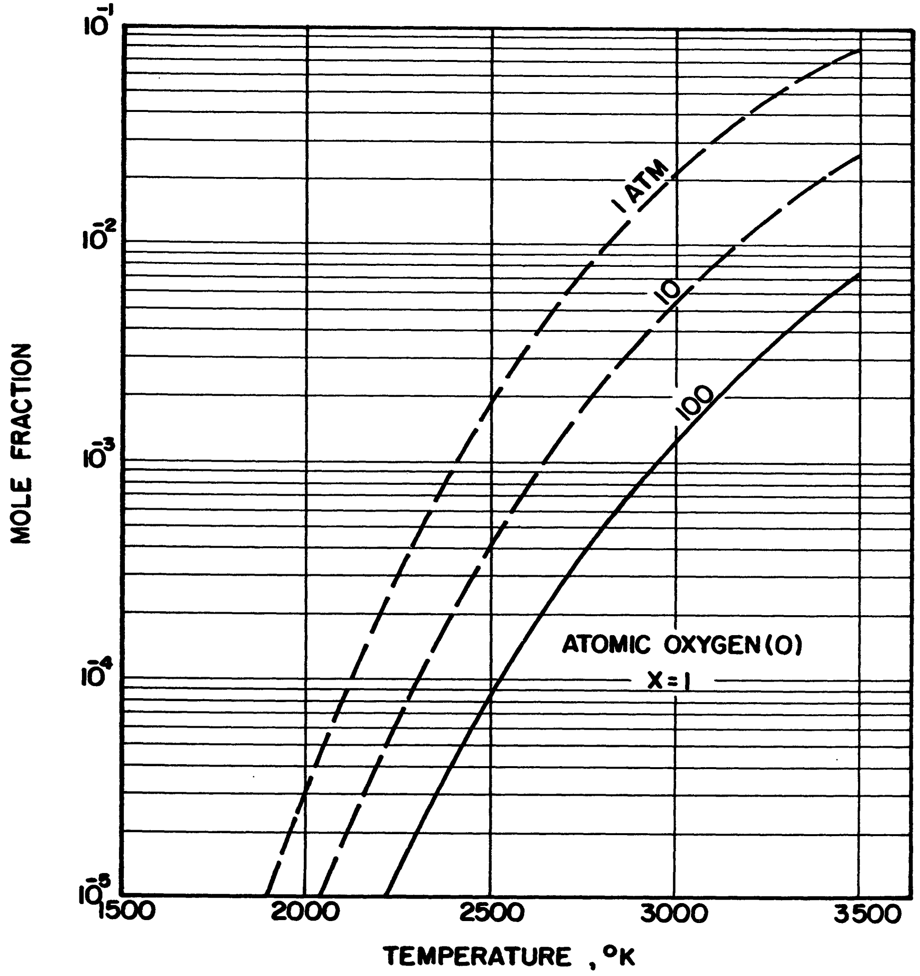


Figure 2j. Mole fraction vs temperature, O.

In order to calculate the composition at a given temperature and pressure, rather than volume, a second trial and error solution must be made. If an initial estimate is made of what the volume might be at the given temperature and pressure and the calculations made as above, the total number of moles can be computed. From the number of moles, the pressure, and the temperature, a new estimate of the volume can be made and the calculations repeated once more, leading to yet a third estimate of the volume. The entire process can then be repeated a third time and so on until the volumes calculated for any two sucessive iterations are within a specified amount of each other. For a reasonable good estimate of the volume initially, only about two additional iterations are required to achieve agreement in the fifth or sixth digit between two sucessive values of the volume.

c. Computation of Frozen Equilibrium

The products of combustion below 1500°K are assumed frozen. In addition to the assumptions made in connection with homogeneous gas equilibrium in Part 2 of this section the following additional assumptions are made for frozen equilibrium:

1) The composition of the products is frozen at the equilibrium composition which would exist at 1500°K.
2) For lean and chemically correct mixtures, only O_2, N_2, CO_2, and H_2O are present.
3) For rich mixtures, only N_2, CO_2, H_2O, CO, and H_2 are present.

Lean and Stoiciometric Mixtures

For the calculation of the composition of lean and stoiciometric mixtures under the assumption of frozen equilibrium the mass balance equations are:

$$F \cdot N_c = CO_2$$

$$F \cdot N_h = 2H_2O$$

$$F \cdot N_O = 2CO_2 + H_2O + 2O_2$$

$$F \cdot N_n = 2N_2$$

Finally, the partial pressures of the constituents are:

$$CO = F \cdot N_c \tag{2-32}$$

$$H_2O = F \cdot N_h/2 \tag{2-33}$$

$$O_2 = \left| F \cdot N_O/2 - F \cdot N_h/4 - F \cdot N_c \right| \tag{2-34}$$

$$N_2 = F \cdot N_n/2 \tag{2-35}$$

where the absolute value of the partial pressure of the oxygen is taken to avoid the possibility of an extremely small negative value of this quantity occurring near the stoiciometric point due to round-off errors. This consideration applies to computer solutions only. The number of moles of each constituent is its partial pressure divided by 'F'.

Rich Mixtures

For the calculation of the composition of rich mixtures under the assumption of frozen equilibrium the mass balance equations are:

$$F \cdot N_c = CO_2 + CO$$

$$F \cdot N_h = 2H_2O + 2H_2$$

$F \cdot N_O = 2CO_2 + CO + H_2O$

$F \cdot N_n = 2 \cdot N_2$

The following reaction is assumed to occur among the products of rich mixtures at 1500°K

$H_2O + CO = CO_2 + H_2$

The expression for the equilibrium constant of this reaction is

$$K = \frac{CO_2 \cdot H_2}{H_2O \cdot CO} \tag{2-36}$$

As this reaction involves no change in the total number of moles, the computation at a given temperature and pressure is equivalent to that at a given temperature and volume. And in fact, the reaction is independent of the pressure of the system. Therefore the composition of the products depends only on the temperature. As a result, fixing the value of the equilibrium constant fixes the composition. Whenever the composition of the products is to be calculated when the temperature is below 1500°K, K is given its value at 1500°K. This freezes the reaction at the temperature level. Letting $Z = \frac{F \cdot N_c}{CO_2}$ and substituting the mass balance equations in the equation for the equilibrium constant,

$$K = \frac{1/2 \frac{N_h}{N_c} - \frac{N_O}{N_c} + 1 + 1/Z}{(\frac{N_O}{N_c} - 1 - 1/Z)\ (Z - 1)}$$

At 1500°K, K is 0.3747(29). Solving the above equation and substituting the value of K,

$$Z = \alpha + \sqrt{\alpha^2 + \frac{6.6752}{(\frac{N_O}{N_c} - 1)}} \qquad (2\text{-}37)$$

where

$$\alpha = \frac{(1 + \frac{N_h}{0.7494 \cdot N_c})}{\left[\frac{N_O}{N_c} - 1\right]} - 1.6688$$

The partial pressures are:

$$CO_2 = \frac{F \cdot N_c}{Z} \qquad (2\text{-}38)$$

$$H_2O = F(N_O - N_c) - CO_2 \qquad (2\text{-}39)$$

$$CO = |F \cdot N_c - CO_2| \qquad (2\text{-}40)$$

$$H_2 = |F \cdot \frac{N_h}{2} - H_2O| \qquad (2\text{-}41)$$

$$N_2 = F \cdot \frac{N_n}{2} \qquad (2\text{-}42)$$

Again absolute values are taken to assure that near the stoiciometric point no small negative partial pressures can be calculated due to round-off errors. The number of moles of each constituent is its partial pressure divided by 'F'.

3. Computer Solution of the Equations of Chemical Equilibrium

The solution technique developed in Part 2 and Appendix E has been programmed on a digital computer. A flow diagram for this program is shown on Figure 23. Appendix E includes a discussion of many important features of the solution. A listing of the program written in the MAD language as an external function called AMOUNT. is included in Appendix I.

III. SIMULATION OF THE FUEL-AIR ENGINE CYCLE ON A DIGITAL COMPUTER

A. General

As the initial step toward the development of an improved model for the analysis of the internal combustion engine which could ultimately be programmed on a digital computer, the constant volume fuel-air engine cycle was programmed. The details of the mathematical analysis and computer program are included in Appendix F. The techniques developed in Chapter II have been used to calculate the composition and thermodynamic properties of the working fluid.

The fuel-air cycle is composed of the following idealized processes (see Figure 3).

Process 1-2. An isentropic compression of the working fluid from volume V_1 to V_2.

Process 2-3. An adiabatic constant volume combustion.

Process 3-4. An isentropic expansion of the working fluid from volume V_2 to V_1.

Process 4-4. A further expansion to the exhaust pressure. That portion remaining in the cylinder undergoes an isentropic expansion.

Process 4-5. A constant pressure adiabatic expulsion of the burned gas leaving some redual exhaust gas in the clearance volume.

Process 5-1. An adiabatic induction and mixing of the fresh charge with the residual exhaust at the intake pressure, thus completing the cycle.

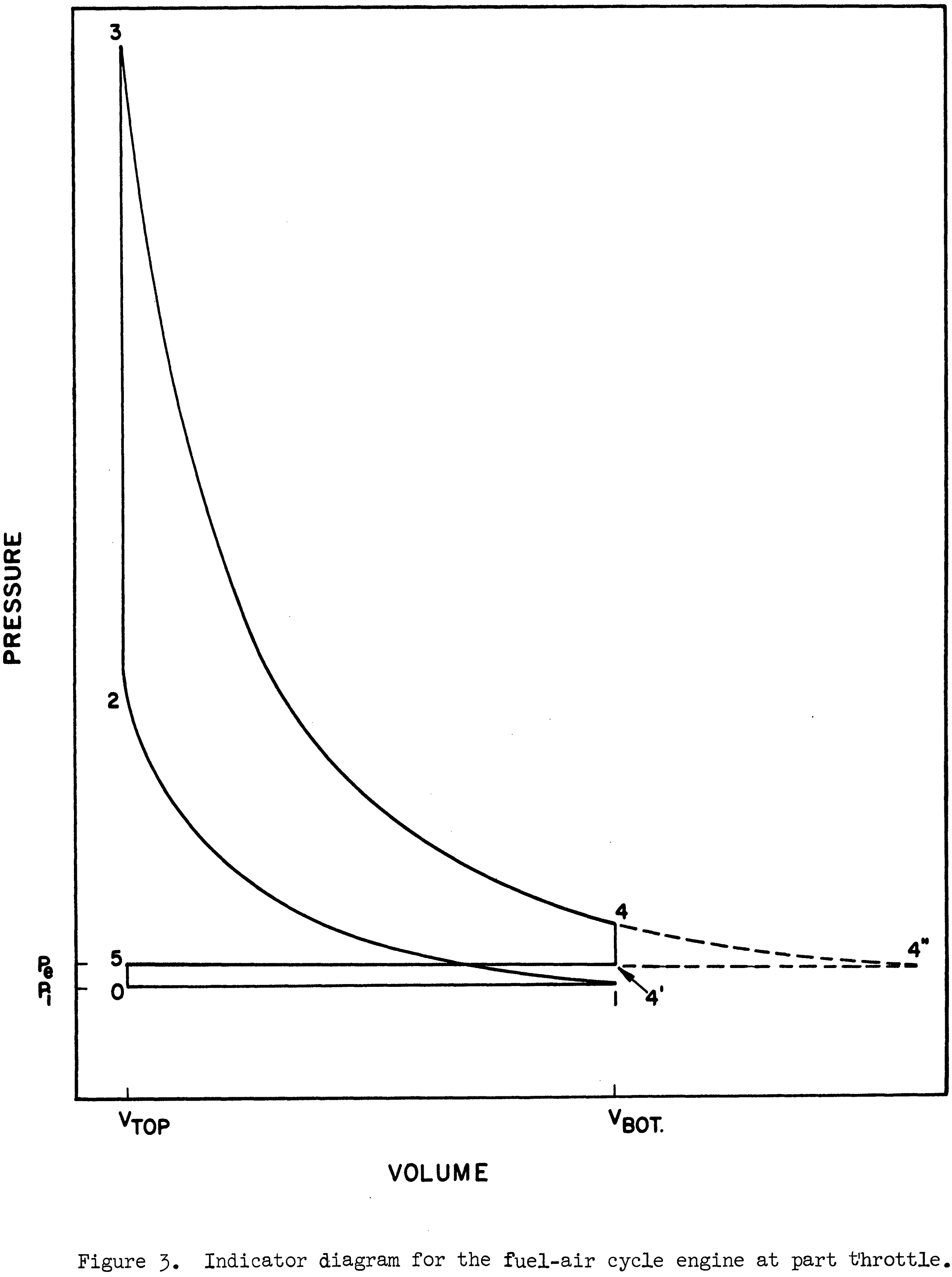


Figure 3. Indicator diagram for the fuel-air cycle engine at part throttle.

The following assumption were made:

1. There is no chemical change in either the fuel or air prior to combustion.
2. After combustion and during expansion, the products are in a state of chemical equilibrium.
3. Equilibrium is frozen below 1500°K.
4. All processes are adiabatic.
5. There are no irreversible fluid flow effects.
6. All valve events occur at top or bottom center.

A complete description of this cycle may be found in References 10 and 45. Calculations made using similar analytical models can be found in References 7, 9, 10, 11, 22, and 45. Reference 22 is of particular interest as the calculations were made on a digital computer.

In as much as a great body of calculations already has been reported using the fuel-air cycle engine model, only selected values of the computer computations will be presented here. These deal with the effects of lean mixtures and high compression ratios on thermal efficiency and mean effective pressure. They are of special interest in light of the increasing effort to raise compression rations and utilize leaner mixtures in internal combustion engines. Thermodynamic charts available for the calculation of the fuel-air cycle are constructed for mixtures no leaner than 120 percent theoretical air and allow computations for compression ratios up to about 20 to 1(11). Both Tizard and Pye(7) and Goodenough and Baker(9) presented results of calculations for the effect of very lean mixtures on thermal efficiency. However these results are based upon now outdated heat capacity and dissociation data and their analytical models differ somewhat from that employed here.

B. Results and Discussion

Figures 4 and 5 are plots of the results calculated by the aforementioned computer program for the fuel-air cycle engine. Figure 4 shows the effects of both compression ratio and air-fuel ratio on the thermal efficiency and mean effective pressure of lean octane-air mixtures. As the mixture becomes leaner, the efficiency approaches that of the air-cycle, Equation (1-2), where 'k' is 1.4 for air. It has been proposed by both Tizard and Pye and Goodenough and Baker that the thermal efficiency of the fuel air cycle can be expressed as

$$\eta = 1 - \left(\frac{1}{r}\right)^n$$

where 'n' is a quantity derived from fuel-air cycle calculations. Goodenough and Baker proposed, for lean octance-air mixtures, that

$$n = 0.3867 - \frac{6.5}{100x - 35} - \frac{0.043}{r}$$

where 'x' is the fraction of theoretical air and 'r' is the compression ratio. In order to better fit the curves of Figure 4, this expression was modified slightly. The modified expression,

$$n = 0.374 - \frac{0.1}{x} - \frac{0.043}{r} \qquad (3\text{-}1)$$

will approximate the thermal efficiencies of Figure 4 within 0.5 percent.

Figure 5 shows the influence of compression ratio on the thermal efficiency and mean effective pressure of a lean octene-air mixture for compression ratios up to 30:1. Edson(22) reports similar calculation for ratios up to 300:1 for a number of fuels and fuel-air ratios. Thermal efficiency and mean effective pressure continually increase as compression ratio is increased. Equation (3-1) is a good approximation for the thermal efficiencies of Figure 5.

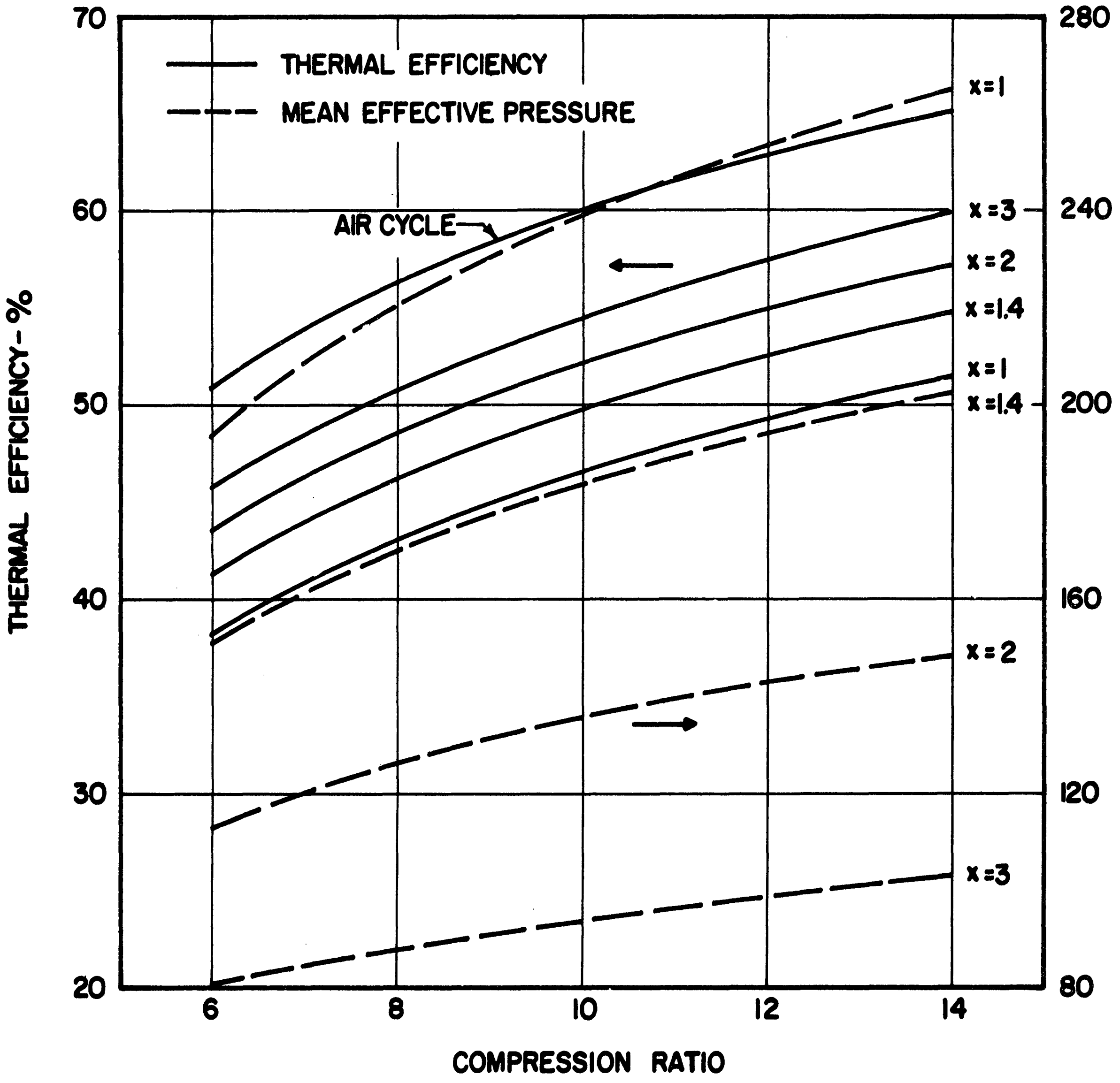


Figure 4. Efficiency and mean effective pressure vs compression ratio for lean mixtures. Fuel-Air cycle analysis. Fuel - octane, T_i = 520°F, $P_i = P_e$ = 1 atm.

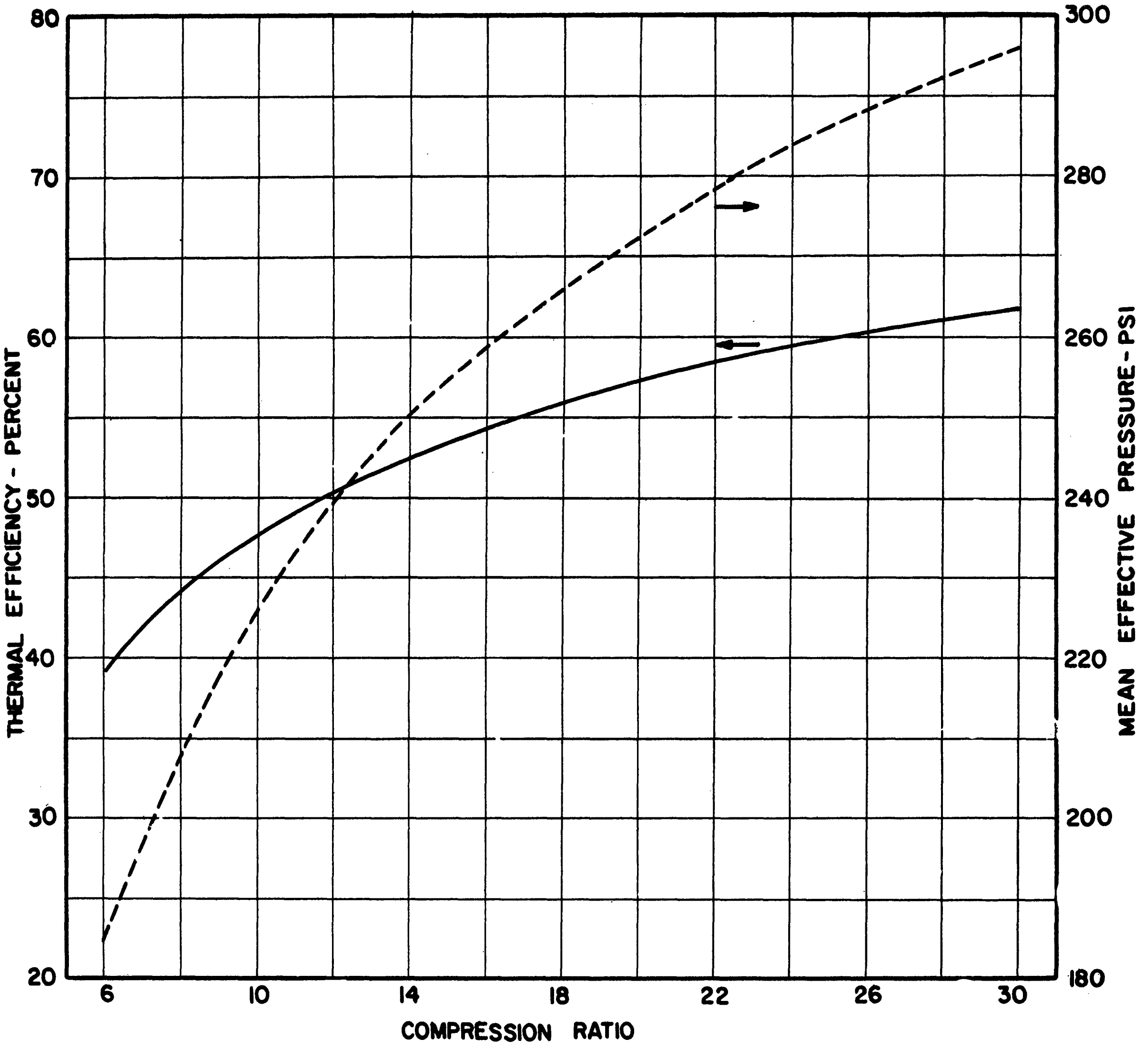


Figure 5. Efficiency and mean effective pressure vs compression ratio for a mixture of octene and 110 percent theoretical air. Fuel-air cycle analysis. $T_1 = 520$, $P_1 = P_e = 1$ atm.

IV. COMBUSTION IN A SPARK-IGNITED ENGINE

Whereas the fuel-air cycle incorporates many important features of the internal combustion engine, it totally disregards two phenomena which are of primary importance. These are the progressive burning of the charge and the heat transfer. Prior to a discussion of their inclusion into the analytical model for the internal combustion engine described in Chapter VI, some discussion of the nature of each is warranted. This chapter deals with the nature of the combustion process and the following chapter deals with that of the heat transfer.

A. General

The combustion process in an internal combustion engine has been investigated photographically and by other methods. The studies of Rassweiler, Withrow, and Cornelius(16, 17, and 18) reveal that in normal combustion the spark induces a kernel of flame which subsequently propagates regularly in all directions. Their photographs show that during combustion two distinct gaseous regions exist in the chamber, a region of burned gas surrounded by a region of unburned gas. The two regions are separated by a definite reaction zone. This reaction zone or flame front, as it is often called, is generally a spherical shell during the early stages of combustion but becomes distorted as it approaches the wall and tends to assume the shape of the combustion chamber.

The apparent rate of flame propagation in an engine is very high. This is due to both the reaction rate and the expansion of the gases during the combustion process. At the beginning of combustion, the expansion rate is high compared to the reaction rate whereas at the end of combustion it is low. The fundamental quantity to be investigated is the flame front motion due to the reaction only. This is the flame propagation relative to the unburned gas.

The remainder of this chapter is devoted to obtaining a general expression for the rate of flame propagation in an internal combustion engine. By necessity a number of assumptions have been made in order to simplify the equations involved. Perhaps the most serious of these are those of steady state and one dimensionality. Thus it must be recognized from the outset that the equation presented for the rate of flame propagation is only approximate. Its validity can be determined only by a direct comparison of calculated with experimental burning rates which can be done indirectly through a comparison of calculated and experimental pressure time diagrams for a particular engine.

B. Flame Propagation

Two regimes of flame propagation are recognized, the laminar and the turbulent. Laminar combustion is characterized by a well defined narrow flame front and a relatively low rate of reaction. Turbulent combustion is characterized by a less well defined thicker flame front and a much higher rate of reaction. Three somewhat separable modes of turbulent flame propagation have been observed(47, 48). They are:

1. Weak turbulence which wrinkles the continuous laminar flame front, thereby causing a higher effective rate of reaction due to the greater surface area through which the basic transport phenomena can occur;

2. Stronger turbulence which disrupts the laminar flame front and creates a distribution of centers of deflagration which can be treated statistically;
3. Still stronger turbulence which shows its effects by locally diluting and preheating the initial centers of deflagration, such that a homogeneous reaction results in the limit.

Observed and calculated rates of flame propagation in internal combustion engines indicate that the combustion is in the turbulent regime (see Rabezanna, Kalmar, and Candelise(19)). However little quantative information concerning the nature of the turbulence in internal combustion engines exists. Semenov(49) presents the results of some experimental studies which show that the turbulent fluctuations vary from point to point in the cycle, but sheds no light on the nature of the turbulence.

A number of theories have been advanced to explain turbulent flame propagation (see Reference 50). Only the first mode of turbulent flame propagation has been studied analytically. Such studies generally assume that the turbulent buring velocity is related to the laminar velocity by a factor which is proportional to the level of turbulence in the reaction zone.

The theory of Scurlock and Grover(51), one of the most recent, assumes a one dimensional steady state situation in which premixed fuel and air are fed into the reaction zone at a rate such that the zone itself remains fixed relative to the source of the gas. As the level of turbulence is increased, the flow rate must be increased in order to prevent the reaction zone from moving upstream toward the source. The velocity at which the premixed gases approach the reaction zone is equal in magnitude and opposite in direction to the flame propagation velocity. Scurlock and Grovers' analytical model assumes that the laminar flame front is wrinkled by large scale turbulence like that of the first mode. Figure 6 illustrates this wrinkling. The theory assumes that in this type of turbulent combustion the fundamental transport phenomena remain unchanged and hence the laminar flame speed normal to the flame front is unchanged. The increased rate of flame propagation due to turbulence is presumed to be caused only by the larger surface area over which the reaction can proceed.

The wrinkles in Figure 6 are assumed to be cones with an average height proportional to $\sqrt{\overline{Y^2}}$, the root mean square displacement of a flame element from its mean flame front position, and an average base width proportional to L_{Eu}, the Eulerian scale of turbulence. The ratio of turbulent to laminar flame speed, derived from purely geometric considerations, is

$$\frac{S_t}{S_\ell} = \frac{A_t}{A_l} = \left[1 + k_3 \left(\frac{\overline{Y^2}}{L_{Eu}^2}\right) \right]^{1/2} \tag{4-1}$$

where $k_3 = 4k_1^2/k_1^2$. Scurlock and Grover consider three effects which are believed important to a determination of $\overline{Y^2}$. These are eddy diffusion, flame propagation, and flame generated turbulence.

Bolz and Burlage(48) have successfully used the theory of Scurlock und Grover to predict the growth of flame kernels in turbulent flow issuing from a jet. Mickelsen and Ernstein(52) in a similar experiment found good agreement between flame speeds obtained experimentally and those predicted by the theory of Scurlock and Grover over a range of fuel-air ratios and levels of

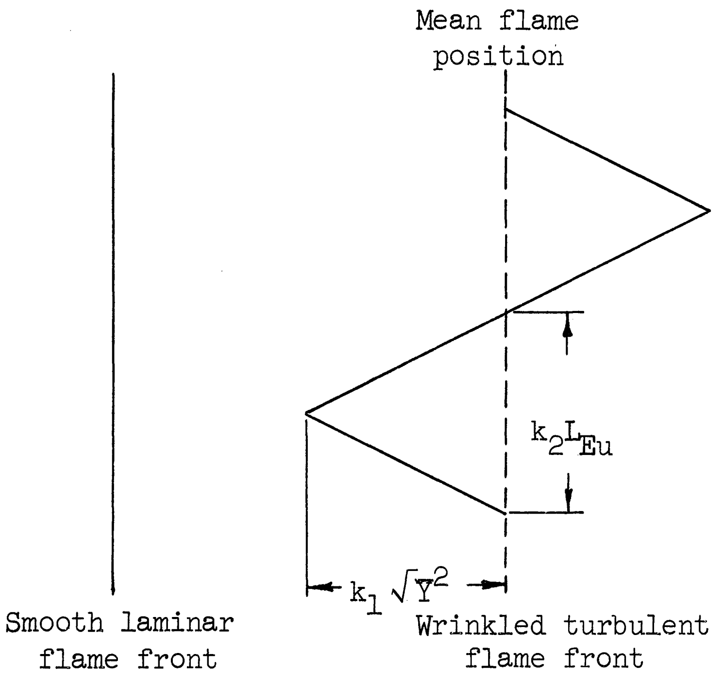


Figure 6. Wrinkled flame front model of Scurlock and Grover(51).

turbulence. However the theoretical values were always higher than the experimental ones. They found that turbulent flame speed is a statistical quantity. Moreover their results indicated that the rate of laminar to turbulent flame speed (at least for propane) is not strongly dependent on fuel-air ratio.

Because quantitative information about the nature of the turbulence in the working fluid of an engine is not available, none of these theories of turbulent flame propagation can be applied directly. However a relationship between the laminar and turbulent flame velocity can be made. Namely,

$$\frac{S_t}{S_\ell} = K \tag{4-2}$$

where K is a quantity dependent only on the level of turbulence in the reaction zone. K must be determined from experimental data and is only valid for a given mean level of turbulence. Now it remains to find an expression for the laminar flame propagation velocity.

The principle mechanisms of flame propagation are the transport of heat and active radicals from the reaction zone to the unburned gas ahead of the flame. A number of theories which take into account one or both of these mechanisms have been advanced to predict laminar propagation velocity (see Reference 50 and 53). Comprehensive theories which take into account both phenomena are difficult to apply and require information about reaction kinetics which is not known for many reactions. Hirshfelder et al. (54, 55) have proposed such a theory and have applied it to a few elementary reactions.

In a number of investigations of the burning velocity of hydrocarbon-air mixtures, less complex theories predict burning velocities which often agreed closely with experimental ones. In particular two theories have been widely employed for several investigations (for example Reference 58, 59, 60, and 61). One is the theory of Tanford and Pease(57) which predicts the velocity from a consideration of the concentration in the reaction zone of certain chemical species, such as H, O, and OH. These are supposed to act as agents to initiate and propagate the reaction. The other is the theory of Semenov(56) which predicts the burning velocity from purely thermal consideration. Reference 60 reports particularly good agreement between experimental values and values calculated from the two theories for the maximum burning velocity of iso-octane-air mixtures at one atmosphere pressure over a range of widely different initial mixture temperatures. Whereas the two theories are based on seemingly unrelated phenomena, the consensus of opinion appears to be that no particular advantage is gained using one of these two simplified theories in preference to the other unless it is definitely known that the basic mechanism of the reaction in question favors one model. In general, equally good agreement has been obtained with either theory.

In light of the above discussion a decision was made to use the thermal theory of Semenov to predict the laminar burning velocity of the hydrocarbon-air mixtures considered in this current study. Reference 59, 60, 62, and 63 treat the reaction between a hydrocarbon such as iso-octane and air as second-order bimolecular. Clarke(62) reports experimental work which shows this reaction to be bimolecular up to 23 atmospheres.

C. Thermal Theory of Flame Propagation for A Bimolecular Second-Order Reaction

Because the thermal theory of laminar flame propagation is so important to the results calculated from the analytical model of Chapter VI, a general development of this theory is made here for a bimolecular second-order reaction. The original full derivation of this theory is in Reference 56. References 50 and 53 review the derivation.

The thermal theory of flame propagation assumes a one dimensional steady state combustion model (see Figure 7). The reaction is propagated solely by the heating of the unburned gas in Zone I, initially at tempera-

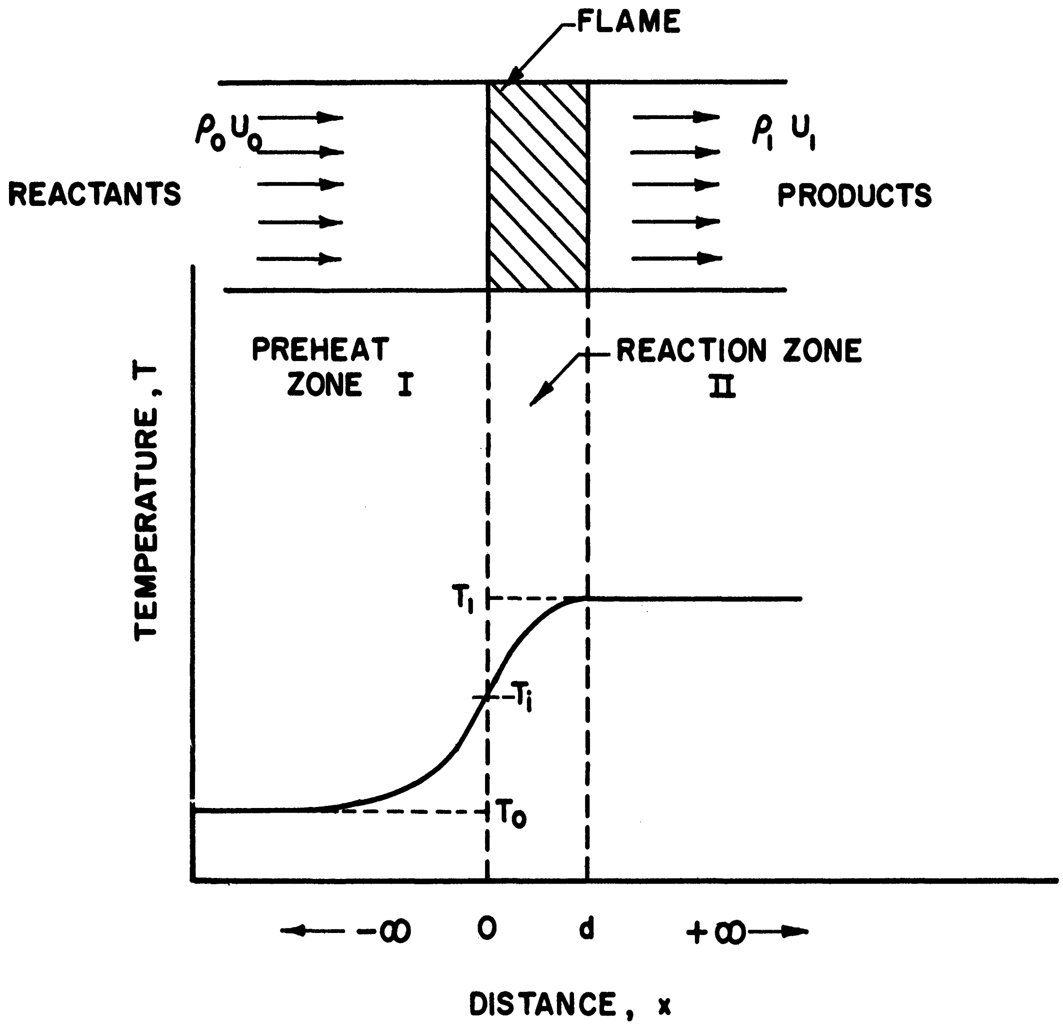


Figure 7. Schematic diagram and temperature profile in the region of the reaction zone.

ture T_0, to a temperature T_i at which point the reaction begins. The reaction occurs completely in Zone II, wherein the temperature is raised to T_1. The width of the reaction zone is 'd'. Beyond Zone II no further reaction occurs.

The notation below is used for the derivation which follows.

Q'	heat of reaction, cal/molecule of reactant
c_p	constant pressure heat capacity, cal/gm-°K
ω	rate of reaction, molecules of reactant/cm^3-sec
a	concentration of fuel, molecules/cm^3
b	concentration of oxygen, molecules/cm^3
P	steric factor
Z	impact coefficient, number of collisions/cm^3-sec
d	depth of reaction zone, cm
M	mass rate of flow, gr/cm^2-sec; molecular weight
ρ	density, gr/cm^3
D	diffusion coefficient, cm^2/sec
λ	thermal conductivity, cal/cm-sec-°K

The general equation for a bimolecular second-order reaction is

$$\omega = ab \cdot P \cdot Z \cdot \exp(-E/RT) \qquad (4-3)$$

The following assumptions are made in connection with this theory;

1. Pressure is constant.
2. c_p and λ are constant.
3. $\lambda/c_p = D\rho$ (which is exact for the diffusion between two ideal gases whose molecules have the same size and weight).

4. The total number of molecules is constant.
5. Below some temperature, T_i, which is near T_1 the reaction rate is essentially zero.
6. In Zone II, the convection term in the energy balance equation is small with respect to the conduction and heat generation terms.

The basic equations in Zone II are as follow:

Continuity equation for the fuel

$$D\rho\frac{d^2\alpha}{dx^2} - M\frac{d\alpha}{dx} + \omega = 0 \qquad (4\text{-}4)$$

$$\alpha = \frac{a_0}{\rho_0} - \frac{a}{\rho}$$

Energy equation

$$\frac{\lambda}{c_p}\frac{d^2\Theta}{dx^2} - M\frac{d\Theta}{dx} + \omega = 0 \qquad (4\text{-}5)$$

$$\Theta = c_p(T - T_0)/Q'$$

Equation of state

$$\rho/\rho_0 = T_0/T \qquad (4\text{-}6)$$

Conservation of mass

$$M = \rho U = \rho_0 U_0 = \rho_0 S_\ell \qquad (4\text{-}7)$$

The boundary conditions for these equations are:

$$\text{For } x = -\infty, \qquad \alpha = 0, \qquad \theta = 0 \tag{4-8}$$

$$\text{For } x = +\infty, \qquad \alpha = \frac{a_0}{\rho_0}, \qquad \theta = c_p\,(T_1 - T_0)/Q' \tag{4-9}$$

In consideration of assumption 3 Equations (4-4) and (4-5) are identical in form and have identical solutions if α and θ coincide over the entire reaction zone. That is

$$c_pT + aQ'/\rho = c_pT_0 + a_0Q'/\rho_0 = c_pT_1 \tag{4-10}$$

This means that the sum of the thermal and chemical energies per unit mass of mixture is constant in the reaction zone. Since this is approximately true, the differential Equation (4-4) can be replaced with the algebraic Equation (4-10). Only the differential Equation (4-5) must now be solved.

In light of assumption 6 Equation (4-5) can be rewritten

$$\frac{d^2T}{dx^2} + \frac{\omega Q'}{\lambda} = 0 \tag{4-11}$$

where at $x = 0$, $T = T_i$ and at $x = d$, $T = T_1$. In region I, $\omega = 0$ according to assumption 5 and the energy equation is

$$\frac{\lambda}{c_p}\frac{d^2T}{dx^2} - M\frac{dT}{dx} = 0 \tag{4-12}$$

where at $x = -\infty$, $T = T_0$ and at $x = 0$, $T = T_i$.

The condition which determines the value of 'M' is that the heat transferred from Zone II to Zone I is equal to that received by Zone I.

That is, at $x = 0$

$$\left(\frac{dT}{dx}\right)_{0,I} = \left(\frac{dT}{dx}\right)_{0,II} \tag{4-13}$$

Solving Equations (4-11) and (4-12) and equating their derivatives according to (4-13), the following equation is obtained

$$S_{\ell} = \frac{M}{\rho_0} = \sqrt{\frac{2\lambda I}{c_p\rho_0(T_1-T_0)}} \tag{4-14}$$

where

$$I = \frac{1}{a_0} \int_{T_0}^{T_1} \omega \, dT \cong \frac{1}{a_0} \int_{0}^{T_1} \omega \, dT \tag{4-15}$$

Since T_i is assumed to be near T_1, the reaction rate, Equation (4-3), can be approximated in order to facilitate the integration of Equation (4-15). The approximate equation is

$$\omega \cong ab \cdot P \cdot Z \cdot \exp(-E/RT_1) \cdot \exp(-\sigma E/RT_1^2) \tag{4-16}$$

where $\sigma = T_1 - T$. From Equation (4-10)

$$\frac{a}{a_0} = \frac{T_0\sigma}{T(T_1-T_0)} \tag{4-17}$$

Semenov suggests that for a lean mixture the concentration of O_2 in the reaction zone can be approximated by its value in the combustion products. This quantity is

$$\frac{b}{b_0} = \frac{T_0}{T}\left[\, 1 - \phi \left(1 - \frac{a}{\frac{a_0T_0}{T}}\right) \right] \tag{4-18}$$

Dugger and Simon(58) have performed the integration in an approximate manner. Their results are as follows:

$$\int_0^{T_1} \omega \, dT \cong a_{eff} b_{eff} P \cdot Z \cdot \frac{RT_1^2}{E} \cdot \exp(-E/RT_1) \qquad (4\text{-}19)$$

where ϕ, the equivalence ratio, is the ratio of the actual fuel-air ratio to the stoiciometric fuel-air ratio. For lean mixtures, $\phi < 1$,

$$a_{eff} = a_0 \frac{T_0}{T_1} \frac{RT_1^2/E}{T_1 - T_0}$$

$$b_{eff} = b_0 \frac{T_0}{T_1} \left[1 - \phi \left(1 - \frac{RT_1^2/E}{T_1 - T_0} \right) \right]$$

For rich mixtures, the roles of the a's and b's are reversed

$$a_{eff} = a_0 \frac{T_0}{T_1} \left[1 - \frac{1}{\phi} \left(1 - \frac{RT_1^2/E}{T_1 - T_0} \right) \right]$$

$$b_{eff} = b_0 \frac{T_0}{T_1} \frac{RT_1^2/E}{T_1 - T_0}$$

The quantity 'Z' is proportional to the square root of temperature and is (Reference 50, p. 151)

$$Z = \left(\frac{d_{col,f} + d_{col,O_2}}{2} \right) \sqrt{8 \pi \frac{R}{A} T \left(\frac{M_f + M_{O_2}}{M_f M_{O_2}} \right)}$$

where d_{col} is the effective collision diameter and M is the molecular weight.

Semenov later relaxes some of the restrictions in assumptions 2, 3, and 4; $\frac{\lambda}{c_p}/D\rho$ is allowed to assume any constant value not necessairly unity; $\frac{\lambda}{c_p}$ is allowed to have the value λ_1/c_{p_1} in Zone II; and the number of moles of products to the number of reactants can be the ratio n_0/n_1.

With the above considered, the final equation for the laminar flame propagation velocity of a second-order bimolecular reaction is

$$S_\ell = \sqrt{\frac{2\ \lambda_1 \int_0^{T_1} \omega\ dT}{a_0\rho_0\ \overline{c}_p(T_1-T_0)} \left(\frac{n_0}{n_1}\right)^2 \cdot \left(\frac{\lambda}{Dc_p\rho}\right)_1^2} \qquad (4\text{-}21)$$

Because of the assumptions involved in the integration, Semenov concludes that for a bimolecular reaction, Equation (4-21) is valid for values of $RT_1/E \leq 0.1$. However recent investigations have demonstrated the reliability of the equation for values of RT_1/E up to 0.15 (58, 59, 60).

D. Use of the Thermal Theory Equations to Predict Turbulent Flame Propagation Velocity

According to Equation (4-2)

$$S_t = K \cdot S_\ell \qquad (4\text{-}22)$$

where S_ℓ can be calculated from Equation (4-21). Because of the unknown constant in Equation (4-22), Equation (4-21) can be considerably simplified by factoring out those quantities which are themselves constants and by expressing other quantities as being proportional to the reaction temperature. In using Equation (4-21), Dugger and Simon(58) suggest that the thermal conductivity be expressed as the following function

$$\lambda = (C_p + 5/4R)\mu/M$$

and the diffusion coefficient as

$$D = 1.336\ \mu/\rho$$

where μ is the viscosity and M is the molecular weight. Dugger(61) proposes that the viscosity can be approximated by the following function of temperature:

$$\mu \propto T^{0.67}$$

Then

$$\frac{\lambda}{c_p}/D\rho = (1 + 5/4\ R/C_p)$$

and

$$\lambda \propto (C_p + 5/4R)/M \cdot T^{0.67}$$

If c_p is approximated by its value at the flame temperature, c_{p_1}, then

$$S_\ell \propto \sqrt{\frac{T_1^{0.67} \int_0^{T_1} \omega dT}{a_0 \rho_0 (T_1 - T_0)} \left(\frac{n_0}{n_1}\right)^2 \left(1 + 5/4\ \frac{R}{C_{p_1}}\right)^3} \qquad (4\text{-}23)$$

The remaining quantities in Equation (4-23) can be calculated by the methods of Chapter II or are known from the initial state of the mixture. The final expression for the turbulent flame speed is

$$S_t = K_1 \sqrt{\frac{a_{eff} b_{eff} T_1^{3.17} \exp(-E/RT\ )}{a_0 \rho_0 (T_1 - T_0)} \cdot \left(\frac{n_0}{n_1}\right)^2 \cdot \left(1 + 5/4\ \frac{R}{C_{p_1}}\right)^3} \qquad (4\text{-}24)$$

where K_1 is determined from experimental data as explained in Chapter VI. K_1 is proportional to the level of turbulence in the reaction zone. For a given value of K_1, Equation (4-24) is valid for predicting the turbulent flame propagation velocity for a situation or variety of situations in which the level of turbulence remains substancially unchanged.

V. HEAT TRANSFER IN A SPARK-IGNITED ENGINE

A. General

There is no question that the heat transferred from the working fluid of an internal combustion engine measurably lowers the thermal efficiency and power output of the engine. Thus it is an important quantity to consider when analytically studying internal combustion engines. Various investigators have attempted to estimate the magnitude of this heat loss. However since the amount of heat transferred depends a great deal on the engine speed, size, combustion chamber geometry, compression ratio, and operating conditions; as well as the coolant type, temperature, and flow rate; there are often large differences between these various estimates.

Lanchester(64) estimates the heat loss from the hot gases during combustion and expansion to be about 10 percent of the heat combustion of which 40 percent of this is lost during combustion. Janeway(65) estimates this heat loss to be 16 to 25 percent of the heat of combustion, depending on the speed, of which a fourth or a fifth is lost during combustion. David and Leah(20) suggest that the heat loss, expressed as a percentage of the heat of combustion, is 1500/N and 7500/N during combustion and expansion respectively where N is the engine speed in revolutions per minute. Pye(66) estimates that during expansion the heat loss is 10 percent and during combustion is 5 percent of the heat of combustion. Ricardo(67) suggests that 6 percent is transferred during combustion and 7 percent during expansion.

How much reduction of the thermal efficiency and mean effective pressure of an engine this heat loss effects depends on the crank angle at which it is transferred. Energy lost near the top center piston position is completely lost in so far as any useful work production in concerned. If an engine without any heat losses has a thermal efficiency of 30 percent and then 5 percent of the heat of combustion is lost at top center, the thermal efficiency will be only 25 percent, a drop of 16 percent. The power output will be reduced by a like amount. However the same heat loss occurring later in the cycle, during expansion, effects a lesser reduction in the thermal efficiency and power output since some work has already been done prior to the decrease of internal energy due to the heat transfer.

Taylor(45) estimates that the reduction in power and efficiency due to heat loss during combustion and expansion is about 10 percent of the equivalent fuel-air cycle power and efficiency. It is generally agreed that the magnitude of the heat transfer during compression prior to combustion is much smaller than that during combustion and expansion. To a first approximation the compression process can be treated as adiabatic.

In addition to the heat transferred directly from the working fluid during compression, combustion, and expansion, additional heat is transferred to the coolant primarily during the exhaust stroke and as a result of piston friction. Because this study is mostly concerned with the analysis of the compression, combustion, and expansion processes, these additional heat quantities are not considered.

The heat transferred from the working fluid to the cylinder surfaces is primarily convective in nature, although some (estimated to be 5 to 10 percent of the total) is lost by radiation. The radiation losses will be discussed later in this chapter. A number of investigators have found the principal heat transfer mechanism to be turbulent forced convection, an observation which correlates well with the nature of the flame propagation described in Chapter IV. These investigators correlated the average gas side Nusselt number with the Reynolds and Prandtl numbers as is commonly done with forced convection through tubes or over flat plates etc.(68). This relationship is

$$\frac{hL}{k} = C\left(\frac{GL}{\mu}\right)^{a} \left(\frac{C_p\mu}{k}\right)^{b}$$

where

$\frac{hL}{k}$ = Nusselt number

$\frac{GL}{\mu}$ = Reynolds number

$\frac{C_p\mu}{k}$ = Prandtl number

and C, a, and b are experimentally determined constants. Pinkel(69) developed a method for determining the average heat transfer coefficient in an internal combustion engine which is based upon this forced convection theory. This method with some modification has been used successfully to predict average heat transfer coefficients in many investigations (69, 70, 71, 72, 73, 74, and 75). Taylor(45), Chapter 8, describes this theory completely. After examining experimental results from 16 different engines, Taylor and Toong(75) proposed the following expression

$$\frac{U_e b}{k_g} = 10.4(Re_g)^{0.75} \qquad (5\text{-}1)$$

U_e is the overall average heat transfer coefficient and Re_g, the gas side Reynolds number, is equal to Gb/μ, where b is the bore and G is the time averaged mass flow into the cylinder divided by the piston area.

While these investigations shed light on the overall heat transfer process, showing that forced convection is the predominate heat transfer mechanism, they yield no information about the instantaneous heat transfer rates or how the convective heat transfer coefficient depends upon the state of working fluid.

Analytical solutions which consider the multi-dimensional nature of the problem as well as the variation of the heat transfer coefficient can not be obtained. However an analytical solution based on a simplified one dimensional model with a constant heat transfer coefficient can be obtained and does yield a great deal of information about the nature of the forced convection.

B. Convective Heat Transfer in Engines

1. Temperature Distribution and Heat Flow in a Finite Plate in Contact With a Uniform Medium Whose Temperature Varies Periodically

To a first approximation, the working fluid in an internal combustion engine can be assumed to be contained in a hollow cylinder capped at both ends by flat plates. Dahl(78) has shown that in considering the temperature distribution in a hollow cylinder, the curvature may be neglected for many practical applications. If the ratio of the outside to the inside cylinder radius, r_0/r_i, is less than 1.4, the error in neglecting the curvature is approximately $25(r_0/r_i-1)$ percent. For the internal combustion engine, where the radius ratio is only slightly greater than one, the error in neglecting the curvature will probably notexceed 3 percent.

Thus the one dimensional flat plate analysis is equally valid for any combustion chamber surface which is either thin walled or has little curvature.

Figure 8 shows the model upon which the heat transfer analysis is based. It has the following characteristics. The wall temperature on the coolant side, T_c, is constant. This approximation has been born out by experimental studies. The gas temperature varies about its mean value, T_0, cosinusoidally. For this one dimensional situation, the equation for heat conduction in the solid wall is(78)

$$\frac{d^2T}{dx^2} = \frac{1}{\alpha}\frac{dT}{dt} \tag{5-2}$$

where $\alpha = c_p\rho/k$. This quantity is approximately constant over the rage of temperatures experienced by the wall and is assumed to be constant for the solution. The gas temperature is presumed to vary as

$$T_g = T_0 + \Theta\cos(\omega t) \tag{5-3}$$

The solution of this problem for large values of time is composed of the sum of two solutions, the steady state and the steady periodic. That is,

$$T(x,t) = T_s(x) + T_p(x,t) \tag{5-4}$$

The boundary conditions are

$$T(d,t) = T_c$$

$$-k\,\frac{dT(0,t)}{dx} = h\left[T_0 + \Theta\cos(\omega t) - T_s(0) - T_p(0,t)\right] \tag{5-5}$$

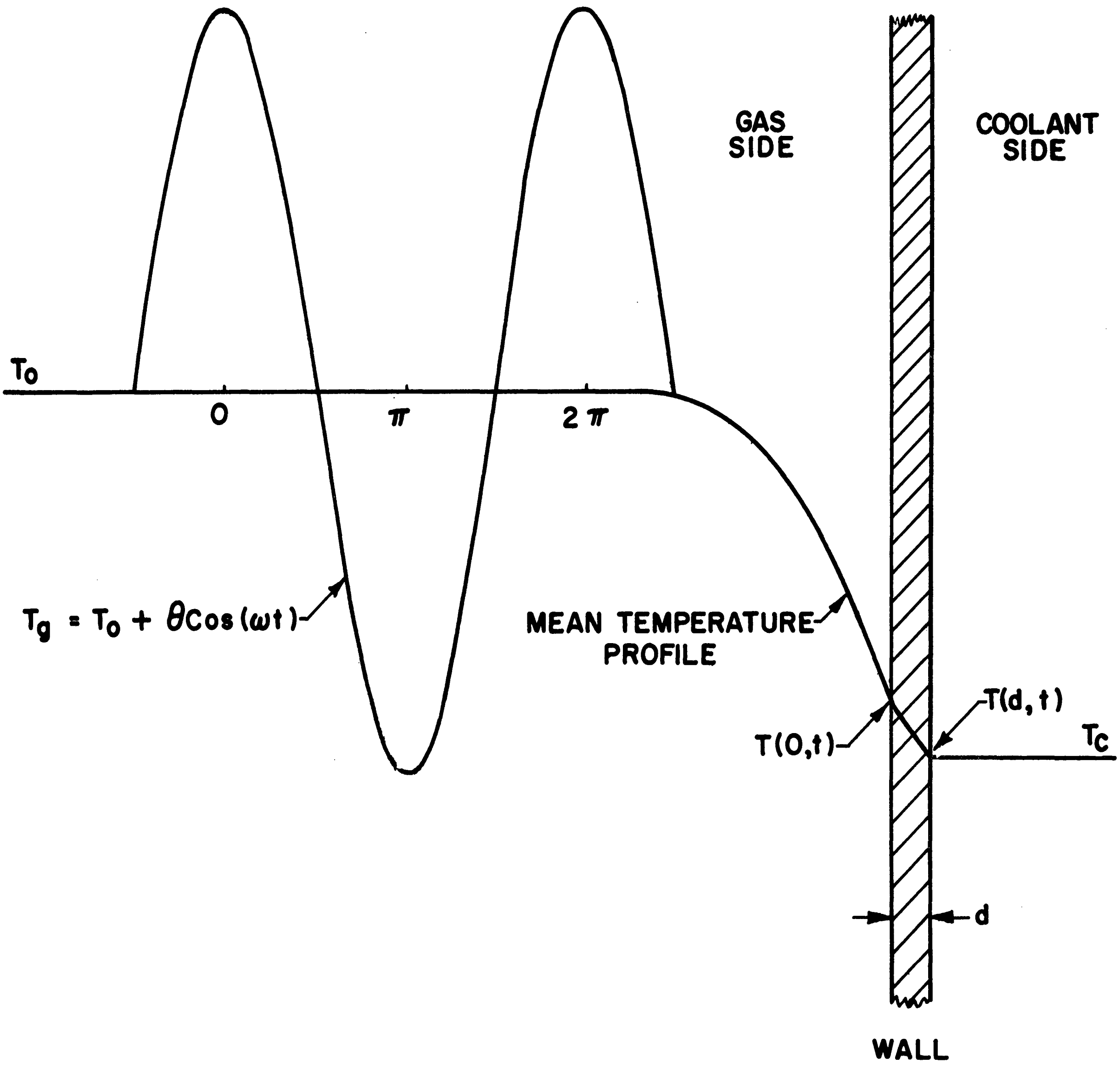


Figure 8. Heat transfer model for the internal combustion engine.

By considering the solution at large values of time, the transient starting solution is eliminated as well as one boundary condition, leaving the two boundary conditions (5-5). To obtain the solution (5-4), the boundary conditions (5-5) can be broken up into two pairs, one for each solution.

For the steady state solution, the differential equation is

$$\frac{d^2T_s}{dx^2} = 0 \tag{5-6}$$

and the boundary conditions are

$$\begin{aligned} T_s(d) &= T_c \\ -k\,\frac{dT_s(0)}{dx} &= h\Big[T_0 - T_s(0)\Big] \end{aligned} \tag{5-7}$$

The solution of (5-6) with these boundary conditions is easily obtained as

$$T_s(x) = T_c + \Big[T_0 - T_c\Big]\frac{h(d-x)/k}{hd/k + 1} \tag{5-8}$$

For the periodic part, the differential equation is

$$\frac{d^2T_p}{dx^2} = \frac{1}{\alpha}\,\frac{dT_p}{dt} \tag{5-9}$$

and the boundary conditions are

$$T_p(\infty,t) = 0$$

$$-k\,\frac{dT_p(0,t)}{dx} = h\Big[\theta\cos(\omega t) - T_p(0,t)\Big] \tag{5-10}$$

The first boundary condition is approximate only. However it will be seen later that the temperature fluctuations in the wall are damped out so quickly that the wall need not be very thick to approximately satisfy this boundary condition. The solution of this equation, according to Jakob(79) is

$$T_p(x,t) = \Theta\eta e^{-mx}\cos(\omega t - mx - \epsilon)$$

where

$$\eta = \sqrt{\frac{1}{1 + 2m/b + 2m^2/b^2}} \tag{5-11}$$

$$\epsilon = \tan^{-1}\frac{1}{1 + b/m}$$

and

$$m = \sqrt{\frac{\omega}{2\alpha}}$$

$$b = h/k$$

The complete solution is

$$T(x,t) = T_c + \left[T_0 - T_c\right]\frac{b(d-x)}{bd + 1} + \Theta\eta e^{-mx}\cos(\omega t - mx - \epsilon) \tag{5-12}$$

Jakob(79) presents a table of η and ϵ for various values of b/m.

By substituting some typical numerical values for iron in Equation (5-12), the temperature distribution in an engine wall can be approximated. For iron, $\alpha = 0.5$ ft^2/hr and $k = 36$ Btu/hr-ft^2-°F(80). A typical engine wall thickness is 0.25 in and speed is 2000 rpm or $4000\,\pi$ radians per min. The gas side heat transfer coefficient varies a good deal, but during the early portion of the expansion stroke, a value of 360 Btu/hr-ft^2-°F is representative(77). Thus $b = 10/\text{ft}$, $m = 700/\text{ft}$, $\epsilon \cong \pi/4$, and $\eta = 0.01$. The average coolant side surface temperature is constant at a given point on the wall and 220°F is a reasonable value when the coolant is water(77). If Θ is 2000°F and T_0 is 2060°F, Equation (5-12), with the above numerical substitutions, is

$$T(x,t) = 220 + 1840 \cdot \frac{(0.208 - 10x)}{1.208} + 20e^{-700x}\cos(4000\pi t - 700x - \pi/4)\,°\text{F}$$

A number of conclusions can be drawn immediately:

1. At the wall ($x = d = 0.25/12$ ft) the boundary condition is satisfied. The temperature fluctuations are reduced by a factor of $e^{+14.5}$ which is approximately 10^{+8}. Thus treating the wall as a very thick plate for the purposes of obtaining the periodic part of the solution is a good assumption.
2. At the wall ($x = 0$) the fluctuations are reduced to 1 percent of those in the gas or to 20°F for the present example. This magnitude is in excellent agreement with experimentally measured temperature fluctuations reported in References 77 and 81.
3. At the wall ($x=0$) the fluctuations lag those in the gas by 45°. Because of the great simplification in the gas temperature fluctuation made for the derivation of (5-12), the 45° figure is too large. Although this lag is always a positive quantity it is considerably less than 45°. The data of Oguri(82) indicates that half this value may be a better estimate.

4. The average surface temperature ($x = 0$) is about 540°F. This is much too high and reflects the fact that the temperature fluctuations are not cosinusiodal in nature. The relatively low temperatures during the exhaust and induction processes greatly reduce the average surface temperature appreciably. For a water side wall temperature of 220°F, Reference 77 reports a gas side wall temperature of 300°F. This value varies somewhat from point to point on the wall.

Thus while Equation (5-12) must be recognized as being very approximate, it yields wall temperature distributions which at least reflect the more complex processes occuring within the cylinder. It shows that the average wall temperatures are much lower than the average gas temperatures and that the temperature fluctuations in the wall are a miniature replica of those in the gas.

The heat transferred to the wall per unit area is

$$q/A = -k \frac{dT(0,t)}{dx} = k\left[T_0 - T_c\right] \frac{b}{bd+1} + 2m\theta\eta\cos(\omega t - \epsilon - \pi/4) \qquad (5\text{-}13)$$

This equation shows that the heat transfer is composed of a steady part plus a periodically varying part which is positive as often as it is negative. Substituting numerical values

$$q/A = 36\cdot\left[15250 + 19750\cos(\omega t)\right]$$

$$= 350\text{Btu/ft}^2\text{-sec} \quad \text{(maximum)}$$

A number of conclusions can be drawn immediately:

1. The periodic term is of the same magnitude as the steady state term and during periods of low temperature some heat is transferred from the wall back to the working fluid (for example during the compression process). Thus the wall acts as a sort of flywheel in this respect.
2. For the cosinusoidal gas temperature variation assumed, the heat transfer fluctuations are in phase with the temperature fluctuations of the gas. However because of the many simplifications introduced into the solution this phase relationship is not exactly correct and in fact the gas temperature fluctuations will lead the heat transfer fluctuations by a few degrees.
3. The heat transfer rate calculated in the numerical example, 350 Btu/ft^2-sec, compares favorably with the magnitude of the rates measures experimentally in Reference 77 for comparable engine operating conditions.

A more complete solution of (5-2) can be made if it is assumed that the gas temperature varies as a Fourier sine and cosine series as follows

$$T_g = T_0 + \sum_{n=0}^{\infty} \left[A_n \cos(n\omega t) + B_n \sin(n\omega t) \right] \qquad (5\text{-}14)$$

where T_0 is still the time averaged gas temperature. The complete solution is

$$T(x,t) = T_c + \left[T_0 - T_c\right]\frac{b(d-x)}{bd+1} + \sum_{n=0}^{\infty} \eta\, e^{-m'x}\left[A_n\cos(n\omega t - \epsilon - m'x) + B_n\sin(n\omega t - \epsilon - m'x)\right] \tag{5-15}$$

where

$$m' = \sqrt{\frac{\omega n}{2\alpha}}$$

The other quantities remain the same as they were in Equation (5-10) except that m is replaced by m' in every case.

If, in an actual engine, the heat transfer fluctuations and the gas temperature fluctuations are not out of phase too much, which appears to be the case (see Oguri(82)), then to a first approximation the heat transfer rate can be expressed as

$$q/A = h(T_g - T_w) \tag{5-16}$$

where T_w is the average wall temperature and T_g is the instantaneous gas temperature of that gas in contact with the surface A. Since it has been shown that T_w is approximately constant at a point on the wall even for widely fluctuating gas temperatures, Equation (5-16) should predict the rate of heat transfer reasonably well when the appropriate value of 'h' is employed in the computation.

2. The Convection Heat Transfer Coefficient

The applicability of the exact solution of the preceeding section is limited, in part, due to the wide fluctuation in the value of the heat transfer coefficient in the working fluid of an internal combustion engine. It may vary by as much as a factor of ten during the cycle. A number of investigators have attempted to express this variation in terms of the temperature, pressure, and density of the working fluid.

Of the several expressions in the literature, two are of special interest. Nusselt(83) was among the first to formulate an expression for the heat transfer coefficient in an internal combustion engine. His expression, based on experimental observation, included radiation as well as convection effects. It is

$$h = \underbrace{0.99\sqrt[3]{P^2T}\,(1+1.24w)}_{\text{convection}} + \underbrace{0.362\,\frac{(T/100)^4-(T_w/100)^4}{T-T_w}}_{\text{radiation}} \quad \text{kcal/m}^2\text{-hr-°K} \qquad (5\text{-}17)$$

where 'w' is the average piston speed in meters per sec. Eichelberg(81) also deduced a formula from experimental data for the heat transfer coefficient. It is

$$h = 2.1\sqrt[3]{w}\,\sqrt{PT} \quad \text{kcal/m}^2\text{-hr-°K} \qquad (5\text{-}18)$$

Although these two equations are somewhat different in form, they have certain features in common. For example, both depend on the temperature and pressure of the working fluid and the engine speed. Moreover since the cycle temperature and pressure vary in a similar manner the square root of PT and the cube root of P^2T tend to predict similar variations in the heat transfer coefficient. Oguri(82) reports that for 'w' in the range of 4-6 meters per sec., both expressions give comparable values of h over the compression, combustion, and expansion processes. Some recent investigations have employed the expression of Eichelberg to predict heat transfer coefficients. Vincent and Henein(85) used Eichelberg's equation to predict thermal loadings of diesel engine cylinder walls. Overbye and Co-workers(77) determined 'h' for a wide range of engine operating conditions. However not particularly good agreement between experimental and calculated values of 'h' was found. On the other hand Oguri(82) reported reasonably good agreement between experimental and calculated (by Eichelberg's equation) values of 'h', at least for the combustion and expansion portions of the cycle. Oguri also presents a dimensionless correlation for the gas side Nusselt number but the expression contains constants which must be determined for each particular engine.

Consequently, at this time it appears as if the formula of Eichelberg is about the best expression available for the convective heat transfer coefficient. In light of this, the equation for the convection heat transfer rate per unit area is presumed to be

$$q/A = 2.1\sqrt[3]{w}\sqrt[2]{PT}\left[T - T_w\right] \text{ kcal/m}^2\text{-hr-°K} \qquad (5\text{-}19)$$

This equation will be used to calculate the rate of heat transfer during the combustion and expansion processes. The compression process, prior to combustion, will be treated as reversible and adiabatic.

C. Radiant Heat Transfer in Engines

The radiant component of heat transfer is small compared to the convective component in internal combustion engines exhibiting normal combustion. Nusselt(83) found that the radiant heat transfer was about 5 percent or less of the total heat transfer (see Equation (5-17)).

Overbye and Co-workers deduced from their experimental observations that the radiant heat transfer was negligible. Baker and Laserson(86) found experimentally that the radiant heat transfer was quite low. In a 4.6 to 1 compression ratio engine the radiant heat transfer amounted to only 22 Btu/ft^2-sec. at its peak. This would be less than 10 percent of the total heat transfer. However for higher compression ratios it is expected that this percentage would increase. Thus a simple calculation is made below to see if this is the case.

Of the principal constituents present in the products of an internal combustion engine, only CO_2 and H_2O emit any appreciable amount of radiation during normal combustion. McAdams(68) and Hottel(87) indicate a procedure by which the amount of radiation from these two constituents may be approximated. Unfortunately the curves from which the estimation is made do not extend into the range of temperatures and pressures found in a modern high compression ratio engine. Thus extensive and often questionable extrapolation is necessary. In Appendix H, a calculation is made of the maximum rate of heat transfer due to radiation by the method of these men. An engine operating on the fuel-air cycle at a compression ratio of 10 to 1 was selected for the calculations. The heat transfer was calculated immediately after the adiabatic combustion at top center in order to obtain the conditions where the radiation would be most severe. It was found that under these conditions the radiant heat transfer was still only 12 percent of the total at most. Because of the idealizations of the fuel-air cycle engine, the percentage is higher than it would be in an actual engine.

Thus it appears that in the operating range of the present day spark-ignited internal combustion engine, the amount of heat transferred by radiation during normal combustion is a small proportion of the total. Because of this, radiation will be neglected in the analytical model for the internal combustion engine being proposed in this study and Equation (5-19) will be employed for all heat transfer calculations.

VI. THE ANALYTICAL MODEL FOR SPARK IGNITED ENGINE CYCLE CALCULATIONS

A. General

The discussion of Chapter I indicates that the fuel-air cycle greatly oversimplifies many internal combustion engine processes in that it neglects fundamental phenomenona which significantly affect engine performance. Of these phenomena, two are of particular importance, namely the heat transfer and the flame propagation. The purpose of this chapter is to describe an analytical model for internal combustion engine cycle calculations which includes these phenomena. Their inclusion into the cycle analysis, especially during the compression, combustion, and expansion processes, makes possible the calculation of a stepwise continuous pressure time diagram which shows many important features of the experimental by determined diagram. Moreover, this allows an explicit evaluation of the effects of these two phenomena on the efficiency and power output of the engine. A consideration of such variables as engine speed, spark advance, and combustion chamber geometry further enhances the similarity between the analytical model and the actual engine.

The analytical model employs many features of the fuel-air cycle, especially in its treatment of the working fluid. The charge is presumed to be composed of a mixture of fuel and air which is burned during the cycle. The following assumptions, made in connection with the fuel-air cycle analysis in Chapter III, are also made for the analytical model:

1. There is no chemical change in either fuel or air prior to combustion.
2. All products of combustion are in a state of chemical equilibrium at temperatures in excess of 1500°K and are in a state of frozen equilibrium below that temperature.
3. Induction, compression, and exhaust processes are adiabatic.
4. There are no irreversible fluid flow effects.
5. All valve events occur at top and bottom center.

The thermodynamic properties of the working fluid as well as the composition of the products of combustion are computed by the methods illustrated in Chapter II, just as they were for the fuel-air cycle engine analysis of Chapter III.

It is the combustion and expansion processes wherein the analytical model differs greatly from the fuel-air cycle. Both processes are assumed to occur in a stepwise manner and allowance for heat transfer is made during each. Figure 9 illustrates the pressure volume diagram for the assumed processes of this analytical model.

B. The Cycle Processes

1. Process 1-2: Compression

The working fluid is compressed from Point 1 (bottom center) to Point 2. Point 2 is an arbitrary crank angle where combustion begins. The compression is treated as a reversible and adiabatic process.

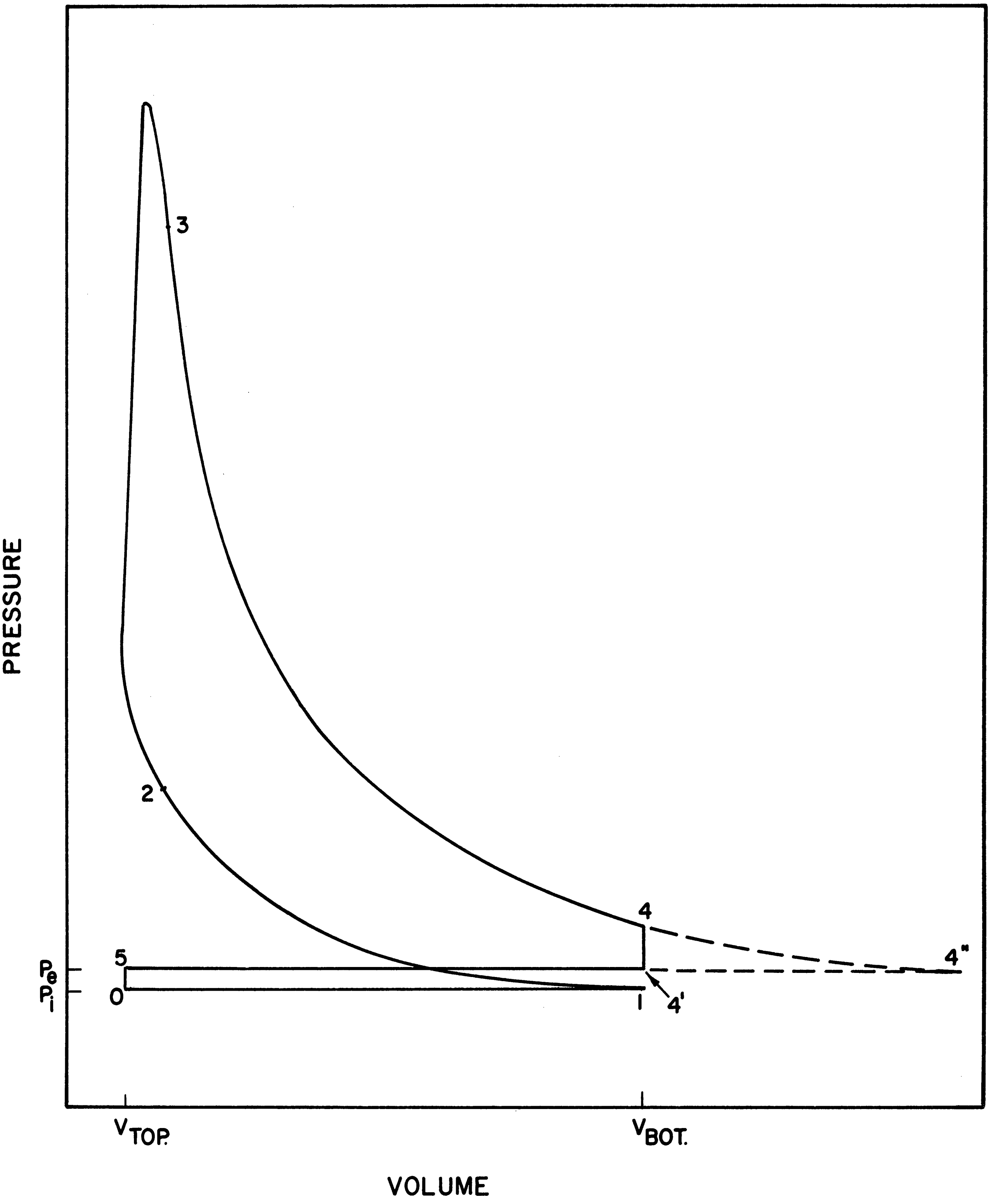


Figure 9. Indicator diagram for the engine on the "analytical model" at part throttle.

Experimental studies have confirmed the general validity of this assumption. They show that during a normal engine cycle little heat is transferred during compression. The state of the system during this process is calculated at regular crank angle intervals in order to construct a pressure time diagram for this part of the cycle. The expression for the volume of the cylinder (including the clearance volume) as a function of crank angle and engine geometry is as follows:

$$V = V_{top} + \pi \frac{\text{Bore}^2}{4} \left[\frac{\text{Stroke}}{2} (1 + \cos \theta) + \text{Rod} \cdot \left(1 - \sqrt{1 - \left(\frac{\text{Stroke}}{2 \text{ rod}} \sin \theta\right)^2} \right) \right]$$

From this expression, the successive volume changes for the isentropic compression processes can be calculated. The total work done during the compression process is

$$W_{1-2} = U_1 - U_2$$

The total heat transferred is zero.

2. Process 2-3: Combustion

The combustion process begins at some crank angle or spark advance corresponding to Point 2. Strictly speaking, this may not be the true spark advance as no provision is made for any ignition delay. Combustion is assumed to progress in a stepwise manner with an arbitrary fraction of the total mass burning during each increment. A single increment is composed of seven steps. During each increment some heat is transferred and some piston motion occurs.

The working fluid during combustion is assumed to be composed of two distinct gaseous regions, one of burned and one of unburned gas.

These are physically separated by a flame front. The unburned gas is compressed continuously during combustion due to the greater volume occupied by the hot products of combustion. Thus each increment that burns does so from slightly different initial conditions. Because of this, a temperature stratification is formed in the burned portion of the gas.

At this stage in the analysis of the combustion process, a number of assumptions must be made, for it is impossible to consider in detail the mixing and heat transfer which may occur within the burned region and between the burned and unburned regions. Within the burned region it must be assumed that either complete uniformity exists because of rapid mixing and heat transfer or that no mixing or heat transfer occur whatsoever, and each burned increment follows an isentropic path subsequent to its combustion. This later assumption was made in an analysis by Hershey.(10) He cites experimental temperature measurements which confirm the stratification although these show it to be less than that calculated. It is not felt that an individual treatment of each burned increment in this manner will lead to significantly different or more meaningful results. Therefore in this analysis complete uniformity will be assumed in the burned region as well as in the unburned region.

It will be assumed however that there is no mixing between the burned and unburned portions. Photographs of normal combustion processes show regular continuous flame fronts and do not indicate that appreciable mixing occurs.

The unburned portion of the gas will be assumed to follow an isentropic path. Pressure and temperature measurements taken in this region by Livengood et al.(88) show this to be a reasonably good assumption. This does not mean that there is no heat transfer to or from the unburned gas, but only that the net amount is very small. Thus one final assumption is made for the combustion process, namely, that heat is transferred from the burned to the unburned gas in an amount exactly equal to that transferred from the unburned gas to the combustion chamber surfaces. In effect this means that the burned gas will be charged with the entire internal energy decrease due to heat transfer and the unburned gas will always follow an isentropic path.

Figures 10 a-h illustrates the seven steps comprising the combustion of the i'th mass increment. To the right of each figure, the total system (burned + unburned) thermodynamic properties are designated by appropriate symbols whenever a single property pertains to both regions. The two homogeneous regions are designated B (burned) and U (unburned). The cross-hatched area represents the currently inflamed mass element and is labeled F (flame element). Let the system pressure, volume, and internal energy at the completion of the (i-1)'st increment be P_o, V_o, and U_o. Figure 10a illustrates the state of the system in this condition.

Step 1 - Figure 10b - Constant pressure combustion of the i'th mass increment. A thin shell of gas whose thickness is $(R_o' - R_o)$ is burned. The system volume increases during this constant pressure combustion to V_1. The state of the previously burned and still unburned portions remains unchanged. The flame element undergoes an isenthalpic process, burning to its equilibrium adiabatic flame temperature.

Step 2 - Figure 10c - Constant pressure mixing of the flame element with the previously burned gases. The current flame element is mixed adiabatically with the previously burned portion. The end of this isenthalpic process finds a single homogeneous region of burned gas. The state of the unburned gas remains unchanged.

Step 3 - Figure 10 d - Recompression to volume V_0. The volume of the system is changed back to V_0 in such a way that the unburned gas follows an isentropic path and the total internal energy of the system after recompression is U_0. During this step the pressure rises to P_3. At this point in the process it is as if the system had experienced the combustion of a small increment of mass adiabatically and at constant volume.

Step 4 - Figure 10e - Isentropic change of state due to piston motion. The combustion of the i'th mass increment has taken a finite amount of time. Call this Δt. During this interval the piston moves causing a change in the volume of the system. Each gaseous region is presumed to undergo an isentropic change of state. The system volume is changed to V_4 and the pressure to P_4. Δt is figured in Step 7 from a knowledge of the flame speed. An initial assumption is made for Δt. The work done in this step, which is the total work done during the combustion of the i'th mass increment, is

$$W_i = U_{i_0} - U_{i_4}$$

Step 5 - Figure 10f - Constant volume heat transfer. Heat is transferred from both regions to the combustion chamber surfaces and from the burned to the unburned gas. The volume of each region remains the same. Because the amount of heat transferred to the unburned gas is just off-set by that from the unburned gas to the walls, the unburned gas undergoes no change of state whatsoever during this step. The burned gas undergoes a constant volume process in which heat is transferred to the walls and to the unburned gas. Thus the internal energy of the gas is reduced by the amount of this heat transfer.

Since heat is transferred from both burned and unburned regions, it is necessary to know, along with Δt, the amount of wall and piston area exposed to both burned and unburned gases. These areas differ with the flame front position and the crank angle and depend on the combustion chamber geometry. During a given combustion increment, subsequent to Step 4, the burned volume occupies a certain fraction of the entire combustion space. Corresponding to this volume fraction there is a certain mean flame front position as well as a definite wall and piston surface area exposed to both burned and unburned regions. By initially assuming that combustion occurs at top center and that the flame front progresses spherically from the center of ignition, these area-length-volume relationships can be found by graphical construction. Such quantities reduced to fractional form are presented in Table VII for the combustion chamber of Figure 1. The proper values can then be found by interpolation in the table (a three point interpolation is used in this work between the length-volume entries and a linear interpolation between the length-area entries).

It is often assumed that a small amount of piston motion does not change these area-length-volume relationships. Taub(89) reports that the result of detailed calculations of the possible effects of piston motion on these relationships indicates that no appreciable changes occurred for moderate amounts of piston motion, at least for the particular geometry investigated. However, for larger piston displacements their validity is questionable and a more detailed analysis of the combustion chamber may be necessary. This is the case for the combustion chamber of Figure 11. To account for the effect of piston displacement on the position of the burned gas region in this chamber, the following assumptions were made. Prior to top center piston position the relations of Table VIII are presumed valid. After top center some burned gas is found in a right cylinder whose height is just equal to the piston displacement from top center and whose radius is equal to the radius of the flame front. The remaining burned gas occupies the combustion chamber according to the volume-length relationships of Table VIII. Refering to Figure 11, for a small amount of piston displacement the burned gas region would look like a short right cylinder which is shaped like the combustion chamber head on one end and has a hemispherical cap on the other, at least prior to the time when the hemispherical dish is filled with burned gas.

Having determined the position of the flame front by the above assumptions, the wall, head, and piston areas exposed to the burned gas can then be calculated. The latter two are calculated from a table such as Table VIII and the wall area is calculated from the crank angle as follows:

$$A_{wt} = \pi \cdot \text{Bore} \left[\frac{\text{Stroke}}{2} (1 + \cos\theta) + \text{Rod} \left(1 - \sqrt{1 - \frac{\sin^2\theta \cdot \text{Stroke}^2}{4 \cdot \text{Rod}^2}}\right) \right] \qquad (6\text{-}2)$$

where the proportion of this exposed to the burned gas can be calculated geometrically. In a similar manner the areas exposed to the unburned gas can be found. For heat transfer calculations the heat and cylinder wall areas are added together.

In Chapter V a decision was made to use the formula of Eichelberg$^{(81)}$, Equation (5-19), to compute the heat transfer. Considering heat transfer from both regions to the walls and piston, the expression for the total heat transfer during the i'th combustion increment is:

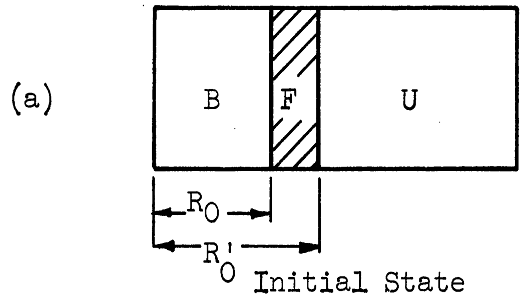
$$Q_i = 2.1 \sqrt[3]{w} \sqrt{P_4} \left[\sqrt{T_{4b}} \left(A_{wb}(T_{4b} - T_{\bar{w}}) + A_{pb}(T_{4b} - T_p)\right) + \sqrt{T_{4u}}\left(A_{wu} (T_{4u} - T_{\bar{w}}) + A_{pu} (T_u - T_p)\right) \right]_i \cdot \Delta t \qquad (6\text{-}3)$$

Equation (6-3) assumes that all the combustion chamber surfaces with the exception of the piston surface are at some constant average temperature and that the piston surface temperature is at some other constant average temperature. In Chapter V, a discussion of the magnitude of the temperature fluxuations at the wall surface indicated that any point on the wall has a relatively constant temperature. However, no two points necessarily have the same temperature. Nevertheless an average overall wall temperature, while a great simplification, would still appear to be a reasonable assumption.

At the end of this step, the burned gas is in a state of chemical equilibrium at volume V_4. Its internal energy has been decreased during this process by Q_i. The pressure in each of the two regions is different.

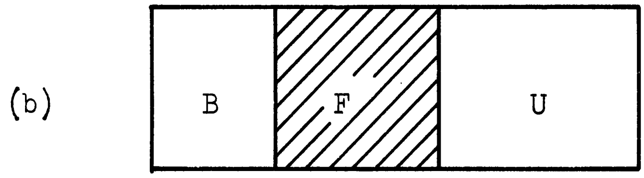
Step 6 - Figure 10g - Adiabatic constant energy readjustment to a uniform pressure. During this step the two regions are allowed to attain pressure equilibrium adiabatically, without a change in the total system volume, and therefore at constant internal energy. The unburned gas undergoes an isentropic change of state. The final pressure is P_6. This step completes the combustion of the i'th increment. However, the time interval Δt is still not known.

Step 7 - Figure 10h - Determination of the time interval required for combustion. The flame element of Figure 10b is isentropically compressed to the final pressure P_6. It is assumed that this equilibrium state represents the average burned state for the i'th increment. The values of T_7, C_{p_7}, and n_7 are substituted into Equation (4-24) as T_1, C_{p_1}, and n_1. The quantities needed in this equation for the state prior to combustion are those in the unburned gas just prior to Step 1. The flame speed, S_t, is now computed from Equation (4-24) with the following consideration. For air-fuel ratios in the region of five percent lean to five percent rich concentrations a_{eff} and b_{eff} are taken as the average of the concentration at these two extremes. This is because in the derivation of these quantities, it was assumed that the concentration of the fuel was much greater than that of the oxygen or vice-versa. This refinement is suggested by Dugger and Simon.(58)



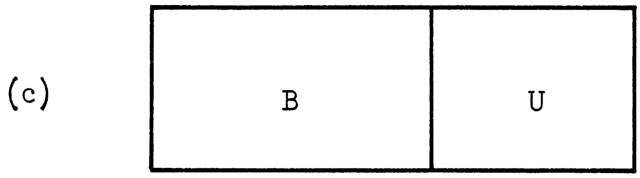
$P = P_0$
$V = V_0$
$U = U_0$
$H = H_0$
$S = S_0$

Initial State



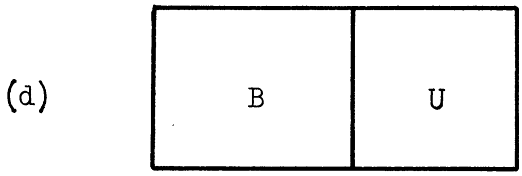
$P = P_0$
$V = V_1$
$U = U_1$
$H = H_0$
$S = S_1$

Step 1 - Constant Pressure Burning



$P = P_0$
$V = V_2$
$U = U_2$
$H = H_0$
$S = S_2$

Step 2 - Constant Pressure Mixing

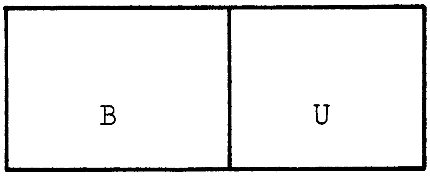


$P = P_3$
$V = V_0$
$U = U_0$
$H = H_3$
$S = S_3$

Step 3 - Recompression to Original Volume

Figure 10. Mathematical Model for Combustion and Heat Transfer.

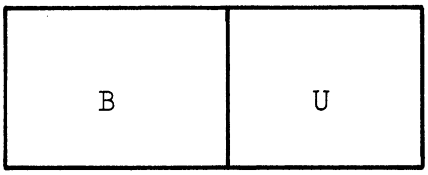
(e)



$P = P_4$
$V = V_4$
$U = U_4$
$H = H_4$
$S = S_3$

Step 4 - Change of Volume Due to Piston Motion

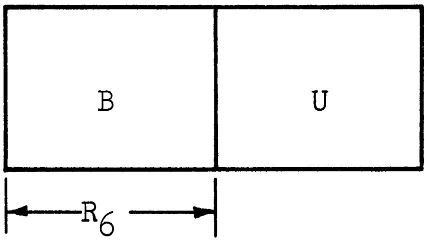
(f)



$P = -$
$V = V_4$
$U = U_5$
$H = H_5$
$S = S_5$

Step 5 - Constant Volume Heat Transfer

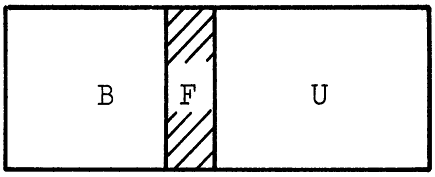
(g)



$P = P_6$
$V = V_4$
$U = U_5$
$H = H_6$
$S = S_6$

Step 6 - Adiabatic Readjustment to Uniform Pressure

(h)



$P = P_6$
$V = -$
$U = -$
$H = -$
$S = -$

Step 7 - Recompression of Flame Element to Final Pressure

Figure 10. (Continued)

Corresponding to the volume fraction inflamed at the end of the (i-1)'st increment, there was some characteristic distance R_0, the radius of the spherical flame front. For the combustion chamber of Figure 11, Table VIII includes values of the flame front radius divided by the longest distance the flame travels if the combustion occurs at top center. The effects of small piston displacements on this volume fraction-distance fraction relationship are neglected. At the end of the combustion of the i'th increment, the flame front is at a distance R_6 from the center of ignition (see Figure 10g). The difference, $R_6 - R_0$ is the total extension of the flame front during the combustion of the i'th increment. Part of this is due to expansion and part to flame propagation. That due to flame propagation is

$$\Delta l = (R_0' - R_0) \qquad (6\text{-}4)$$

For the first increment this quantity is

$$\Delta l = (3/4 \cdot \pi \cdot V_{f0})^{1/3} \qquad (6\text{-}5)$$

wherein it is assumed that after the combustion of the first increment the burned gas is spherical in shape. V_{f0} is the volume of the first mass increment prior to combustion.

The time required for the increment to burn is

$$\Delta t = \Delta l / S_t \qquad (6\text{-}6)$$

If the Δt assumed in Step 4 is not suitably close to that just calculated, Steps 4, 5, 6, and 7 are repeated until the change in successive Δt's is within a specified limit. When this is the case the i'th increment is completed and the (i+1)'st begun. The combustion process is continued until all the mass is consumed. This occurs at Point 3 on Figure 9. For this process the total heat transferred is

$$Q_{2-3} = \sum_{\text{combustion}} Q_i$$

The total work is

$$W_{2-3} = \sum_{\text{combustion}} W_i$$

If the flame speed constant, K_1, Equation (4-24), is not known; some experimental data must be used to establish its value. The necessary information may be obtained from the experimental pressure-time diagram for the particular engine under consideration. It is necessary to know only the spark advance and the crank angle where the maximum pressure is obtained.

The constant, K_1, is determined as follows. The incremental combustion process is presumed to begin at the known spark advance. After the combustion of several increments the cylinder pressure will be observed to have reached a peak and then begin to decline. If the crank angle at which this peak occurs is not sufficiently close to the crank angle where the peak occurs experimentally, then the constant can be corrected by a factor which is the ratio of the experimentally determined number of degrees from the beginning of combustion to the point where the maximum pressure occurs to this same quantity just determined analytically. The combustion process is then repeated and the constant recorrected until the two peaks are suitably close together. When this is the case, the combustion process is then continued. Varying K_1 primarily affects only the crank angle where the peak pressure occurs but indirectly affects the magnitude of the peak pressure in that the cylinder volume is a function of the crank angle.

3. Process 3-4: Expansion

Some expansion has already occurred during the latter stages of the combustion process. However, Process 3-4 can be distinguished in that combustion is already completed and a single homogeneous region of burned gas is present. The expansion process is presumed to occur also in a stepwise manner. A single expansion increment consists of two steps. It corresponds to an incremental change in crank angle $\Delta\theta_e$. It is assumed that prior to the i'th expansion increment the pressure, temperature, an internal energy are P_0, T_0, and U_0.

Step 1 - Constant volume heat transfer. At volume V_0 heat is transferred from the hot gases, causing a reduction in the internal energy of the gases. The amount of this heat transfer is

$$Q_i = 2.1 \sqrt[3]{w} \sqrt{P_0 T_0} \left[A_{wt}(T_0 - T_w) + A_{pt}(T_0 - T_p)\right] \cdot \Delta t \qquad (6\text{-}7)$$

where the total exposed wall area, A_{wt}, is computed from Equation (6-2) for the current crank angle and $\Delta t = \Delta\theta_e/6/\text{rpm}$. The entropy at the end of Step 1 is S_1 and the internal energy is $U_1 = U_0 - Q_i$.

Step 2 - Isentropic change of state due to piston motion. During the time interval Δt the system undergoes a change of state due to piston motion. The working fluid is presumed to expand isentropically to this new volume. At the end of Step 2, $S_2 = S_1$ and the internal energy is U_2. The work done during this expansion increment is

$$W_i = U_2 - U_1$$

The expansion process is continued until the piston reaches bottom center, Point 4 on Figure 9. The total heat transferred during this process is

$$Q_{3-4} = \sum_{\text{expansion}} Q_i$$

The total work is

$$W_{3-4} = \sum_{\text{expansion}} W_i$$

4. Process 4-4: Expansion to the Exhaust Pressure

At bottom center the exhaust valve opens and the gases expand to the exhaust pressure. Those which remain in the cylinder are presumed to have undergone an isentropic change of state. This process is identical to that of the fuel-air cycle and is more fully described in Appendix F, Part B, Section 7.

5. Process 4'-5: Exhaust

The piston returns to top center, expelling all the gas except that remaining in the clearance volume. This process is presumed to be adiabatic. The gases remaining in the clearance volume undergo no change of state. The fraction of gas remaining in the clearance volume is $F = V_5/V_{4''}$. This process is identical to that of the fuel-air cycle and is discussed in Appendix F, Part B, Section 8.

6. Process 5-1: Induction and Mixing

This adiabatic process is the same as that for the fuel-air cycle and is described in Appendix F, Part B, Section 2.

C. The Cycle Characteristics

1. Net Work

The net cycle work is the sum of the work performed during compression, combustion, and expansion plus any pumping work. This quantity is

$$W_t = W_{1-2} + W_{2-3} + W_{3-4} + (V_{bot} - V_{top})(P_i - P_e)J \qquad (6\text{-}8)$$

2. Net Heat Transferred

The net heat transferred is the sum of the heat transferred during combustion and expansion. This quantity is

$$Q_t = Q_{2-3} + Q_{3-4} \qquad (6\text{-}9)$$

3. Thermal Efficiency

The indicated thermal efficiency is the net work divided by the enthalpy of combustion of the fuel consumed. This is

$$\eta = \frac{W_t \cdot 100}{\Delta H_c^\circ \cdot F_0} \qquad (6\text{-}10)$$

where ΔH_c° is the enthalpy of combustion per mole of fuel at 298.16°K and 1 atmosphere pressure and F_0 is the moles of fuel inducted per cycle.

4. Mean Effective Pressure

The mean effective pressure is

$$\text{mep} = \frac{W_t}{(V_{bot} - V_{top})J} \tag{6-11}$$

5. Volumetric Efficiency

The volumetric efficiency is defined as the quotient of the actual mass of fresh charge inducted to that which would just fill the displaced volume at the inlet density. This quantity is

$$\eta_v = \frac{F_0 \cdot Z \cdot (cx + x) \cdot RT_i \cdot 100}{P_i(V_{bot} - V_{top})} \tag{6-12}$$

D. Computational Method

The analytical model has been programmed on an IBM 709 digital computer. The MAD compiler language was used throughout. Appendix I contains a description of the program, a flow diagram, and a listing of the MAD statements. The following chapter reports the results of the computer calculations.

VII. CALCULATED RESULTS FROM THE ANALYTICAL MODEL

A. General

The scope of the calculations presented herein employing the analytical model is designed to accomplish three purposes. The first is to compare the characteristics of a calculated and an experimental cycle for a particular engine. The second is to predict performance characteristics for the engine operating under conditions for which no experimental data are available, assuming the flame speed and heat transfer representation is correct. Finally, the third is to study the availability and irreversibility associated with an engine cycle.

For this work, a single engine was employed. This engine was selected because its combustion chamber geometry was relatively easy to describe mathematically and because its high compression ratio and advanced design were characteristic of current practice. Moreover the high compression ratio would diminish the influence of the exhaust residual whose composition and temperature were not known and could not be calculated accurately by the analytical model. Figure 11 is a sketch of the combustion chamber of this engine. It has a relatively flat head with an off-set hemispherical dish in the piston. Pertinent characteristics of the chamber are listed in Table VII. Table VIII lists its volume-area-length relationships. The compression ratio is 10 to 1. Experimental data for this engine were obtained through Professor Jay A. Bolt of the University of Michigan Department of Mechanical Engineering.

It is known that there will be differences between the calculated and experimental cycle characteristics. These are due to both over-simplifications in the analytical model and differences in operating conditions between the analytical model and the actual engine. Those due to over-simplifications in the model will be discussed later. Differences in operating conditions are due to either a difference in fuel type or to the fact that no experimental value is available for the parameter in question. The experimental data were taken using a blended hydrocarbon of approximate composition $C_{7.35}H_{14.7}$ whereas all calculations were made assuming iso-Octane, C_8H_{18} as a fuel. The thermodynamic properties of the fuel were approximated by those of n-Octane (Tables II and III) and the activation energy was assumed to be 39000 cal/mole as reported in NACA Report 1300.(50) While it is felt the discrepancies between the analytical and experimental results introduced by this fuel difference are small, no investigation of the effects of fuel type has been conducted.

Certain parameters which are necessary in the calculations were given assumed values because no experimental data were available. These are the wall, piston, and exhaust temperatures. They were given the values 420°K, 500°K, and 1000°K respectively and all calculations reported are made with these values unless otherwise noted.

B. The "Normal Cycle"

A single cycle was selected as a normal cycle against which the resulting analytical model calculations could be compared. Table

IX lists the operating conditions under which the actual engine was run and those for which calculations have been made. For the calculated cycle, the heat transfer was determined directly from Equation (5-19) and the flame speed from Equation (4-24) with K_1 equal to 135,000. This is equivalent to a ratio of turbulent to laminar flame speed of slightly under 4 to 1. The numerical value was arrived at by comparing the experimental with the calculated pressure-time diagram and attempting to achieve good agreement over the early portion of the combustion process. This procedure is explained in Chapter VI. The heat transfer and flame speed calculated in this manner are termed "normal" and the resulting cycle is termed the "normal cycle."

The curve designated as that for normal heat transfer in Figure 12 is the pressure-time curve resulting from the calculations. Figure 13 shows the corresponding pressure-volume diagram. The experimental curves are shown in each case. It must be remembered that these experimental curves represent average values for a large number of cycles and do not necessarily conform to any one single cycle. The complete calculated data for these operating conditions are presented in the first set of data in Data Set A, Appendix K.

C. Comparison of the Analytical and Experimental "Normal Cycles"

1. The Pressure-Time and Pressure-Volume Diagrams

a. The compression process

On both Figures 12 and 13 it is seen that the assumption of a reversible and adiabatic compression process is a close approximation to the real process.

b. The combustion process

1) The ignition delay. No ignition delay was provided for in the calculations. The agreement between the calculated and experimental curves over the early portion of the combustion process indicates that the ignition delay is very small. This observation is in good agreement with the recent findings of Curry(90) who experimentally found the ignition delay to be very small.

2) First portion of the combustion process. Up to about 8 degrees after top center the calculated pressure-time diagram corresponds closely to the experimental one. At this point about one half of the mass of mixture has been consumed. During this early portion of the combustion process the flame front is passing through the hemispherical dish in the piston but has not yet reached the surface of the piston. Thus, very little heat is transferred as the hot gases are in contact with relatively little wall area. Figure 21 shows the magnitude of the flame speed as a function of crank angle. During this portion of the combustion process the flame speed nearly doubles. The close agreement between the experimental and calculated pressure-time diagrams in this region tends to validate Equation (4-24) for the flame speed.

3) Last portion of the combustion process. At about 8 degrees after top center, the hemispherical dish in the piston becomes completely filled with burned gas. In Figure 12 it is seen that at this point in the cycle the calculated curve abruptly departs from the experimental curve. The analytical model predicts that once the

piston cavity is filled with burned gas, the burning of successive mass increments requires a longer period of time. This is because the flame front must move further in the narrow quench region to burn equal mass increments than it did when the flame was propagating into the hemispherical dish. The experimental curve does not show this.

Because of the many assumptions and simplifications inherent in the analytical model it is difficult to attribute the above deviation to a single factor. Nevertheless some comments are in order. First it must be recognized that the actual flame propagation does not occur spherically as shown in Figure 12 but occurs in such a way that the shape of the flame front tends to reflect the shape of the enclosing combustion chamber. Thus the surface area over which the reaction can occur becomes somewhat larger than that assumed by the analytical model. Moreover, the burned gas tends to move in mass toward a more central position in the chamber (experimentally shown by ionization gap studies) and this causes more surface area over which reactions can proceed than the analytical model assumes. Both these effects would tend to increase the effective burning rate slightly and in particular would cause the hemispherical dish to be completely filled by burned gas slightly later in the cycle. Thus, the inability to describe accurately the shape and position of the burned gas region leads to discrepancies between the calculated and experimental pressure-time diagrams. This is due to a necessary simplification in the analytical model. Second, as the hemispherical dish is filled, the flame front arrives at a sudden change in combustion chamber contour. Rabezanna _et al._(19) have experimentally studied chambers with sudden changes in contour and have found that in every case there is a sudden appreciable increase in the flame propagation rate whenever such a section change is encountered. This increase which is normally attributed to an increase in turbulence may be as much as 25 or 30 percent of the original flame speed. It is suspected that this latter over-simplification of the combustion process is the major cause of the differences observed between the experimental and calculated pressure-time curves during the last portion of the combustion process.

In consequence of these factors the analytical model predicts a lower peak pressure and longer combustion time than is experimentally observed. The observed peak pressure is 875 psia whereas the calculated is 795 psia. The observed duration of combustion is 45 crank degrees whereas the calculated is 54 degrees.

c. The Expansion Process

During the expansion portion of the cycle, the calculated curve lies above that of the experimental curve. This indicates that its internal energy is greater. The difference between the two curves is due primarily to three factors. First, the analytical model gives less work done by the engine near the top center piston position and consequently more internal energy is present in the gas during the expansion stroke than would be the case if the experimental peak pressure were attained. This is clear from Figure 13 in which the area under the curve is proportional to the work. Second, complete combustion is assumed in the analytical model. In this respect the model represents an optimum condition which is approached but never attained in practice. This assumption of complete combustion would tend to raise the calculated pressure-time curve higher than the measured one during the expansion stroke. Third, the volumetric efficiency of the engine represented by the calculated curve is slightly greater than that actually measured (97.6 percent verses a measured 94 percent). Thus there is slightly more mass present in the cylinder. Again this would tend to raise the calculated expansion curve higher than the measured curve.

2. Relationship Between Mass Burned and Volume of the Burned Charge

Figure 22 shows the relationship between the mass burned and the volume of the burned charge. Good agreement is seen between the calculated data and the curve presented by Rabezanna *et al.*(19)

3. Heat Transfer

The total heat transferred during the cycle is 17.5 percent of the heat of combustion of which about one third of this is transferred during the combustion process. Although no experimental data are available concerning the actual heat transfer in this engine, these figures agree well with the estimates of Pye(66), Ricardo(67), and Janeway(65). From this and the shape of the pressure-time diagram it appears as if Equation (5-18), the expression proposed by Eichelberg(81), provides a reasonably good estimate of the convective heat transfer coefficient.

4. Rate of Pressure Rise

The calculated pressure-time curve shows good agreement with the experimental curve especially in so far as the rate of pressure rise is concerned. Additional analysis with different combustion chamber geometries is needed before the analytical model can be used in combustion chamber design.

5. Power and Efficiency

The calculated thermal efficiency of the cycle is 36.5 percent and the measured is 35.8 percent (see Table IX). Most of this difference can be attributed to incomplete combustion of the charge in the actual engine. The differences present in fuel type and volumetric efficiency are believed to affect the thermal efficiency only slightly. If slightly incomplete combustion had been considered and the shape of the pressure volume diagram had remained essentially the same, the calculated thermal efficiency would have been slightly less instead of slightly greater than that measured.

The calculated mean effective pressure is 182 psia whereas that measured was 166 psia. Most of this difference can be attributed to three factors, incomplete combustion, difference in volumetric efficiency, and fuel type.

D. Effect of Exhaust Temperature

Because the analytical model does not treat the exhaust process in detail, the temperature of the exhaust becomes a variable of the problem. For the high compression ratio engine considered in this study the effects of the exhaust residual on the temperatures and pressures of the cycle is slight and thus the temperature and composition of the exhaust residual do not have to be known with great accuracy. However the effect of a 200°K variation in the exhaust temperature was studied.

A single cycle was calculated with all operating conditions identical to those of the normal cycle except for the exhaust temperature. Instead of 1000°K, the exhaust temperature was assumed to be 1200°K. The calculated results for this cycle are presented as Data Set E, Appendix K. This change in exhaust temperature produced no significant changes in any of the cycle calculations.

E. Influence of Heat Transfer and Flame Propagation Rates

This section describes the results of calculations which show the influence of changes in heat transfer and flame propagation rates on the engine cycle characteristics. The "normal" cycle was presumed to be the standard against which the other cycles could be compared. The operating conditions were exactly the same as those for the "normal cycle" with the exception that both the heat transfer coefficient and the flame speed were changed. In particular three different heat transfer rates were considered, no heat transfer, normal heat transfer as defined above, and twice normal heat transfer. Three different flame propagation rates were considered in combination with the three heat transfer rates, a normal rate of flame propagation as defined above, 115 percent of normal, and 85 percent of normal. The results of these calculations are presented in Data Sets A, B, and C of Appendix K.

Figures 12 and 13 are the resulting pressure-time and pressure-volume diagrams for the normal rate of flame propagation. Figures 14 and 15 are the pressure-volume diagrams for the rapid and reduced rates of flame propagation respectively.

Looking at Figure 12, it is seen that the pressure-time curves for the three heat transfer rates become distinguishable near the peak pressure shortly after the hemispherical dish is filled with burned gas. This is the first point in the cycle where burned gas comes into contact with an appreciable wall area. The effects of the three different rates of heat transfer on the pressure-volume diagrams are similar for each of the three flame speeds considered. Increasing the amount of heat transfer causes the expansion curve to fall below that for a lesser amount of heat transfer. In each case the peak pressure changes only slightly.

Figure 16 shows the effect of changing the rate of flame propagation while maintaining a normal rate of heat transfer. It is seen that the pressure-time diagrams and peak pressures are quite different for each different rate of flame propagation.

Figure 17 shows the thermal efficiency and mean effective pressure for these nine sets of operating conditions. The most significant changes in thermal efficiency and mean effective pressure are caused by the changes in heat transfer rate. The changes effected by the differences in flame propagation rate are not large. It must be noted however, that the magnitude of the changes in heat transfer rate is much larger than that of the changes in flame propagation rate. From these results it appears that cycle to cycle variations in the flame propagation rate effect thermal efficiency and power output less than the pressure-time diagram appears to indicate. This is because moderate variations in the pressure-volume diagram do not cause large variations in either thermal efficiency or mean effective pressure. However, it is apparent that appreciable increases in these quantities can be effected by reducing the heat transfer.

On Figure 17 are indicated the mean effective pressure and thermal efficiency calculated by a fuel-air cycle analysis, the results of which are included in Appendix K, Data Set D and are summarized in Table IX. These idealized values are approached by the analytical model engine with no heat transfer and rapid combustion. In fact the analytical model engine would attain these values of thermal efficiency and mean effective pressure if the combustion rate were greatly increased and the spark advance decreased toward zero degrees. The calculated peak pressure for the cycle with no heat transfer and rapid flame propagation was only about 835 psia whereas that of the fuel air cycle was 1326 psia. Thus a finite combustion time is very beneficial in that it keeps the peak pressures at reasonable levels and yet only slightly lowers thermal efficiency and mean effective pressure.

Table X presents the amount of heat transferred as a percent of the heat of combustion for the two non-zero heat transfer rates and the three flame propagation rates. It is seen that the more rapid the rate of flame propagation, the higher the heat transfer. This is because the highest flame speed cycles were associated with the highest pressures and since the heat transfer coefficient is proportional to the square root of the cylinder pressure the amount of heat transfer increased as the flame speed increased. From this it can be inferred that the highest heat transfer during normal combustion is associated with the most efficient cycles.

Figure 18 is the entropy-volume diagram for the normal rate of flame propagation. Since the compression process is presumed to be reversible and adiabatic no entropy increase occurs. However the combustion process is highly irreversible as it occurs at a finite rate. Thus a large increase of entropy occurs during combustion. For the adiabatic cycle no further entropy change occurs during expansion. However, when heat transfer is taken into account the entropy is seen to decrease during the expansion stroke. This is because heat is transferred from the hot gases and thus the entropy change is negative.

F. Availability and Irreversibility

The availability is the maximum work which can be done by a system when it changes from a given state to a standard state. This maximum work can be realized only through reversible processes including reversible heat transfer to the surroundings. When irreversibilities occur the work realized is less than the maximum. The difference between the maximum and the actual work is termed the irreversibility of the process. The system in question is the closed system comprising the contents of the engine cylinder. For such a system the availability is:

$$\text{Availability} = (U - T_0 S) - (U - T_0 S_0)$$

where the subscript refers to the standard state.

Because the composition of the system changes due to combustion and dissociation, some difficulty arises in the definition of the standard state. For this work the standard state is taken as the products of combustion at 1 atmosphere pressure and 298.16°K. The products are presumed to consist only of N_2,CO_2, H_2O, and CO for the rich mixture considered here.

The lower curve of Figure 19 shows the availability versus the crank angle for the operating conditions reported in the first set of data of Data Set A, Appendix K. These were conditions of normal heat transfer and normal flame propagation. Under these conditions the mole fractions constituting the products are as follows:

N_2	0.718
CO_2	0.105
CO	0.028
H_2O	0.150

and the total number of moles is 0.02059. The molal properties of these constituents in the standard state are given in Table II. The value of $U_0 - T_0S_0$ is then -702.7 cal.

During the compression portion of the cycle, prior to combustion, the state changes are presumed to be reversible and adiabatic and thus the avaiability is increased by the amount of work done on the system. During combustion and expansion the availability decreases. If these processes were reversible the expansion work would be equal to the change in availability. However, this is not the case. The combustion process is highly irreversible as the entropy-volume diagram of Figure 18 shows. Both during combustion and expansion additional irreversibility is introduced due to heat transfer. This is shown in Figure 19. Note that subsequent to the completion of the combustion process no additional irreversibility is introduced from this source and further increases are due to heat transfer only.

Figure 20 shows the availability as a function of crank angle for the normal rate of flame propagation with no heat transfer. For this cycle the only irreversibility is due to combustion.

It is interesting to note the large amount of availability existent at the end of the expansion stroke in both Figures 19 and 20. It is a substantial fraction of the original availability. The thermal efficiency of the engine could be greatly increased if some method were found for taking advantage of all or a part of this potential energy.

G. The Analytical Model and the Fuel-Air Cycle

It has already been shown that the fuel-air cycle is the limiting case of the analytical model for rapid rates of flame propagation. In turn it was shown that the air cycle is the limiting case of the fuel-air cycle for extremely lean mixtures.

The number of additional parameters included in the analytical model, not the least of which are the heat transfer and flame propagation, allow a mathematical analysis whose results show close similarity to the experimental data in many respects. Thus the analytical model provides a distinct improvement over the fuel-air cycle for internal combustion engine analysis. It must be pointed out however, that the analytical model calculations must be made on a digital computer whereas those of the fuel-air cycle require no such aid.

Table IX lists the operating conditions and experimental results for the normal cycle, the calculated results from the analytical model, and those from the fuel-air cycle for similar engine operating conditions. A comparison of the quantities presented indicates the improvement in the cycle analysis made possible by the analtyical model.

H. Concluding Remarks

The correlation between the calculated and experimental data was largely satisfactory for the normal cycle considered. The major discrepancies appear to be caused by two factors. The first is the inability to describe accurately the shape and location of the burned gas region. The second and most influencial factor is the inability to predict the effect of section changes on turbulent flame propagation rate. In those portions of the cycle where the effects of these two factors are small the heat transfer and flame propagation appear to be described satisfactorily.

Before the analytical model can be employed to evaluate new engine designs or to even aid in the design of combustion chambers, much more work will be needed to verify the calculated results. In particular the influence of combustion chamber geometry, different fuel type, and different engine operating conditions must be studied.

More information is needed to describe the combustion process accurately. The expression employed in this study for the flame propagation rate needs improvement. In particular more information is needed about the turbulence in an engine so that the flame speed can be predicted directly from engine operating conditions without relying on an experimentally determined constant whose value under new operating conditions is highly questionable.

In summary the analytical study of the internal combustion engine must proceed along two paths. First the analytical model must be studied by employing it to calculate engine cycles under widely varying operating conditions. Second, a research program must be undertaken to obtain the following information:

1. The nature of the turbulence in the cylinder of a spark ignited engine.
2. The influence of section change on the turbulent flame propagation rate.
3. The introduction of the preceding information into the analytical model for the prediction of the turbulent flame speed.

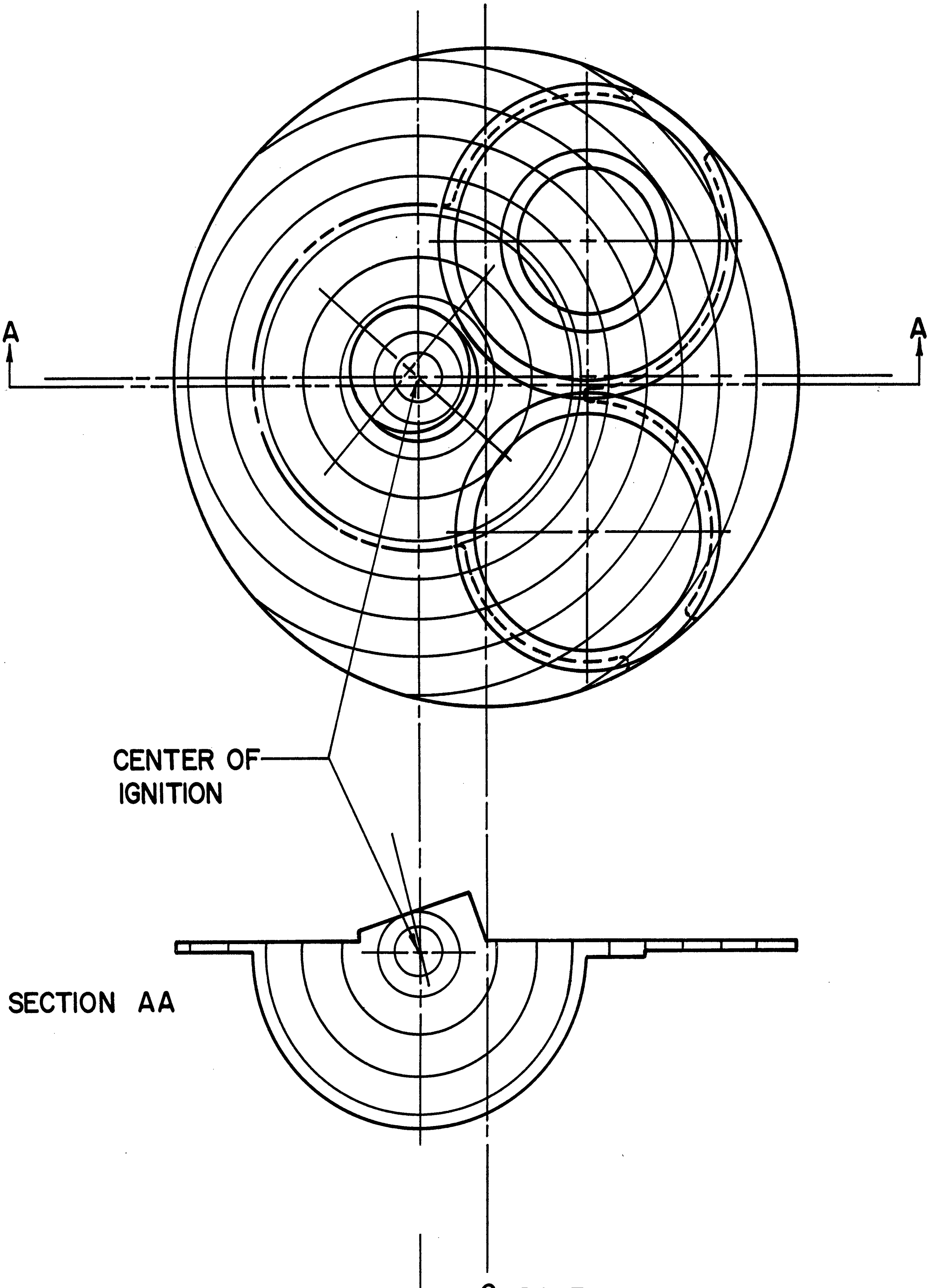


Figure 11. View of engine combustion chamber showing spherical flame propagation pattern.

TABLE VII

PERTINENT DIMENSIONS FOR ENGINE OF FIGURE 11

Dimension	Symbol	Numerical Value	
Bore	Bore	3.94 in	10 cm
Stroke	Stroke	2.46 in	6.25 cm
Connecting Rod	Rod	7.065 in	17.9 cm
Radius of Hemispherical Dish		1.06 in	2.79 cm
Quench Height		0.05 in	1.27 cm
Compression Ratio	r	10 to 1	10 to 1
Clearance Volume	V_{top}	3.33 in^3	54.6 cm^3
Swept Volume	V_{bot}	30.00 in^3	492 cm^3
Head Area	A_h	12.13 in^2	78.4 cm^2
Piston Surface Area	A_p	15.35 in^2	99.0 cm^2
Maximum Flame Travel Length If Combustion Occurs at Top Center	L_t	2.4 in	6.1 cm

TABLE VIII

VOLUME-AREA-LENGTH RELATIONSHIPS FOR THE COMBUSTION CHAMBER OF FIGURE 11

L/L_t	A_{hb}/A_{ht}	A_{pb}/A_{pt}	V/V_t		V/V_t	L/L_t
0.0	0.0	0.0	0.0	0	0.0	0.0
0.05	0.0	0.0	0.00285	1	0.05	0.150
0.1	0.0	0.0	0.01875	2	0.1	0.196
0.15	0.0335	0.0	0.05353	3	0.15	0.230
0.2	0.0596	0.0	0.10629	4	0.2	0.260
0.25	0.0934	0.0	0.18093	5	0.25	0.282
0.3	0.1341	0.0	0.29034	6	0.3	0.304
0.35	0.1840	0.0	0.43688	7	0.35	0.322
0.4	0.2385	0.0	0.63774	8	0.4	0.340
0.45	0.299	0.449	0.77300	9	0.45	0.354
0.5	0.369	0.504	0.80343	10	0.5	0.368
0.55	0.446	0.566	0.83313	11	0.55	0.380
0.6	0.533	0.634	0.85971	12	0.6	0.392
0.65	0.625	0.706	0.88276	13	0.65	0.403
0.7	0.709	0.770	0.90933	14	0.7	0.414
0.75	0.777	0.825	0.93317	15	0.75	0.430
0.8	0.837	0.874	0.94724	16	0.8	0.490
0.85	0.894	0.917	0.96561	17	0.85	0.580
0.9	0.938	0.954	0.98163	18	0.9	0.686
0.95	0.979	0.985	0.99101	19	0.95	0.804
1.0	1.0	1.0	1.0	20	1.0	1.0

TABLE IX

NORMAL ENGINE CYCLE OPERATING CONDITIONS
(wide open throttle)

Compression Ratio: 10 to 1

Operating Condition	Experimental	Analytical Model	Fuel-Air Cycle
Fuel	Blended	Iso-Octane	Iso-Octane
Air-Fuel Ratio (fraction Theoretical air)	.92	.92	.92
Piston Temperature	Unknown	500°K	----
Wall Temperature	Unknown	420°K	----
Manifold Temperature	320°K	320°K	320°K
Manifold Pressure	.99 atm	.99 atm	.99 atm
Exhaust Temperature	Unknown	1000°K	1240°K
Exhaust Pressure	1.03 atm	1.03 atm	1.03 atm
Spark Advance	16°BTC	16°BTC	----
Speed	2800 rpm	2800 rpm	----
Peak Pressure	875 psia	795 psia	1326 psia
Max. Rate of Pressure Rise	85 psi/deg	85 psi/deg	∞
Duration of Combustion	46 degrees	54 degrees	----
Thermal Efficiency	35.8 percent	36.5 percent	42.7 percent
Mean Effective Pressure	166 psia	182 psia	213 psia
Volumetric Efficiency	94 percent	97 percent	97.5 percent

TABLE X

AMOUNT OF HEAT TRANSFERRED

(Percent of heat of combustion)

Compression Ratio: 10 to 1
Fuel: Iso-Octane
Speed: 2800 rpm
Ignition: 16° BTC

Rate of Flame Propagation	Normal Heat Transfer			Twice Normal Heat Transfer		
	During Combustion	During Expansion	Total	During Combustion	During Expansion	Total
Normal	6.06	11.4	17.5	11.8	17.4	29.2
Rapid	5.71	12.3	18.0	11.2	18.8	30.0
Reduced	6.90	9.5	16.4	13.2	14.4	27.6

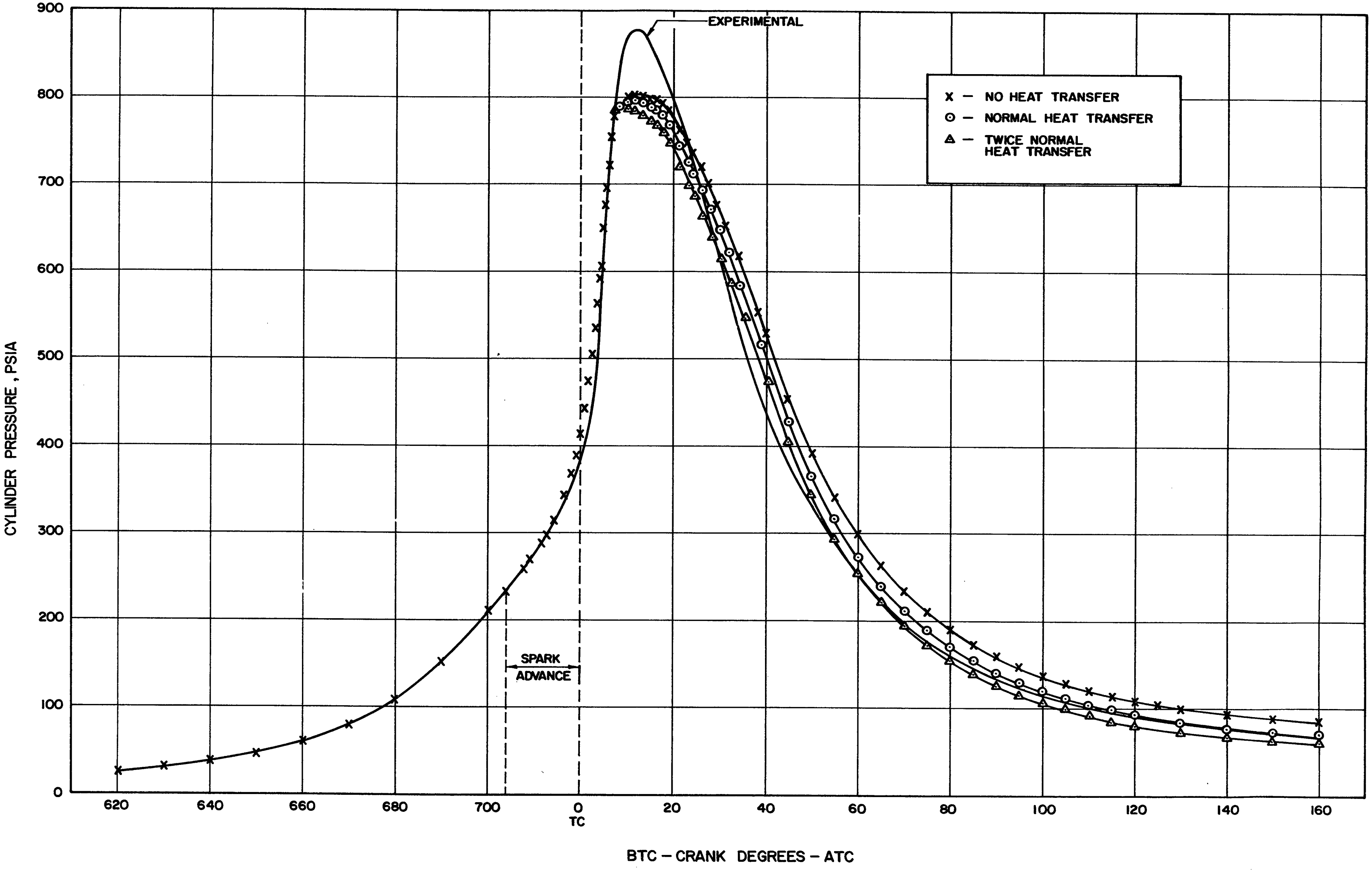


Figure 12. Cylinder pressure vs crank angle for a 10:1 compression ratio engine with normal rate of flame propagation (Data Set A): operating conditions listed in Table IX.

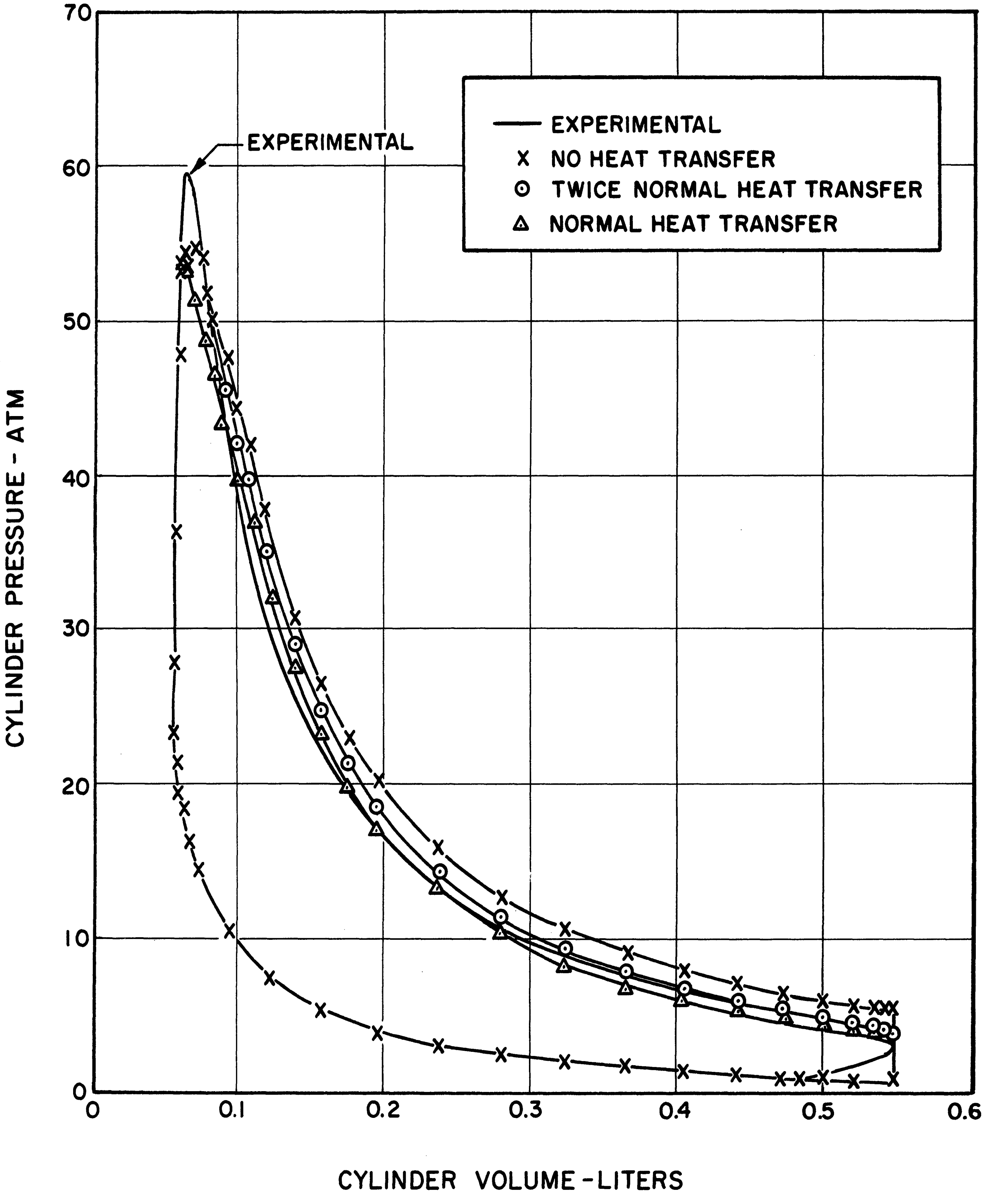


Figure 13. Pressure-volume diagram for a 10:1 compression ratio engine with normal rate of flame propagation (Data Set A). Operating conditions listed in Table IX.

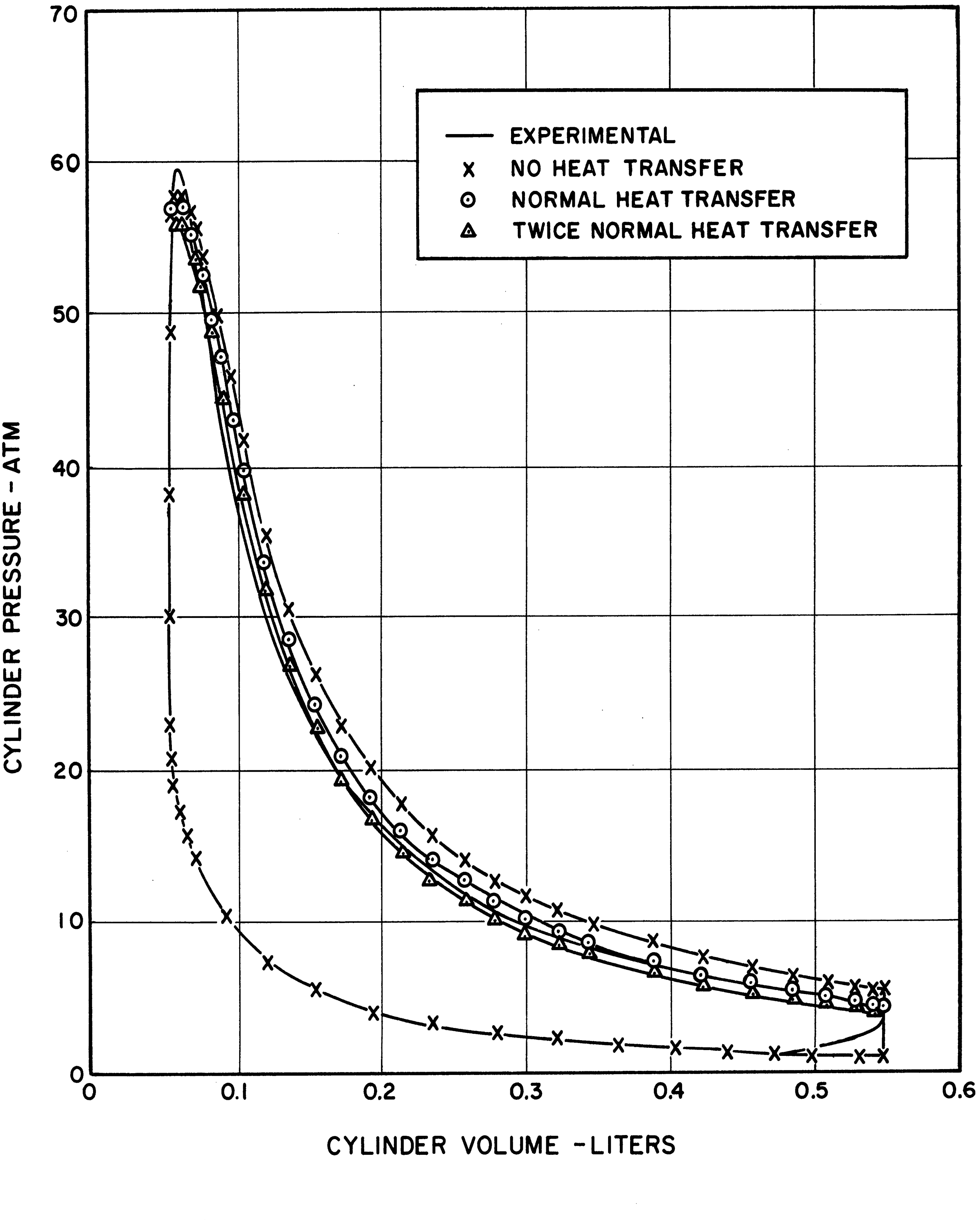


Figure 14. Pressure-volume diagram for a 10:1 compression ratio engine with rapid rate of flame propagation (Data Set B). Operating conditions listed in Table IX.

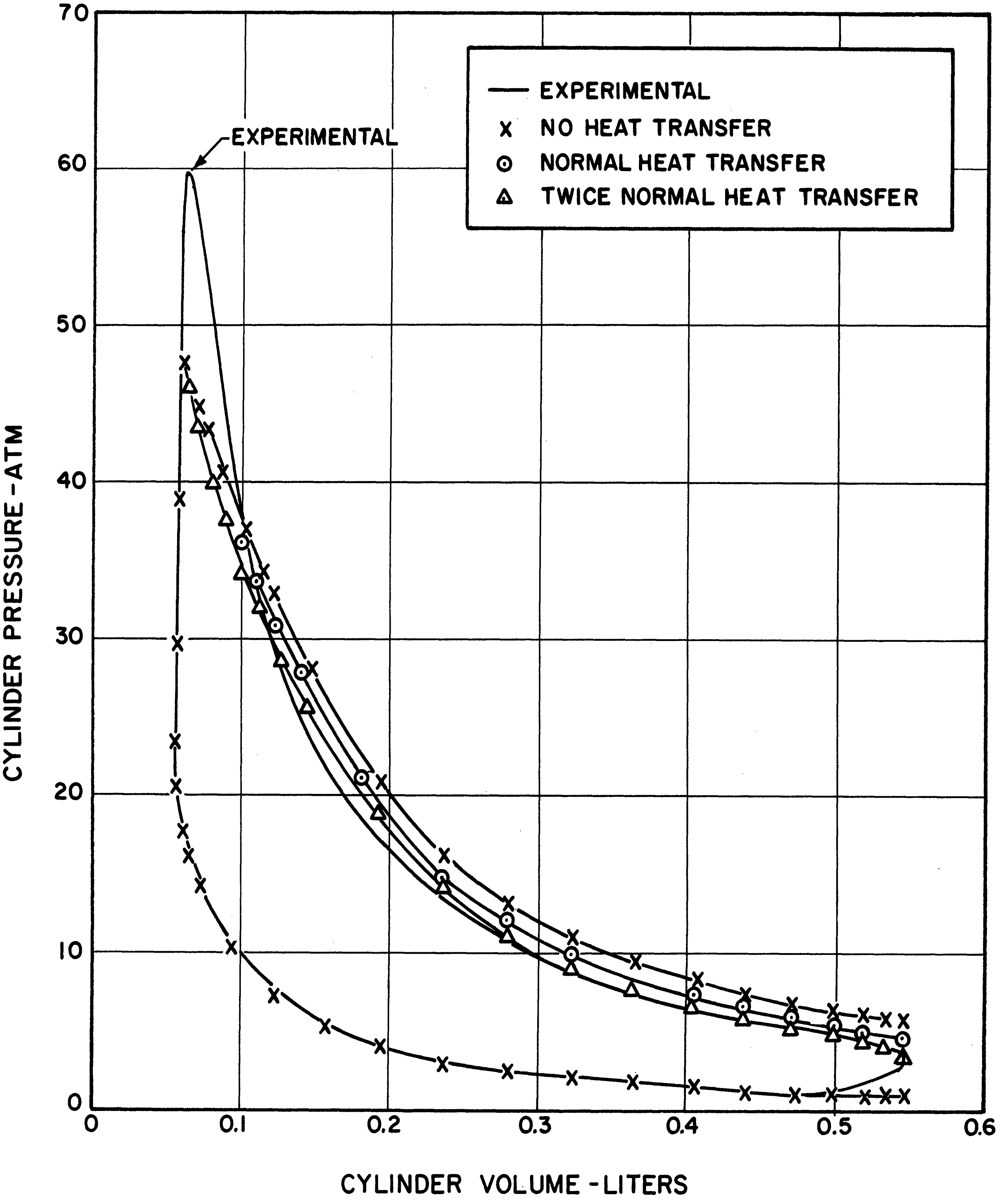


Figure 15. Volume diagram for 10:1 compression ratio engine with reduced rate of flame propagation (Data Set C). Operating conditions listed in Table IX.

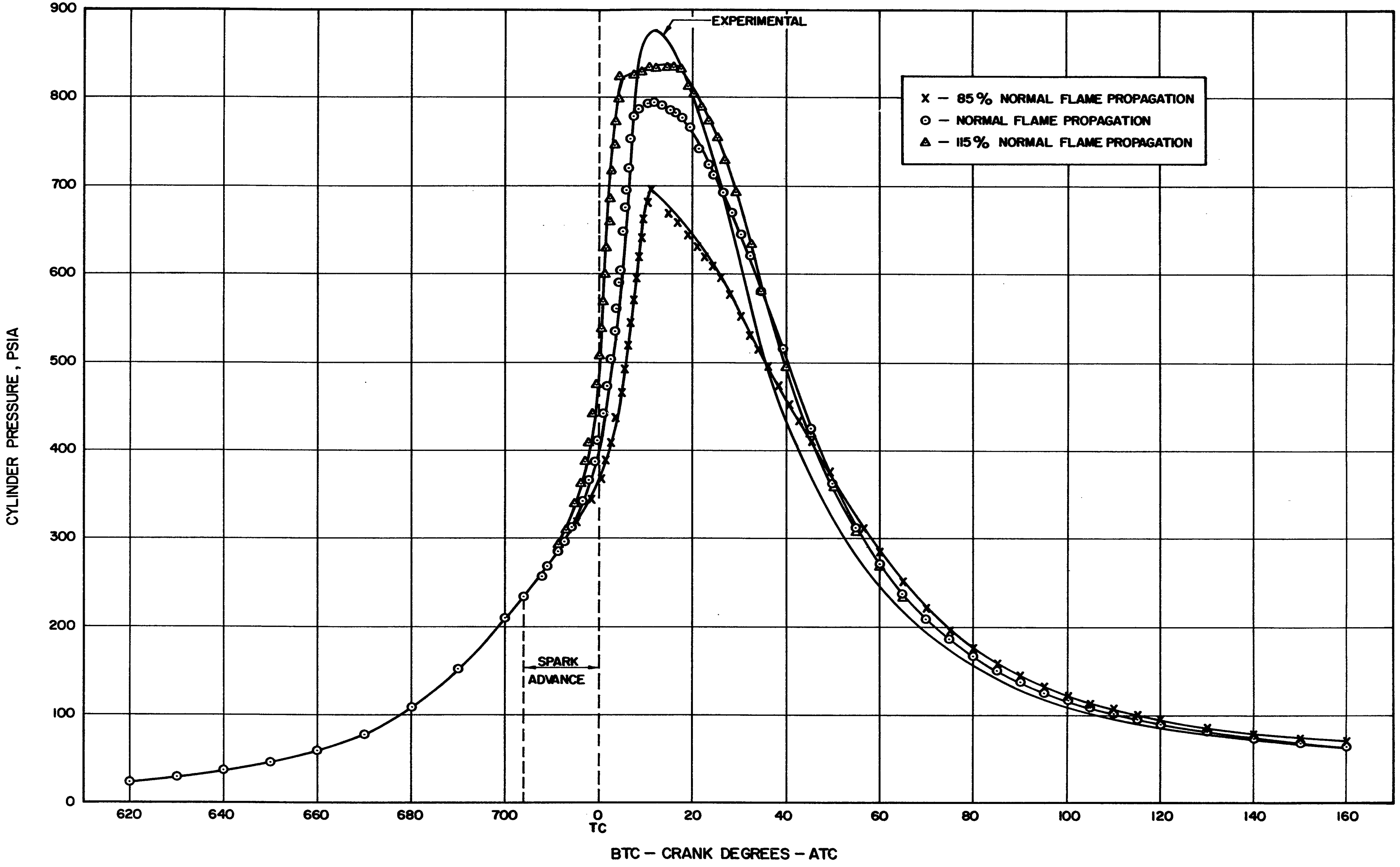


Figure 16. Cylinder pressure vs crank angle for a 10:1 compression ratio engine with normal rate of heat transfer. Operating conditions listed in Table IX.

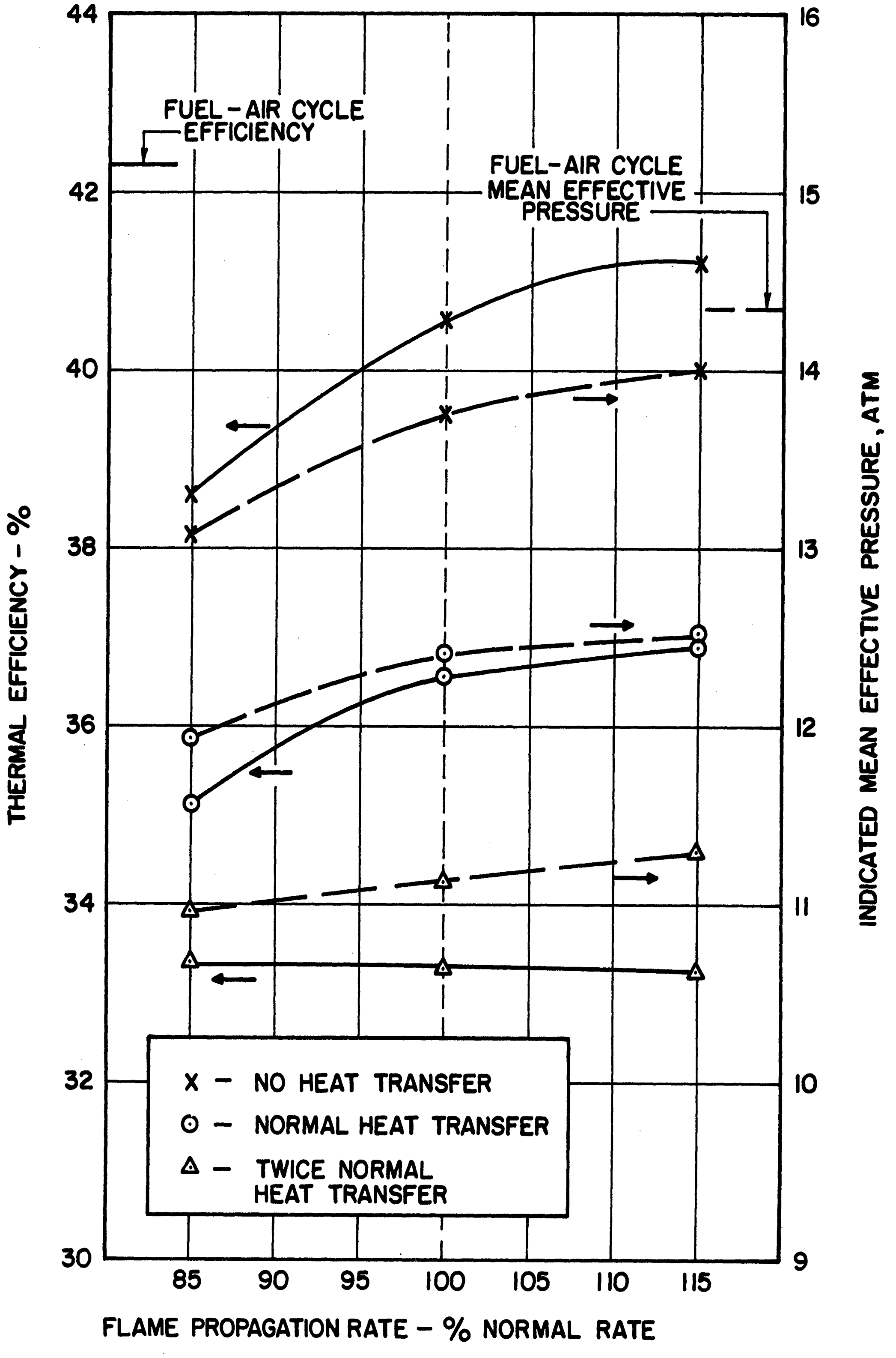


Figure 17. Calculated thermal efficiency and mean effective pressure vs flame propagation rate for a 10:1 compression ratio engine. Operating conditions listed in Table IX.

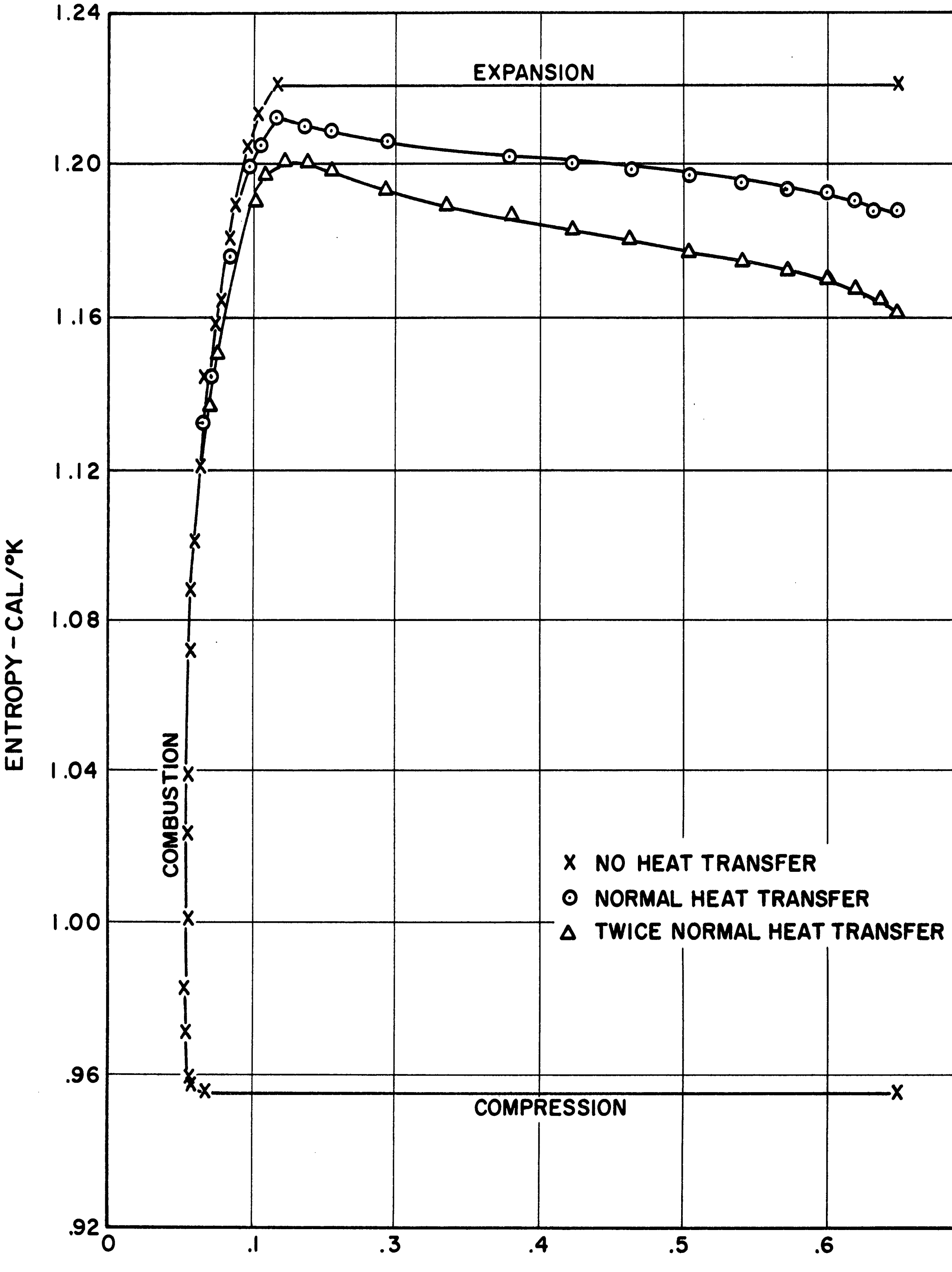


Figure 18. Entropy-volume diagram for a 10:1 compression ratio engine with normal rate of flame propagation (Data Set A).

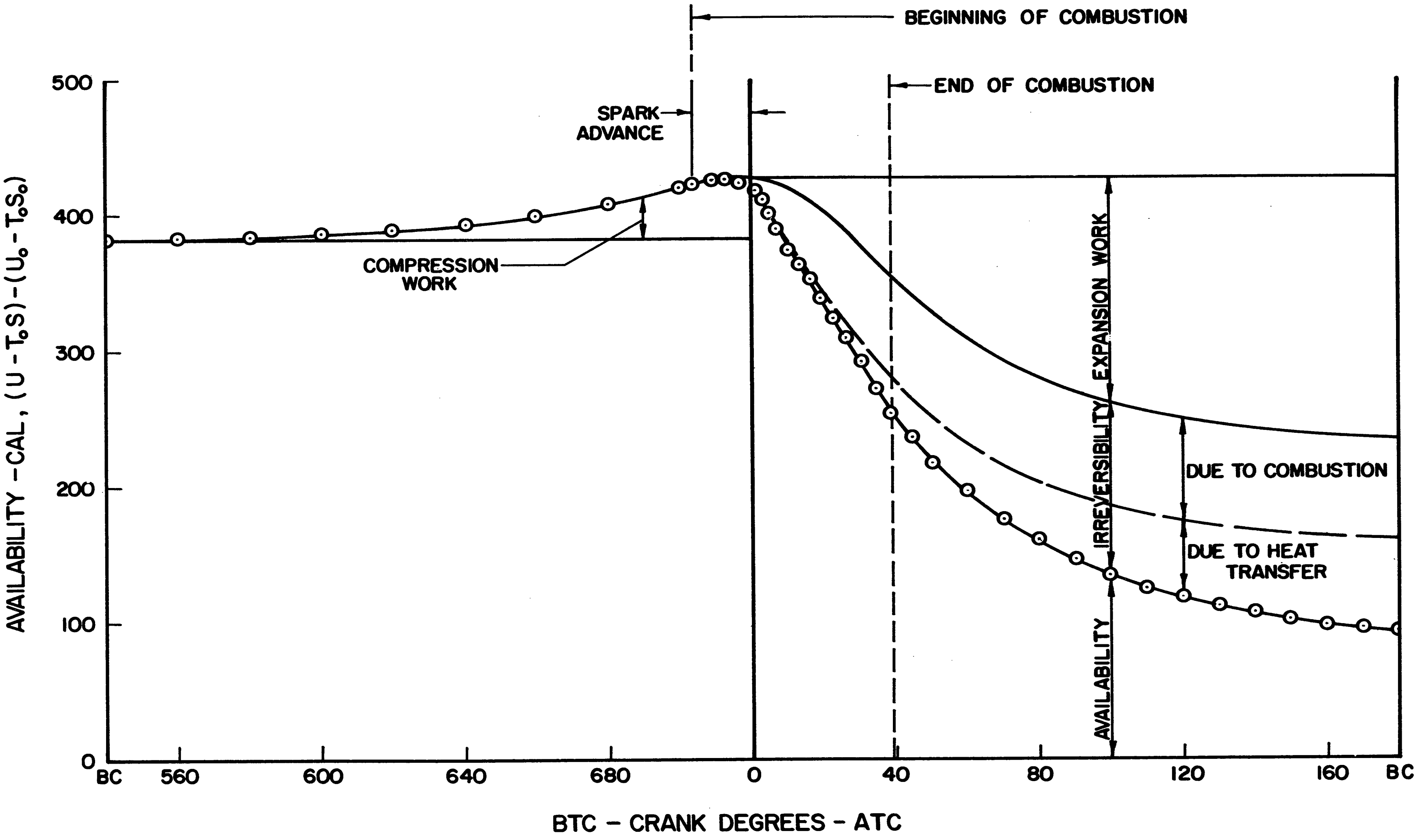


Figure 19. Availability vs crank angle for a 10:1 compression ratio engine with normal rate of flame propagation and heat transfer (Data Set A).

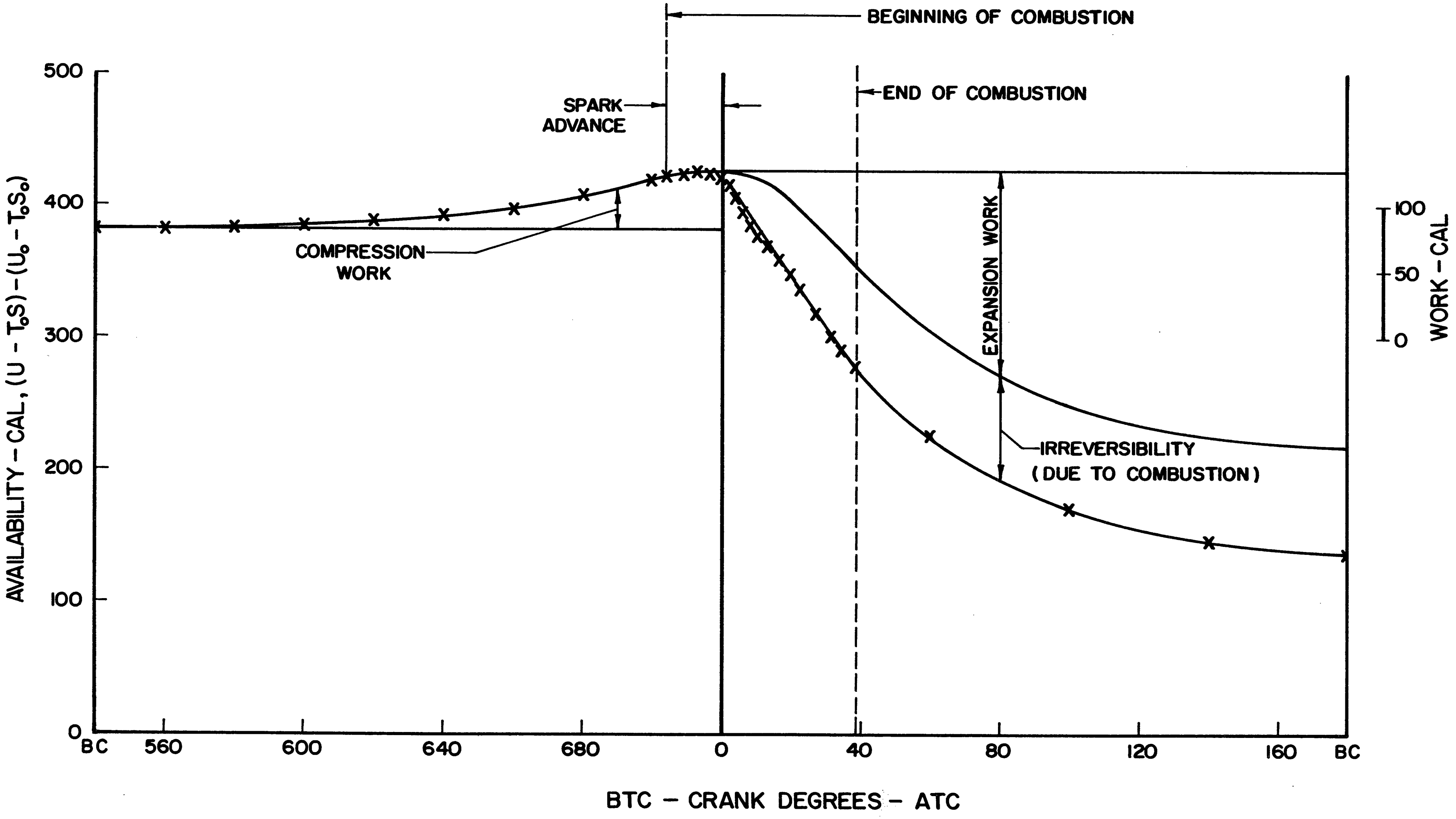


Figure 20. Availability vs crank angle for a 10:1 compression ratio engine with no heat transfer and normal flame propagation rate (Data Set A).

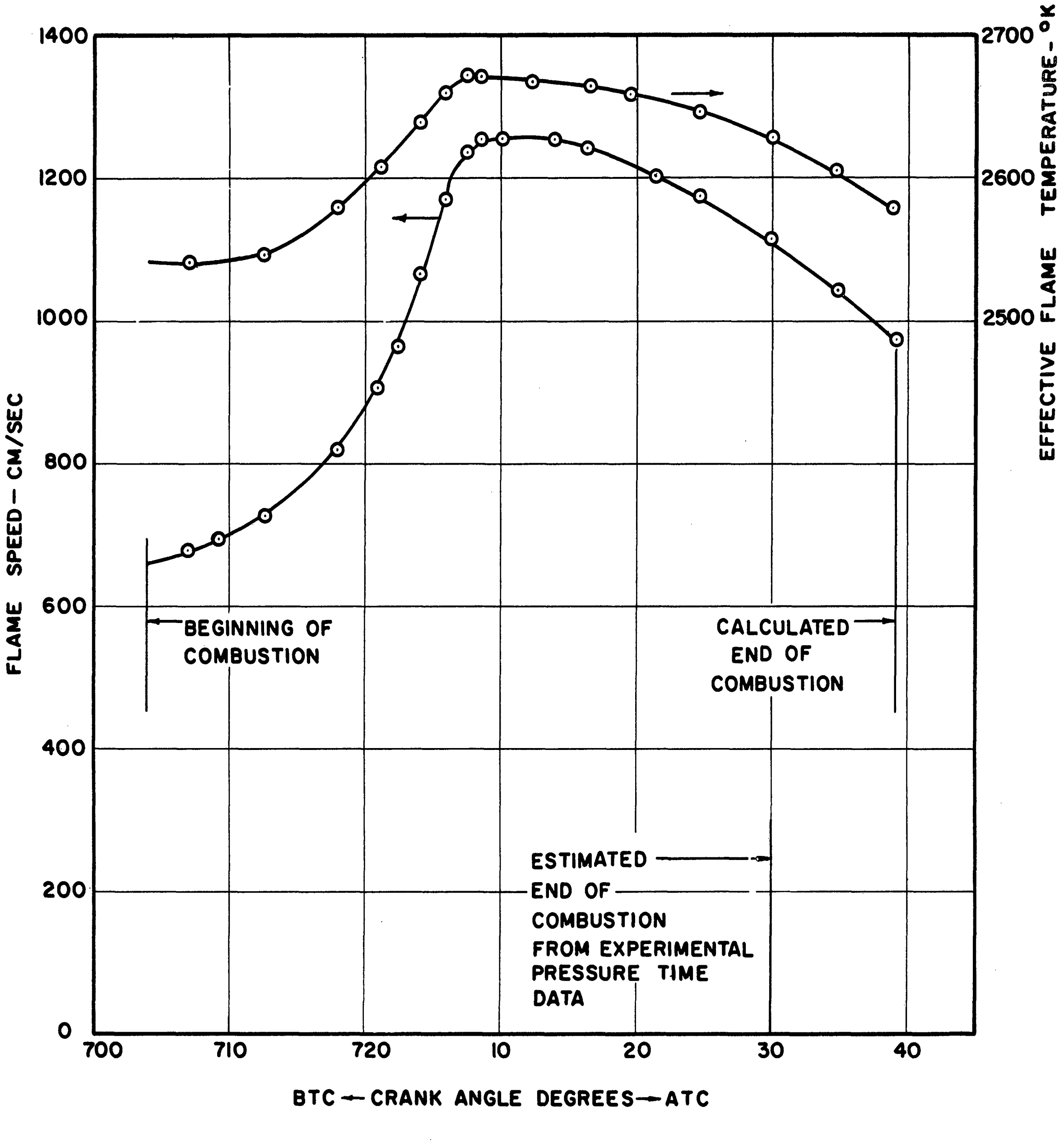


Figure 21. Flame speed and effective flame temperature vs crank angle for a 10:1 compression ratio engine with normal flame propagation and heat transfer rates (Data Set A).

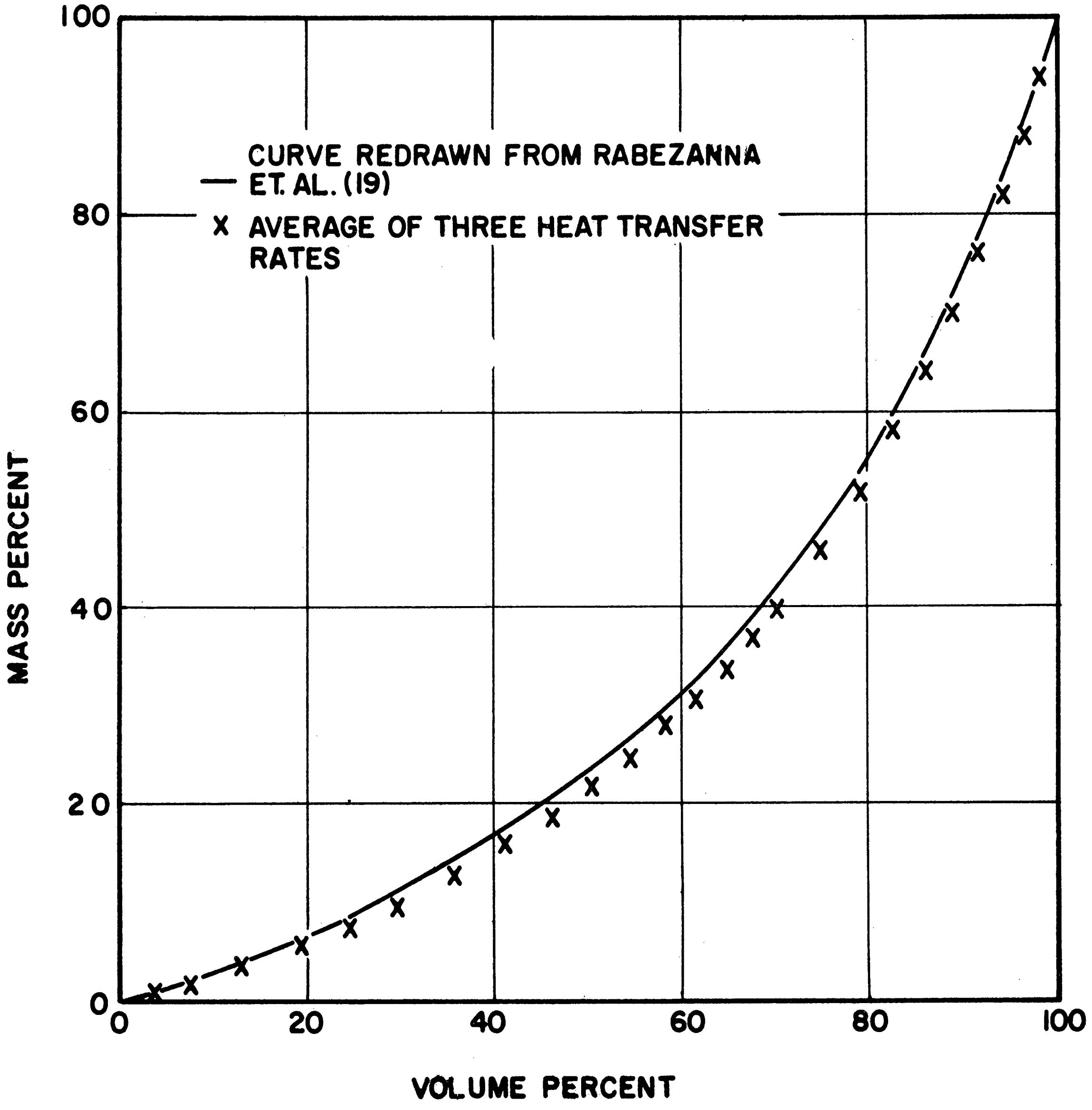


Figure 22. Relationship between mass and volume of the burned charge for a 10:1 compression ratio engine with normal rate of flame propagation (Data Set A).

APPENDIX A

POLYNOMIAL APPROXIMATION BY THE METHOD OF LEAST SQUARES

In the discussion below the most important features of polynomial approximation by the method of least squares are presented along with an adaptation of this general method to the specific problem of obtaining empirical heat capacity equations from tabular data. For a complete treatment of the least squares method see a standard work on numerical analysis such as Reference 31.

If a function f(x) is specified at a set of m + 1 equally reliable discrete points, x_0, x_1, ... x_m, an n'th degree polynomial of the form

$$f(x) \cong a_0 + a_1 x + a_2 x^2 + \ldots = \sum_{k=0}^{n} a_k x^k = y(x)$$

may be used to approximate f(x) over the set of points.

Defining the error 'v' by the equation

$$v = f(x) - y(x) = f(x) - \sum_{k=0}^{n} a_k x^k$$

the principle of least squares defines the value of the a_k's in such a way that the sum of the v^2's is a minimum. Relating v_i to x_i, this principle may be formally stated as follows:

$$\sum_{i=0}^{m} v_i = \sum_{i=0}^{m} \left[f(x_i) - \sum_{k=0}^{n} a_k x_i^k \right]^2 = \text{A Minimum}$$

For a given set, x_0, x_1, ... x_m, the above expression is a function of the a_k's only.

To determine this minimum value, this function is differenciated with respect to each of the a_k's and the resulting expressions equated to zero.

Thus:

$$2\sum_{i=0}^{m} v_i = 0 \qquad (k = 1)$$

$$2\sum_{i=0}^{m} v_i x_i = 0 \qquad (k = 2)$$

$$\vdots \qquad\qquad \vdots$$

$$2\sum_{i=0}^{m} v_i x_i^n = 0 \qquad (k = n)$$

Noting that

$$v_i = f(x_i) - y(x_i) = y_i - \sum_{k=0}^{n} a_k x_i^k$$

where $y_i = f(x_i)$, the above equations can be rewritten as follows:

$$a_0(m + 1) + a_1 \sum x_i + \ldots .\ a_n \sum x_i^n = \sum y_i$$

$$a_0 \sum x_i + a_1 \sum x_i + \ldots .\ a_n \sum x_i^{n+1} = \sum x_i y_i$$

$$\vdots \qquad \vdots \qquad \vdots \qquad \vdots$$

$$a_0 \sum x_i^n + a_1 \sum x_i^{n+1} + \ldots .\ a_n \sum x_i^{n+n} = \sum x_i y_i$$

The summations are over all m + 1 points. The above set of n + 1 equations can then be solved for the n + 1 unknowns (the a_k's).

Note the coefficient matrix.

$$\begin{matrix} m+1 & \sum x_i & \cdots & \sum x_i^n \\ \sum x_i & \sum x_i^2 & \cdots & \sum x_i^{n+1} \\ \vdots & \vdots & & \vdots \\ \sum x_i^n & \sum x_i^{n+1} & \cdots & \sum x_i^{n+n} \end{matrix}$$

is symmetric.

For the special case when $f(x) = C_p$, $x = T$, and $n = 3$, so that

$$C_p = a_0 + a_1T + a_2T^2 + a_3T^3$$

the above set of equations reduces to:

$$a_0\,(m+1) + a_1\sum T + a_2\sum T^2 + a_3\sum T^3 = \sum C_p$$

$$a_0\sum T + a_1\sum T^2 + a_2\sum T^3 + a_3\sum T^4 = \sum C_pT$$

$$a_0\sum T^2 + a_1\sum T^3 + a_2\sum T^4 + a_3\sum T^5 = \sum C_pT^2$$

$$a_0\sum T^3 + a_1\sum T^4 + a_2\sum T^5 + a_3\sum T^6 = \sum C_pT^3$$

Hildebrand(31), Chapter 10, describes a number of methods for solving such a system of non-homogeneous linear equations for a_0, a_1, a_2, and a_3.

The root mean square error involved in such a polynomial approximation is defined as:

$$\text{RMS Error} = \left[\sum_{i=0}^{m} v_i^2/(m+1) \right]^{1/2}$$

APPENDIX B

EQUILIBRIUM CONSTANT AS A FUNCTION OF TEMPERATURE

Introduction

The reader is referred to a text on chemical engineering thermodynamics for a more complete treatment of this subject. See, for example, Weber and Meissner(32), Chapter 21, Lewis and Randall(33), Chapter 20, or Hougen, Watson, and Ragatz(25), Chapter 25.

If $\bar{G}$ is defined as the partial molal free-energy of a substance in any given state of pressure and temperature and $\bar{G}^{o}$ that in the standard state, then

$$\bar{G} - \bar{G}^{\circ} = RT \ln f/f^{\circ} \qquad \text{(B-1)}$$

where f is the fugacity in the given state and f° is the fugacity in the standard state. For a chemical reaction of the form

$$\ell L + mM + \ldots = qQ + rR + \ldots \qquad \text{(B-2)}$$

where ℓ, m, ... q,r, ... are the moles of component L,M, ... Q,R, ... respectively, the change in free-energy for this reaction in any state is

$$\Delta G = (q\bar{G}_Q + nG_R + \ldots) - (\ell\bar{G}_L + m\bar{G}_M + \ldots) \qquad \text{(B-3)}$$

By definition,

$$a = f/f^{\circ} \qquad \text{(B-5)}$$

where 'a' is the activity in the nonstandard state. Combining Equations (B-1) through (B-5), the following equation is obtained:

$$\Delta G = \Delta G° + RT\ell n \frac{a_Q^q\, a_R^r \ldots}{a_L^\ell\, a_M^m \ldots} \tag{B-6}$$

When the reaction has reached a point such that there is no net change in the number of moles of any constituent, it is said that chemical equilibrium has been attained. The criterion for this equilibrium is that at constant temperature and pressure, there can be no change in the free-energy of the system. Consequently, when these limitations are imposed on Equation (B-6), ΔG must be zero for equilibrium and the following familiar expression for the equilibrium constant is obtained:

$$\Delta G° = - RT\ \ell n\ K_a$$

$$K_a = \frac{a_Q^q\, a_R^r \ldots}{a_L^\ell\, a_M^m \ldots}$$

For a system in which the behavior of each component can be described by the equation of state

$$P\ v = RT \tag{B-7}$$

the fugacity of each component becomes identically equal to its partial pressure in the system at all temperatures and pressures for which (B-7) is valid. When this is the case, the equilibrium constant is denoted by K_p. Choosing the standard state as the pure component at one atmosphere pressure, the equations become,

$$\begin{aligned} \Delta G° &= - RT\ \ell n\ K_p \\ K_p &= \frac{p_Q^q\, p_R^r \ldots}{p_L^\ell\, p_M^m \ldots} \end{aligned} \tag{B-8}$$

where p_i is the partial pressure of the i'th component. K_p is then referred to as the equilibrium constant at one atmosphere. The free-energy change is termed the standard free-energy change of the reaction. This quantity depends upon temperature, the definition of the standard state of each component, and the number of moles entering into the stoichiometric Equation (B-2). Once the standard state pressure is fixed, the equilibrium constant becomes independent of the system pressure.

Analogically to expression (B-4), expressions for ΔH° and ΔS°, the standard state change in enthalpy and entropy for the reaction can be found. It immediately follows that

$$\Delta G^\circ = \Delta H^\circ - T\Delta S^\circ$$

Effect of Temperature on K_p

To determine the effect of temperature on the equilibrium constant, Equation (B-8) can be differentiated as follows:

$$\left[\frac{\partial}{\partial T}(\ell n\ K_p)\right]_P = -\left[\frac{\partial}{\partial T}\left(\frac{\Delta G^\circ}{RT}\right)\right]_P$$

$$= -\frac{1}{R}\left[\frac{1}{T}\frac{\partial \Delta H^\circ}{\partial T} - \frac{\Delta H^\circ}{T^2} - \frac{\partial \Delta S^\circ}{\partial T}\right]_P$$

where $\frac{\Delta G^\circ}{T} = \frac{\Delta H^\circ}{T} - \Delta S^\circ$.

However since $\left(\frac{\partial \Delta H^\circ}{\partial T}\right)_P = T\left(\frac{\partial \Delta S^\circ}{\partial T}\right)_P$, the above simplifies to:

$$\left[\frac{\partial}{\partial T}(\ell n\ K_p)\right]_P = \left[\frac{\Delta H^\circ}{RT^2}\right]_P$$

Since the quantity $\frac{\Delta H^\circ}{RT^2}$ is independent of pressure, this restriction can be removed. Then:

$$\frac{d}{dT}(\ell_n K_p) = \frac{\Delta H^\circ}{RT^2}$$

Integrating this equation between T and T_0, where T_0 is some reference temperature, and recalling that:

$$\Delta H^\circ = \Delta H^\circ_{T_0} + \int_{T_0}^{T} \underset{\text{Products}}{\sum n_i C^o_{pi}} dT + \int_{T}^{T_0} \underset{\text{Reactants}}{\sum n_i C^o_{pi}} dT$$

the following equation for equilibrium constant as a function of temperature is obtained:

$$\ell_n K_{p_T} - \ell_n K_{p_{T_0}} = \frac{\Delta H^\circ_{T_0}}{R}\left[\frac{1}{T_0} - \frac{1}{T}\right] + \int_{T_0}^{T} \frac{1}{RT^2}\left[\int_{T_0}^{T}\left(\underset{\text{Products}}{\sum n_i C^o_{pi}} - \underset{\text{Reactants}}{\sum n_i C^o_{pi}}\right)dT\right]dT \qquad \text{(B-9)}$$

APPENDIX C

CALCULATION OF THERMODYNAMIC PROPERTIES FROM EMPIRICAL HEAT CAPACITY EQUATIONS

A. General

For a system of 's' chemical species, it is assumed that the ideal gas molal heat capacity at one atmosphere of the i-th component can be expressed as follows:

$$C_p^o = a_{0i} + a_{1i}T + a_{2i}T^2 + a_{3i}T^3$$

$$298.16 - 1500\,°K$$

$$C_p^o = b_{0i} + b_{1i}T + b_{2i}T^2 + b_{3i}T^3$$

$$1500 - 3500\,°K$$

and that the molal enthalpy of formation and entropy at 298.16 and 1 atm pressure are $(\Delta H^o_{f298})_i$ and $(S^o{}_{298})_i$. The standard state is the ideal gas at one atmosphere pressure. The calculation of the thermodynamic functions is made most conveniently by matrix algebra.

The following matrix is defined for the temperature range 298.16 - 1500°K:

$$A = \left\| \begin{array}{cccc} a_{01} & a_{02} & \cdots\cdots & a_{0s} \\ a_{11} & a_{12} & \cdots\cdots & a_{1s} \\ a_{21} & \cdot & \cdots\cdots & \cdot \\ a_{31} & \cdot & \cdots\cdots & \cdot \\ (\Delta H^o_{f298})_1 & \cdot & \cdots\cdots & \cdot \\ (S^o{}_{298})_1 & \cdot & \cdots\cdots & \cdot \end{array} \right\|$$

and for the range 1500 - 3500°K:

$$B = \left\| \begin{array}{cccc} b_{01} & b_{02} & \cdots\cdots & b_{0s} \\ b_{11} & b_{12} & \cdots\cdots & b_{1s} \\ b_{21} & \cdot & \cdots\cdots & \cdot \\ b_{31} & \cdot & \cdots\cdots & \cdot \\ (H^o_{1500})_1 & \cdot & \cdots\cdots & \cdot \\ (S^o_{1500})_1 & \cdot & \cdots\cdots & \cdot \end{array} \right\|$$

where

$$(H^o_{1500})_i = (\Delta H^o_{f298})_i + (H^o_{1500} - H^o_{298})_i$$

For a selected number of substances the appropriate constants for matrix A and B are presented in Tables I and II.

It is assumed that the composition of the system of 's' species whose properties are desired is known and that there are n_i moles of component 'i'. The following matrix will then be defined to represent the composition of the system:

$$N = \left\| \begin{array}{c} n_1 \\ n_2 \\ \cdot \\ \cdot \\ \cdot \\ n_s \end{array} \right\|$$

B. Method of Calculation

1. Computation of the Ideal Gas Enthalpy

$$H = \sum n_i(\Delta H^o_{f298})_i + \sum n_i(H^o_T - H^o_{298})_i$$

Consider the second summation. For the temperature range 298.16 to 1500°K

$$\sum n_i(H^o_T - H^o_{298})_i = \sum n_i \int_{T_0=298.16}^{T} C^o_{p_i}\,dT$$

$$= \sum n_i \left[T_0 a_{0i}(\theta_A - 1) + \frac{T_0^2 a_{1i}}{2}(\theta_A^2 - 1) + \frac{T_0^3 a_{2i}}{3}(\theta_A^3 - 1) + \frac{T_0^4 a_{3i}}{4}(\theta_A^4 - 1) \right]$$

For the temperature range 1500 to 3500°K

$$\sum n_i(H^o_T - H^o_{298})_i = \sum n_i \left[\int_{T_0'=1500}^{T} C^o_{p_i}\,dT + (H^o_{1500} - H^o_{298})_i \right]$$

$$= \sum n_i \left[T' b_{0i}(\theta_B - 1) + \frac{T_0'^2 b_{1i}}{2}(\theta_B^2 - 1) + \frac{T_0'^3 b_{2i}}{3}(\theta_B^3 - 1) + \frac{T_0'^4 b_{3i}}{4}(\theta_B^4 - 1) + (H^o_{1500} - H^o_{298})_i \right]$$

where

$$\theta_A = T/298.16$$

$$\theta_B = T/1500$$

If the matrices K_A and K_B are defined as follows:

$$K_A = \left\| \begin{matrix} 298.16 \ (\theta_A - 1) \\ \frac{(298.16)^2}{2}(\theta_A^2 - 1) \\ \frac{(298.16)^3}{3}(\theta_A^3 - 1) \\ \frac{(298.16)^4}{4}(\theta_A^4 - 1) \\ 1 \\ 0 \end{matrix} \right\| = \left\| \begin{matrix} 298.16 \ (\theta_A - 1) \\ 44,449.69 \ (\theta_A^2 - 1) \\ 8,835,413.6 \ (\theta_A^3 - 1) \\ 19,757,752 \cdot 10^2 (\theta_A^4 - 1) \\ 1 \\ 0 \end{matrix} \right\|$$

$$K_B = \left\| \begin{array}{c} 1500 \quad (\theta_B-1) \\ \frac{(1500)^2}{2}(\theta_B^2-1) \\ \frac{(1500)^3}{3}(\theta_B^3-1) \\ \frac{(1500)^4}{4}(\theta_B^4-1) \\ 1 \\ 0 \end{array} \right\| = \left\| \begin{array}{c} 1500\ (\theta_B-1) \\ 1125\cdot 10^3(\theta_B^2-1) \\ 1125\cdot 10^6(\theta_B^3-1) \\ 1{,}265{,}625\cdot 10^6(\theta_B^4-1) \\ 1 \\ 0 \end{array} \right\|$$

the enthalpy of the mixture then can be calculated as the product of matrices.

$$H = \begin{cases} K_A^t \cdot A \cdot N & \\ K_B^t \cdot B \cdot N & \end{cases} \quad \begin{cases} 298.16 \leq T \leq 1500 \\ 1500 < T \leq 3500 \end{cases} \qquad \text{(C-1)}$$

(in cal)

2. Computation of the Ideal Gas Entropy

$$S = \Sigma\, n_i S^o_{298_i} + \Sigma\, n_i (S^o_T - S^o_{298})_i - R\, \Sigma\, n_i \ln(x_i P)$$

where

x_i = mole fraction of the i-th component

P = total system pressure

Consider the second summation. For the temperature range 298.16 to 1500°K

$$\Sigma\, n_i (S^o_T - S^o_{298})_i = \Sigma\, n_i \int_{T_0=298.16}^{T} \frac{C^o_{p_i}}{T}\, dT$$

$$= \Sigma\, n_i \left[a_{oi} \ln\theta_A + T_o a_{1i}(\theta_A-1) + \frac{T_0^2 a_{2i}}{2}(\theta_A^2-1) + \frac{T_0^3 a_{3i}}{3}(\theta_A^3-1) \right]$$

For the temperature range 1500 to 3500°K

$$\Sigma\, n_i(S^o_T - S^o_{298})_i = \Sigma\, n_i \left[\int_{T'_0=1500}^{T} \frac{C_{p_i}}{T} dT + (S^o_{1500} - S^o_{298})_i \right]$$

$$= \Sigma\, n_i \Big[b_{0i} \ln\theta_B + T'_0 b_{1i}(\theta_B - 1) + \frac{T'^2_0 b_{2i}}{2} (\theta^2_B - 1) + \frac{T'^3_0 b_{3i}}{3} (\theta^3_B - 1)$$

$$+ (S^o_{1500} - S^o_{298})_i \Big]$$

where

$\theta_A = T/298.16$

$\theta_B = T/1500$

If the matrices K_A and K_B are defined now as follows:

$$K_A = \left\| \begin{array}{c} \ln(\theta_A) \\ 298.16(\theta_A - 1) \\ 44449.693(\theta^2_A - 1) \\ 8835413.6(\theta^3_A - 1) \\ 0 \\ 1 \end{array} \right\| \quad K_B = \left\| \begin{array}{c} \ln(\theta_B) \\ 1500(\theta_B - 1) \\ 1125 \cdot 10^3(\theta^2_B - 1) \\ 1125 \cdot 10^6(\theta^3_B - 1) \\ 0 \\ 1 \end{array} \right\|$$

the entropy of the mixture then can be calculated as follows:

$$S = \left\{ \begin{array}{c} K^t_A \cdot A \cdot N \\ K^t_B \cdot B \cdot N \end{array} \right\} - R\, \Sigma\, n_i \ln\,(x_i P) \quad \left\{ \begin{array}{l} 298.16 \leq T \leq 1500°K \\ 1500 < T \leq 3500°K \end{array} \right. \qquad (C\text{-}2)$$

(in cal per °K)

3. Computation of $(\frac{\partial H}{\partial T})_P$

The procedure here is the same as in Parts 1 and 2. If a matrix K is defined as follows:

$$K = \left\| \begin{matrix} 1 \\ T \\ T^2 \\ T^3 \\ 0 \\ 0 \end{matrix} \right\|$$

$(\frac{\partial H}{\partial T})_P$ then can be computed as the following product:

$$(\frac{\partial H}{\partial T})_P = C_p = K^t \cdot \left\{ \begin{matrix} A \\ B \end{matrix} \right\} \cdot N \qquad \left\{ \begin{matrix} 298.16 \leq T \leq 1500°K \\ 1500 < T \leq 3500°K \end{matrix} \right. \qquad \text{(C-3)}$$

(in cal per °K)

4. Computation of $(\frac{\partial S}{\partial T})_P$

Identically to Part 3, if a matrix K is defined as follows:

$$K = \left\| \begin{matrix} 1/T \\ 1 \\ T \\ T^2 \\ 0 \\ 0 \end{matrix} \right\|$$

$(\frac{\partial S}{\partial T})_P$ then can be computed as the following product:

$$(\frac{\partial S}{\partial T})_P = K^t \cdot \left\{ \begin{matrix} A \\ B \end{matrix} \right\} \cdot N \qquad \left\{ \begin{matrix} 298.16 \leq T \leq 1500°K \\ 1500 < T \leq 3500°K \end{matrix} \right. \qquad \text{(C-4)}$$

(in cal per $°K^2$)

5. Computation of the Equilibrium Constant K_p

A general expression for K_p as a function of T with reference state at T_0 is as follows: (see Equation (B-9))

$$\ln K_{p_T} - \ln K_{p_{T_0}} = \frac{\Delta H^o_{T_0}}{R}\left[\frac{1}{T_0} - \frac{1}{T}\right] + \int_{T_0}^{T} \frac{1}{RT^2}\left[\left(\underset{\text{Products}}{\Sigma n_i C^o_{p_i}} - \underset{\text{Reactants}}{\Sigma n_i C^o_{p_i}}\right)dT\right]dT$$

$$= \frac{\Delta H^o_{T_0}}{RT_0}\left[1 - \frac{1}{\theta}\right] + \frac{1}{R}\left[C_1(\ln\theta + \frac{1}{\theta} - 1)\right.$$

$$\left. + \frac{C_2T_0}{2}(\theta + \frac{1}{\theta} - 2) + \frac{C_3T_0^2}{6}(\theta^2 + \frac{2}{\theta} - 3) + \frac{C_4T_0^3}{12}(\theta^3 + \frac{3}{\theta} - 4)\right]$$

where

$$\theta = T/T_0$$

$$C_j = \underset{\text{Products}}{\Sigma n_i b_{ji}} - \underset{\text{Reactants}}{\Sigma n_i b_{ji}} \qquad (j = 0, 1, 2, 3)$$

For the temperature range $1500 \leq T \leq 3500$°K, let $T_0 = 1500$°K, then $\theta = \theta_B = T/1500$ and note that

$$\ln K_{p_{1500}} = \frac{-\Delta G^o_{1500}}{R \cdot 1500}$$

Then substituting

$$\ln K_{p_T} = \frac{-\Delta G^o_{1500}}{2980.785} + \frac{\Delta H^o_{1500}}{2980.785}\left[1 - \frac{1}{\theta_B}\right] + \frac{1}{R}\left[C_1(\ln\theta_B + \frac{1}{\theta_B} - 1)\right. \tag{C-5}$$

$$+ 750 \cdot C_2(\theta_B + \frac{1}{\theta_B} - 1) + 375 \cdot 10^3 \cdot C_3(\theta_B^2 + \frac{2}{\theta_B} - 3)$$

$$\left. + 28125 \cdot 10^4 \cdot C_4(\theta_B^3 + \frac{3}{\theta_B} - 4)\right]$$

where ΔG^o_{1500} and ΔH^o_{1500} are the standard free-energy and enthalpy of reaction at 1500°K in cal per mole and are listed in Table II for selected reactions.

C. Computer Programs

The computation of the thermodynamic properties and equilibrium constants by a computer is most conveniently made if the computational schemes are incorporated into a number of computer sub-programs or external functions. Such programs have been written in the MAD language for an IBM 704 or 709 computer and are listed in Appendix I. The functions for computing enthalpy, entropy, $\frac{dH}{dT}$, and $(\frac{\partial S}{\partial T})_P$, are called ENTHAL., ENTROP., HPRIME., and SPRIME., respectively. That for computing the equilibrium constants is called EQUIL.

APPENDIX D

THE TIME RATE OF TEMPERATURE CHANGE DURING EXPANSION

In order to calculate the time rate of temperature change, $\partial T/\partial t$ during the expansion process of an internal combustion engine, the overall expansion can be approximated by a polytropic process. The maximum rate of change of volume with time is

$$\frac{dV}{dt} = (2\pi r N\ 60)(\pi b^2/4)$$

where

r = the crank radius

b = the bore

N = the engine speed, rpm

The temperature in the polytropic process is

$$T = T_1 \left(\frac{V}{V_1}\right)^{1-n}$$

and

$$\frac{\partial T}{\partial t} = T\,(1-n)\,\left(\frac{V}{V_1}\right)^{-n} \cdot \frac{d}{dt}\,\left(\frac{V}{V_1}\right)$$

Substituting

$$-\frac{\partial T}{\partial t} = \frac{T_1}{V_1}\,(n-1)\,\left(\frac{V}{V_1}\right)^{-n} \cdot \pi^2 r b^2 N/120 \qquad \text{(D-1)}$$

where

T_1 = the temperature at TC

V_1 = the volume at TC

n = the polytropic exponent

Some typical values of the constants are as follows:

$b = 4$ in

$r = 1.25$ in

$V_1 = 3.33$ cu in

$T_1 = 2500\,°K$

$N = 3000$ rpm

$n = 1.3$

Substituting these values in (D-1),

$$-\frac{\partial T}{\partial t} \simeq 10^6 \cdot \left(\frac{V_1}{V}\right)^{1.3} \ °K/sec$$

$\left(\frac{V_1}{V}\right)^{1.3}$ will be between 0.1 and 1 so that,

$$-\frac{\partial T}{\partial t} \simeq 10^5 \text{ to } 10^6 \ °K/sec$$

APPENDIX E

METHOD OF SOLUTION OF THE EQUATIONS OF SIMULTANEOUS GAS EQUILIBRIUM

Equations (2-19) through (2-21) are repeated here for convenience

$$Z = - \frac{X}{4K_4} + \sqrt{\left(\frac{X}{4K_4}\right)^2 + \frac{F \cdot N_n}{2}} \tag{2-19}$$

$$Y = \frac{-(X/K_3 + 1/K_6) + \sqrt{(X/K_3 + 1/K_6)^2 + 8\,(1 + X/K_2) \cdot F \cdot N_h}}{4(1 + X/K_2)} \tag{2-20}$$

$$F \cdot N_0 = \frac{X/K_1 \cdot F \cdot N_c}{1 + X/K_1} + \frac{Y^2X}{K_2} + 2X^2 + \frac{YX}{K_3} + \frac{ZX}{K_4} + F \cdot N_c + \frac{X}{K_5} \tag{2-21}$$

The problem is to find the value of X wich satisfies Equation (2-21). This equation can be restated as follows:

$$f(X) = 0 \tag{E-1}$$

For any estimated value X_1 the right hand side in general is not zero,

$$f(X_1) \neq 0$$

and some correction to $f(X_1)$, $\Delta f(X_1)$ must be made in order to equate it to zero.

$$f(X_1) + \Delta f(X_1) = 0 \tag{E-2}$$

From (E-2), it is hoped that a correction ΔX_1 to X_1 can be found giving a value X_2 which is closer to the correct answer. This correction is

$$\Delta f(X_1) \cong \left(\frac{df(X)}{d(\ln X)}\right)_1 \cdot \Delta \ln X \tag{E-3}$$

Equating Equations (E-2) and (E-3),

$$f(X_1) = -\left(\frac{df(X)}{d(\ln X)}\right)_1 \cdot \Delta\ln X = -\frac{f'(X_1)}{X_1} \cdot \Delta\ln X$$

Re-arranging,

$$\ln X_2 - \ln X_1 = -\frac{f(X_1)}{X_1 f'(X_1)}$$

or

$$X_2 = X_1 \cdot \exp\frac{-f(X_1)}{X_1 f'(X_1)}$$

In general, for the i-th trial,

$$X_{i+1} = X_i \cdot \exp\frac{-f(X_i)}{X_i f'(X_i)} \qquad \text{(E-4)}$$

The reason for generating X_{i+1} in this particular manner is to assure that it will always be positive if X_1 initially is assumed positive. Thus the possibility of obtaining a solution with some negative partial pressures is eliminated.

The calculation of f'(X) presents some problem. In the following equations the argument X will be dropped for convenience.

$$f' = \frac{df}{dX} = \left(\frac{\partial f}{\partial Y}\right)\left(\frac{dY}{dX}\right) + \left(\frac{\partial f}{\partial Z}\right)\left(\frac{dZ}{dX}\right) + \frac{\partial f}{\partial X} \qquad \text{(E-5)}$$

From Equation (2-21)

$$\frac{\partial f}{\partial Y} = \frac{2XY}{K_2} + \frac{X}{K_3} \qquad \frac{\partial f}{\partial Z} = \frac{X}{K_4}$$

$$\frac{\partial f}{\partial X} = \frac{f \cdot N_c \cdot K_1}{(X + K_1)^2} + 4X + \frac{Y^2}{K_2} + \frac{Y}{K_3} + \frac{Z}{K_4} + \frac{1}{K_5} \qquad \text{(E-6)}$$

From Equation (2-20)

$$\frac{dY}{dX} = \left\{ - \alpha \left[\frac{1}{K_3} - \left(\frac{\delta}{K_3} + \frac{4F \cdot N_h}{K_2}\right) / \gamma \right] - 4/K_2 \left(\gamma - \delta\right) \right\} / \alpha^2 \qquad \text{(E-7)}$$

where

$$\alpha = 4 \left(1 + X/K_2\right)$$

$$\delta = X/K_3 + 1/K_6$$

$$\gamma = \sqrt{\delta^2 + 2\alpha F \cdot N_h}$$

From Equation (2-19)

$$\frac{dZ}{dX} = \frac{X/K_4\beta - 1}{4K_4} \qquad \text{(E-8)}$$

where

$$\beta = \sqrt{\left(\frac{X}{K_4}\right)^2 + 8\ F \cdot N_n}$$

If f(X) and f'(X) are evaluated at X_i by Equations (2-21) and (E-5), a new values of X, X_{i+1}, can be calculated from Equation (E-4). The process can be repeated until $\left|\frac{X_{i+1} - X_i}{X_i}\right|$ is less than some prescribed value ϵ_2. The number of iterations required for convergence is about four, plus an additional four for each power of ten from which the estimate differs from the correct answer. Table XI gives the accuracy with which the partial pressures are calculated for various values of ϵ_2. It is assumed that the partial pressures are of the form $0.XXXXXXXX \cdot 10^{XX}$. The number entered in the table is the digit which changes when the value of ϵ_2 was decreased by successive powers of 10.

In connection with the actual mechanics of the computer subroutine (see the flow diagram, Figure 23) which solves these equations for the partial pressures and moles of each component, it should be pointed out that when Equation (E-4) is being computed and the quantity $\left| \frac{f(X_i)}{X_i f'(X_i)} \right|$ exceeds 16, X_1 is multiplied or divided by the quantity 'e', the base of the natural logarithms. This precludes any wild fluctuation of the successive estimates for X. In the many thousands of times which this subroutine has been called upon to compute the equilibrium composition, it has never failed to converge on the correct answers regardless of the value of the initial estimate.

TABLE XI

DIGIT CHANGED IN THE PARTIAL PRESSURE OF EACH CONSTITUENT FOR SELECTED VALUES OF RELATIVE ERROR

Stoiciometric Octene-Air Mixture
Temperature, 2500°K
Pressure, 19 Atm

Relative Error $\epsilon_2 \leq \frac{X_{i+1} - X_i}{X_i}$	O_2	N_2	CO_2	H_2O	CO	H_2	OH	NO	O	H
0.1	-	-	-	-	-	-	-	-	-	-
0.01	4	7	5	6	4	4	4	4	4	4
0.001	5	8	6	7	5	5	5	5	5	5
0.0001	7	8	NC	7	7	7	7	7	7	7
0.00001	NC	NC	NC	NC	NC	8	NC	8	8	8

NC - No Change

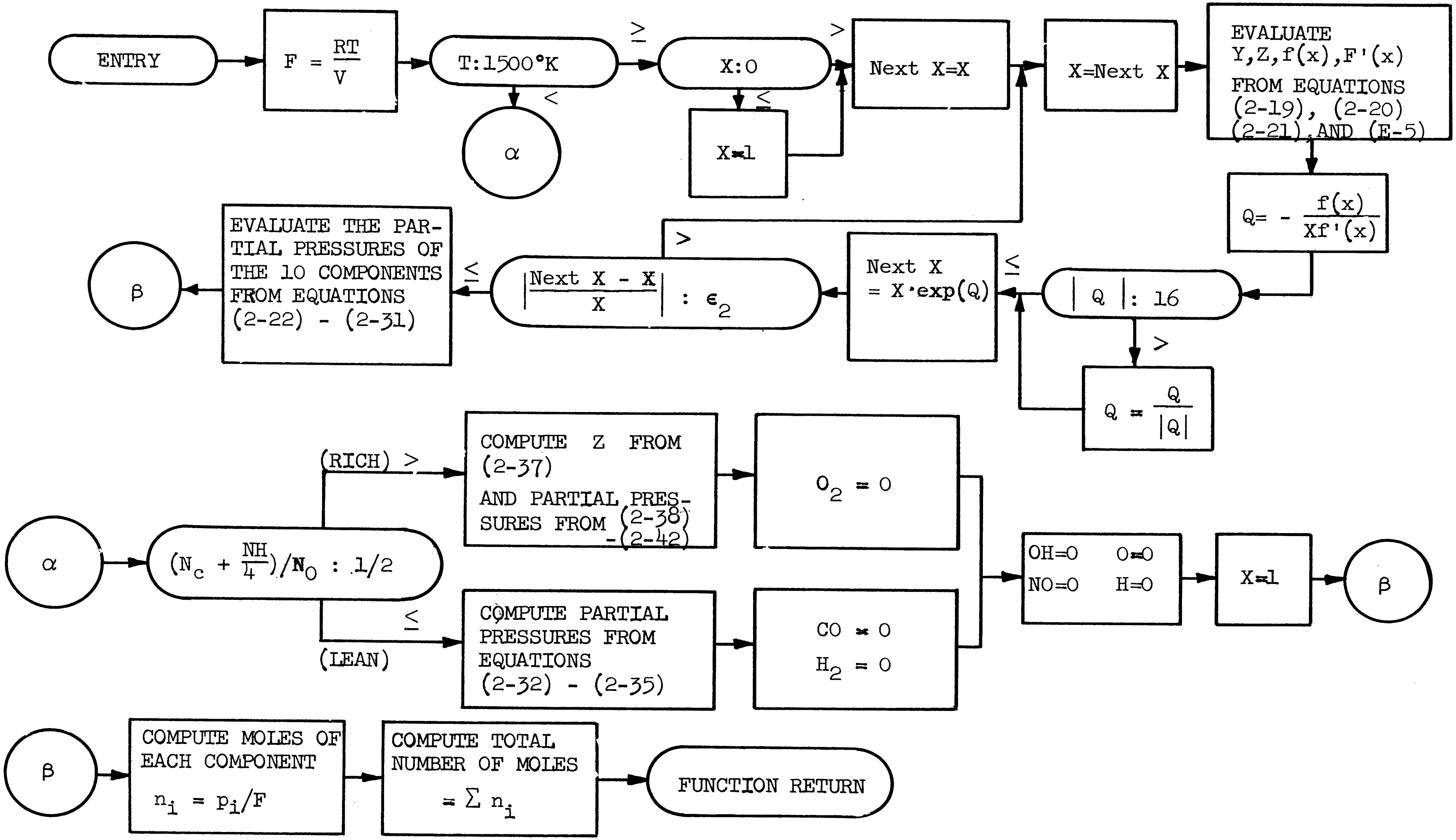


Figure 23. Flow diagram for the subroutine computing the composition of the products of combustion.

APPENDIX F

MATHEMATICAL ANALYSIS, FLOW DIAGRAM, AND COMPUTER PROGRAM LISTING FOR THE FUEL-AIR CYCLE

A. General

The mathematical analysis of the fuel-air cycle treats a number of quantities as variables. These are the fuel, the air-fuel ratio, the manifold temperature and pressure, the exhaust pressure, and the compression ratio. The fuel is described by specifying the number of carbon and hydrogen atoms per molecule of fuel; its enthalpy of combustion at the reference state; the constants for its empirical heat capacity equation, Table I; and its enthalpy of formation and entropy at the reference state, Table II. Two additional variables arise because of the iterative nature of some of the calculations. These are ϵ_1, the allowable relative error in those thermodynamic properties calculated by trial and error methods, and ϵ_2, the allowable error in the equilibrium composition (see Appendix E).

Among the quantities calculated from the cycle analysis are the pressure, temperature, enthalpy, entropy, and internal energy at each point of Figure 3. The indicated thermal efficiency, mean effective pressure, and exhaust gas residual fraction are also calculated.

The analysis assumes that all enthalpies and entropies and their derivatives are computed by the methods of Chapter II, Section B, and the equilibrium composition of the products of combustion is computed by those of Chapter II, Section D. Internal energies and their derivatives are computed from the corresponding quantities for the enthalpy.

For a perfect gas, these are

$$U = H - nRT \text{ and } \frac{dU}{dT} = \frac{dH}{dT} - nR$$

Subscripts on thermodynamic properties refer to points on Figure 3. The metric system is used throughout.

B. Mathematical Analysis

1. Exhaust Residual - Initial Approximation

Computation begins with an assumption of the residual exhaust gas temperature T_5. If the clearance volume is one liter and the pressure is P_e, the total number of moles remaining in the clearance volume is

$$n_5 = P_e/RT_5 \qquad \text{(F-1)}$$

An approximate exhaust gas composition can be calculated if it is assumed that the total number of moles of products per mole of fuel burned is the sum of the coefficients of the products in Equation 2-2. This quantity is

$$n_{t0t} = a + b/2 + (a + b/4)(cx + x - 1) \qquad \text{(F-2)}$$

The number of moles of each constituent present in the exhaust then will be its coefficient from Equation (2-2) multiplied by $\frac{n_5}{n_{t0t}}$. In the case of oxygen, the absolute value is taken to avoid a negative value for rich mixtures. Calculated in this manner, the exhaust composition is only approximate.

This initial approximation is not repeated for subsequent cycles. At the end of the complete cycle, a new exhaust temperature and composition is computed from equilibrium considerations. The cycle is then repeated until there is an insignificant change in these quantities from cycle to cycle. To facilitate the computation of the first cycle, the allowable relative error ϵ_1, discussed later, is increased by a factor of 100.

2. Mixing of the Fresh Charge and Exhaust Residual

The inlet conditions, Point 0, being known, the thermodynamic properties of the fresh charge can be calculated per mole. After induction, the mixture will be contained in a volume of 1·r liters, where 'r' is the compression ratio. The number of moles of fresh charge and the final temperature of the mixture are to be found.

If an initial guess T_1' is made for the mixture temperature, the number of moles of fresh charge is

$$n_0' = \frac{P_i r}{RT_1'} - n_5 \tag{F-3}$$

The prime denotes a temporary or approximate value. In a manner similar to that of Part 1, the individual number of moles of fuel, oxygen, and nitrogen can be calculated. If this entering mass is lumped with the residual exhaust gas and the enthalpy of the mixture is calculated, at T_1' a value H_1' is found.

For the ideal adiabatic inlet process envisioned here and described in detail in Reference 45, Chapter 4, the enthalpy of the mixture is

$$H_1 = H_0' + U_5 + P_i rJ \tag{F-4}$$

Whenever

$$\left| \frac{H_1' - H_1}{H_1} \right| > \epsilon_1 \tag{F-5}$$

where ϵ_1 is defined as the relative error, a corrected value for T_1', T_1'', must be found. This corrected value can be found by Newton's method, a derivation for which is found in Appendix G. The new Value is

$$T_1'' = T_1' - \frac{H_1' - H_1}{\left(\frac{dH_1}{dT}\right)'} \qquad \text{(F-6)}$$

where, in light of Equations F-3 and F-4,

$$\left(\frac{dH_1}{dT}\right)^1 = \frac{H_0'}{T_1'} \; (1 - \frac{n_5}{n_0'}) + \frac{dH_0'}{dT} \qquad \text{(F-7)}$$

This process is repeated until Equation (F-5) is not satisfied. The conditions at Point 1 are now known.

3. Isentropic Compression

At Point 2, the volume is one liter and $S_2 = S_1$. The composition remains unchanged during the compression. The temperature can be found by the following trial and error method. Assume a temperature T_2'. Then

$$P_2' = n_2 R T_2' \qquad \text{(F-8)}$$

where $n_2 = n_1$. The entropy S_2' then can be calculated. Whenever

$$\left| \frac{S_2' - S_2}{S_2} \right| > \epsilon_1 \qquad \text{(F-9)}$$

a new value T_2'' must be found.

$$T_2'' = T_2' - \frac{S_2' - S_2}{\left(\frac{\partial S_2}{\partial T}\right)^1_V} \qquad \text{(F-10)}$$

where

$$\left(\frac{\partial S_2}{\partial T}\right)'_V \quad \left(\frac{\partial S_2}{\partial T}\right)'_P \quad \frac{n_2 R}{T_2'} \qquad \text{(F-11)}$$

The process is repeated until Equation (F-9) is not satisfied. The conditions at Point 2 are now known.

4. Constant Volume Adiabatic Combustion

This process occurs at constant internal energy and constant volume, that is $U_3 = U_2$ and $V_3 = 1$. Moreover the products are in a state of chemical equilibrium. The problem is to find the adiabatic flame temperature and pressure at Point 3. If a temperature T_3' is assumed, the composition can be calculated according to the methods of Chapter II. The internal energy U_3' can then be calculated. Whenever

$$\left| \frac{U_3' - U_3}{U_3} \right| > \epsilon_1 \tag{F-12}$$

a new value T_3'' must be found. One method for finding this is to use Newton's method,

$$T_3'' = T_3' - \frac{U_3' - U_3}{\left(\frac{dU_3}{dT}\right)}, \tag{F-13}$$

wherein it is assumed that the difference between T_3'' and T_3' is so small that the effects of composition change are negligible. Because this is not always true, convergence may be slow or may not be obtained at all. However a second method can be employed, the Half-Interval convergence method. This method, which will always converge on the correct answer, is described in Appendix G. In this analysis both methods are employed. If a satisfactory solution is not found after using Newton's convergence method to generate five successive approximations to T_3, the Half-Interval method is used. If at the end of this fifth trial, the difference between T_3'' and T_3' is ΔT, the next trial for T_3 will be

$$T_3'' = T_3' - \Delta T \cdot \frac{U_3' - U_3}{|U_3' - U_3|} \tag{F-14}$$

Then whenever the quantity $(U_3' - U_3)$ changes sign, ΔT is halved. This half-interval method is continued until Equation F-12 is not satisfied. The conditions at Point 3 are then known.

5. Isentropic Expansion

At Point 4, the volume is 'r' liters and $S_4 = S_3$. The products are still in a state of chemical equilibrium. The temperature T_4 can be found by a method similar to that described in Section 3 for the compression. A temperature T_4' is assumed, the composition calculated, and the entropy S_4' determined. Whenever

$$\frac{S_4' - S_4}{S_4} > \epsilon_1 \tag{F-15}$$

a new value T_4'' must be found. Newton's method can be successfully used to generate T_4''. Whenever Equation F-15 is not satisfied, the conditions at Point 4 can be considered to be known.

6. Expansion to Exhaust Pressure

When the exhaust valve opens the contents of the cylinder expand to the exhaust pressure, the overall process being irreversible. Nevertheless, those gases remaining in the cylinder have undergone an isentropic expansion. At Point 4' $V_4' = r$, $\overline{S}_4' = \overline{S}_4$ and the pressure is P_e. For the purposes of calculating T_4', let $S_4'' = S_4$, that is, assume all the gas has expanded isentropically. The temperature T_4' can be found by a method identical to that of Section 5. The equilibrium composition is calculated for the case where the pressure and temperature, rather than the volume and temperature are known.

7. Exhaust Residual

At Point 5, the piston has exhausted all the products except those remaining in the clearance volume. The molar thermodynamic properties are identical to those at Point 4'. The fraction of total mass retained in the cylinder is $1/V''_4$. Thus the temperature and composition of the exhaust residual are completely determined.

Whenever

$$\left| \frac{T_{4'} - T_5}{T_5} \right| > \epsilon_1 \tag{F-16}$$

where T_5 is the exhaust gas temperature at the beginning of the cycle and $T_{4'}$ is that at the end, the entire cycle is repeated starting with Section 2. Prior to the second time the cycle is executed the relative error, ϵ_1, is reduced to its initial value by dividing it by a factor of 100. The cycle is always repeated at least once. When $\epsilon_1 = .00001$, about four complete cycles must be exhausted before Equation (F-16) is not satisfied.

8. Net Work

The net work is the difference between the expansion and compression work plus any pumping work. This quantity is

$$W_t = (U_3 - U_4) - (U_2 - U_1) + (r-1)(P_i - P_e)\ J \tag{F-17}$$

9. Thermal Efficiency

The indicated thermal efficiency, defined as the net cycle work divided by the heat of combustion of the fuel consumed, is

$$\eta = \frac{W_t \cdot 100}{\Delta H_c^o \cdot F_0} \tag{F-18}$$

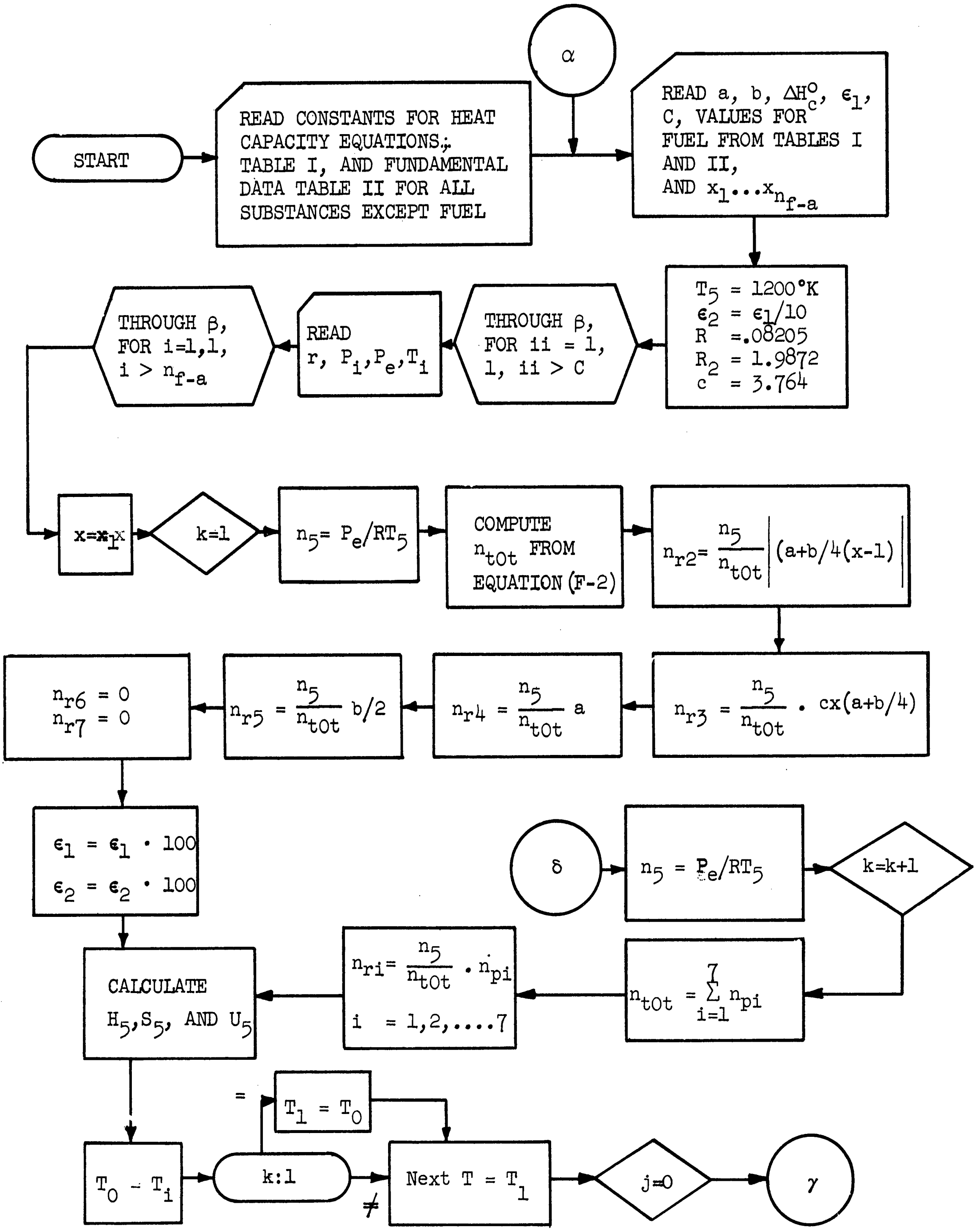
where F_0 are the moles of fuel consumed, calculated in Section 2, and ΔH_c^o is the higher heating value of the fuel per mole at 298.16°K and one atmosphere pressure.

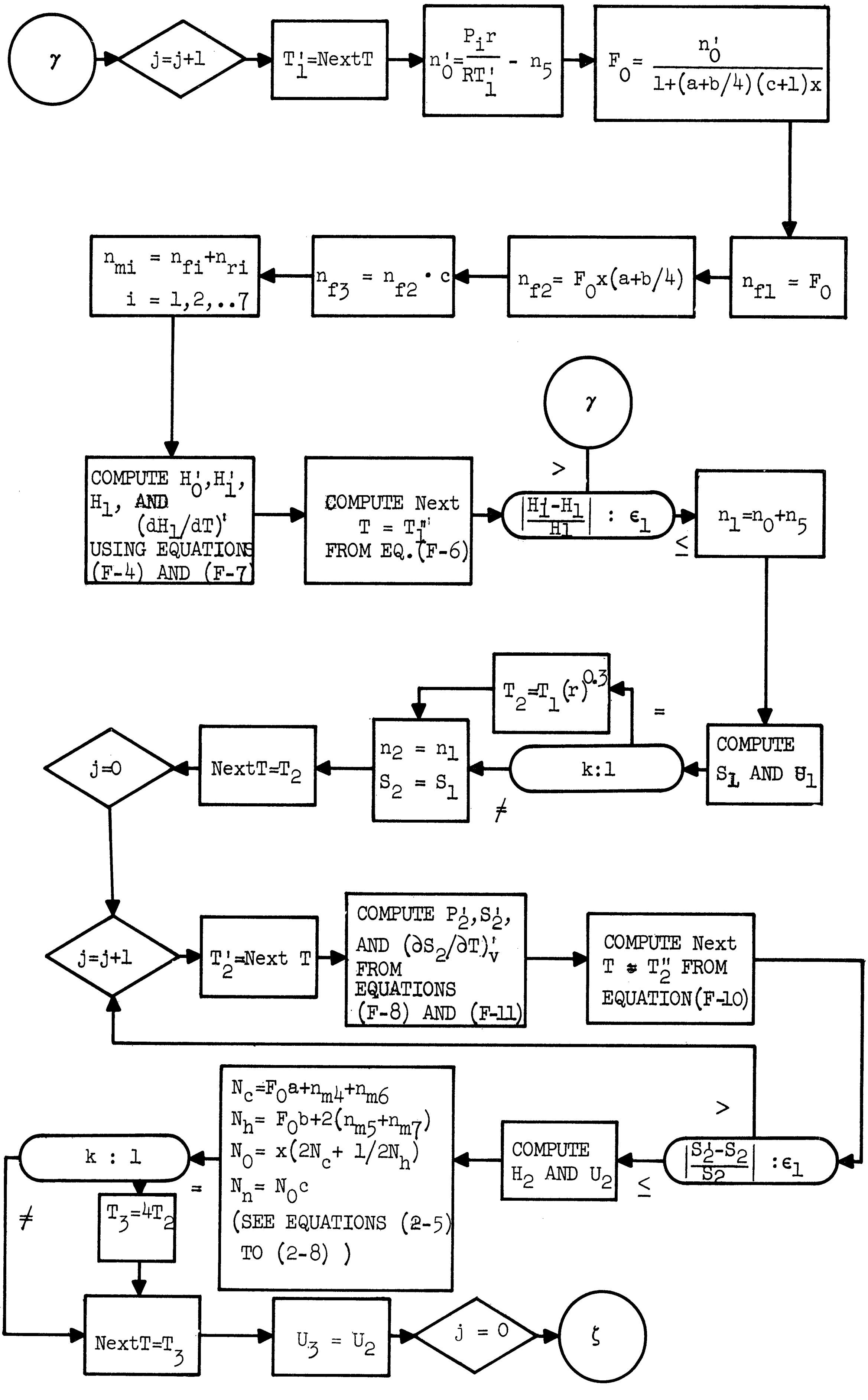
10. Mean Effective Pressure

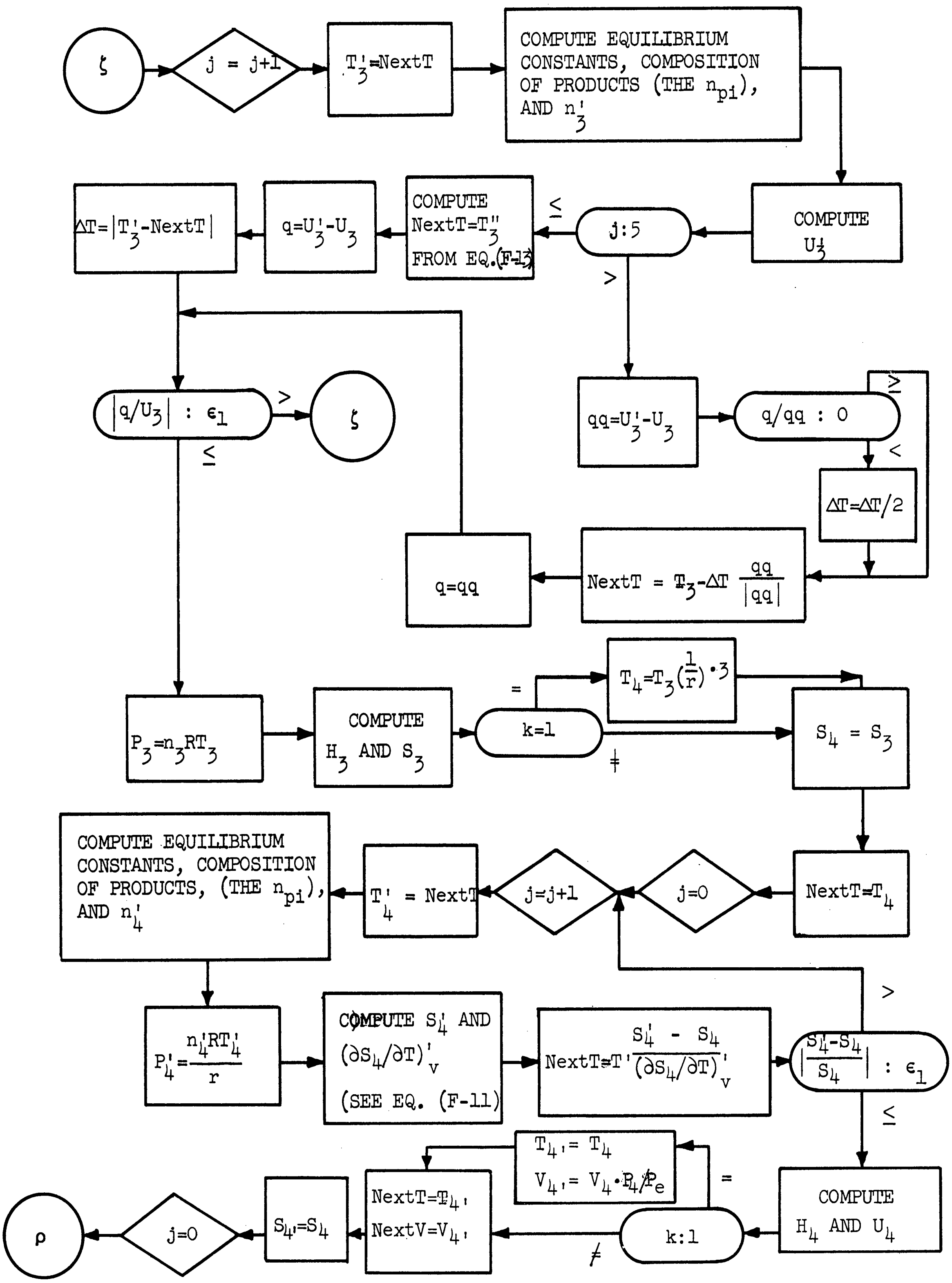
The mean effective pressure is defined as the net work divided by the displacement of the engine. This quantity is

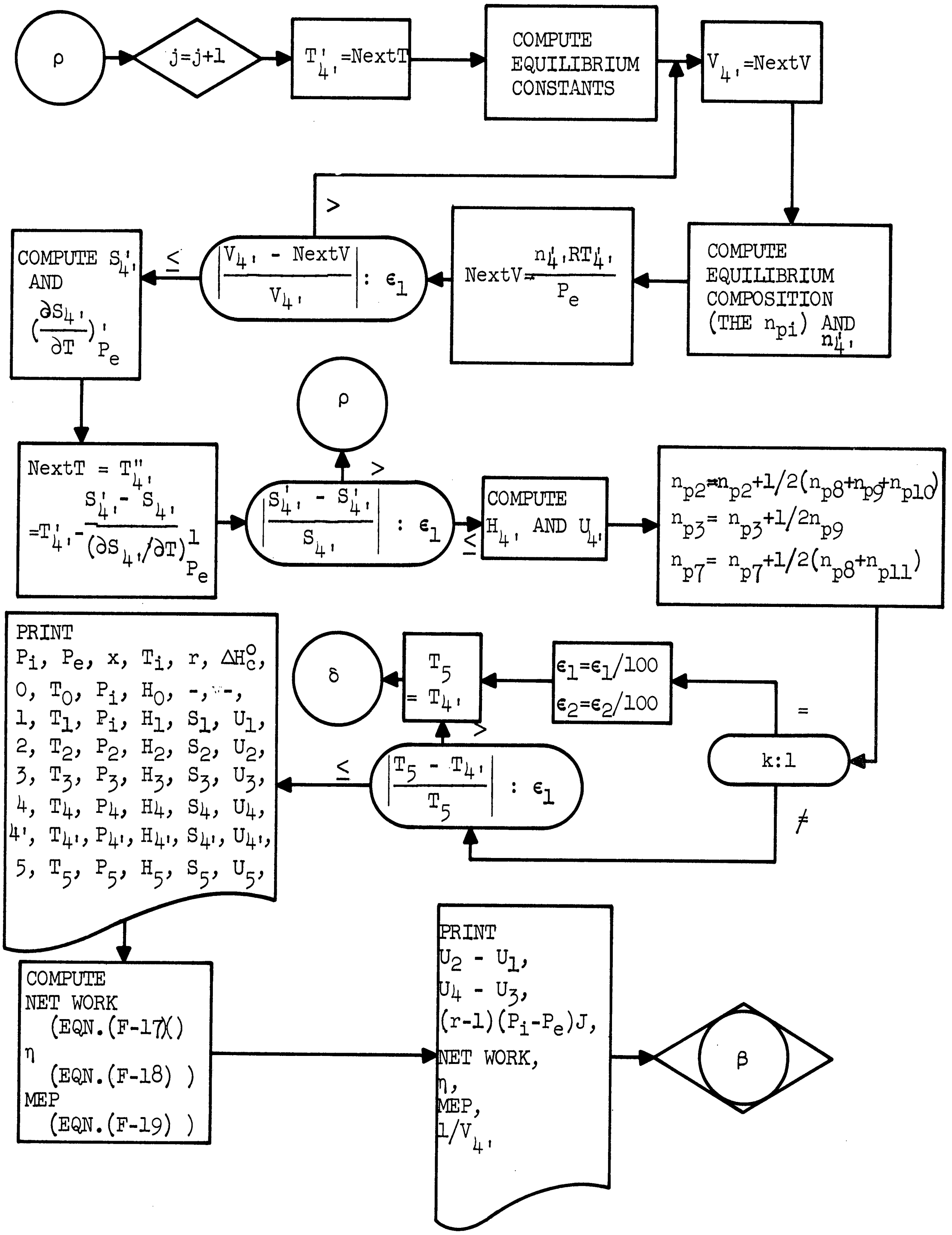
$$\text{mep} = \frac{W_t}{(r - 1)J} \qquad \text{(F-19)}$$

C. Flow Diagram




γ
$j=j+1$
$T_1'=\text{Next}T$
$n_0'=\frac{P_i r}{RT_1'}-n_5$
$F_0=\frac{n_0'}{1+(a+b/4)(c+1)x}$
$n_{f1}=F_0$
$n_{f2}=F_0 x(a+b/4)$
$n_{f3}=n_{f2}\cdot c$
$n_{mi}=n_{fi}+n_{ri}$ $i=1,2,..7$
COMPUTE H_0', H_1', H_1, AND $(dH_1/dT)'$ USING EQUATIONS (F-4) AND (F-7)
COMPUTE Next $T=T_1''$ FROM EQ. (F-6)
γ
>
$\left|\frac{H_1'-H_1}{H_1}\right|:\epsilon_1$
≤
$n_1=n_0+n_5$
COMPUTE S_1 AND U_1
k:1
=
$T_2=T_1(r)^{0.3}$
≠
$n_2=n_1$
$S_2=S_1$
$\text{Next}T=T_2$
$j=0$
$j=j+1$
$T_2'=\text{Next } T$
COMPUTE P_2', S_2', AND $(\partial S_2/\partial T)_v'$ FROM EQUATIONS (F-8) AND (F-11)
COMPUTE Next $T=T_2''$ FROM EQUATION (F-10)
>
$\left|\frac{S_2'-S_2}{S_2}\right|:\epsilon_1$
≤
COMPUTE H_2 AND U_2
$N_c=F_0a+n_{m4}+n_{m6}$
$N_h=F_0b+2(n_{m5}+n_{m7})$
$N_0=x(2N_c+1/2N_h)$
$N_n=N_0c$
(SEE EQUATIONS (2-5) TO (2-8))
k : 1
=
≠
$T_3=4T_2$
$\text{Next}T=T_3$
$U_3=U_2$
$j=0$
ζ


ζ
$j = j+1$
$T_3' = \text{NextT}$
COMPUTE EQUILIBRIUM CONSTANTS, COMPOSITION OF PRODUCTS (THE n_{pi}), AND n_3'
COMPUTE U_3'
$j:5$
≤
>
COMPUTE $\text{NextT} = T_3''$ FROM EQ.(F-13)
$q = U_3' - U_3$
$\Delta T = |T_3' - \text{NextT}|$
$qq = U_3' - U_3$
$q/qq : 0$
≥
<
$\Delta T = \Delta T/2$
$\text{NextT} = T_3 - \Delta T \frac{qq}{|qq|}$
$q = qq$
$|q/U_3| : \epsilon_1$
>
ζ
≤
$P_3 = n_3 R T_3$
COMPUTE H_3 AND S_3
$k=1$
=
≠
$T_4 = T_3 (\frac{1}{r})^{\cdot 3}$
$S_4 = S_3$
$\text{NextT} = T_4$
$j=0$
$j=j+1$
$T_4' = \text{NextT}$
COMPUTE EQUILIBRIUM CONSTANTS, COMPOSITION OF PRODUCTS, (THE n_{pi}), AND n_4'
$P_4' = \frac{n_4' R T_4'}{r}$
COMPUTE S_4' AND $(\partial S_4/\partial T)_v'$ (SEE EQ. (F-11))
$\text{NextT} = T' \frac{S_4' - S_4}{(\partial S_4/\partial T)_v'}$
$\left|\frac{S_4' - S_4}{S_4}\right| : \epsilon_1$
>
≤
COMPUTE H_4 AND U_4
$k:1$
=
≠
$T_{4'} = T_4$
$V_{4'} = V_4 \cdot P_4/P_e$
$\text{NextT} = T_{4'}$
$\text{NextV} = V_{4'}$
$S_{4'} = S_4$
$j=0$
ρ


ρ
$j=j+1$
$T'_{4'}$=NextT
COMPUTE EQUILIBRIUM CONSTANTS
$V_{4'}$=NextV
COMPUTE EQUILIBRIUM COMPOSITION (THE n_{pi}) AND $n'_{4'}$
NextV=$\frac{n'_{4'}RT'_{4'}}{P_e}$
$\left|\frac{V_{4'} - \text{NextV}}{V_{4'}}\right| : \epsilon_1$
>
≤
COMPUTE $S'_{4'}$ AND $\left(\frac{\partial S_{4'}}{\partial T}\right)'_{P_e}$
NextT = $T''_{4'}$ $=T'_{4'}-\frac{S'_{4'}-S_{4'}}{(\partial S_{4'}/\partial T)^1_{P_e}}$
$\left|\frac{S'_{4'} - S'_{4'}}{S_{4'}}\right| : \epsilon_1$
ρ
>
≤
COMPUTE $H_{4'}$ AND $U_{4'}$
$n_{p2}=n_{p2}+1/2(n_{p8}+n_{p9}+n_{p10})$
$n_{p3}= n_{p3}+1/2n_{p9}$
$n_{p7}= n_{p7}+1/2(n_{p8}+n_{p11})$
k:1
=
≠
$\epsilon_1=\epsilon_1/100$
$\epsilon_2=\epsilon_2/100$
$T_5 = T_{4'}$
δ
$\left|\frac{T_5 - T_{4'}}{T_5}\right| : \epsilon_1$
>
≤
PRINT
P_i, P_e, x, T_i, r, ΔH^o_c,
0, T_0, P_i, H_0, -, -,
1, T_1, P_i, H_1, S_1, U_1,
2, T_2, P_2, H_2, S_2, U_2,
3, T_3, P_3, H_3, S_3, U_3,
4, T_4, P_4, H_4, S_4, U_4,
4', $T_{4'}$, $P_{4'}$, $H_{4'}$, $S_{4'}$, $U_{4'}$,
5, T_5, P_5, H_5, S_5, U_5,
COMPUTE NET WORK (EQN.(F-17)) η (EQN.(F-18)) MEP (EQN.(F-19))
PRINT
$U_2 - U_1$,
$U_4 - U_3$,
$(r-1)(P_i-P_e)J$,
NET WORK,
η,
MEP,
$1/V_{4'}$
β

D. Computer Program for the Fuel-Air Cycle

The following pages contain a listing of the computer program for the fuel-air cycle engine written in the MAD language for an IBM 704 computer. The external functions ENTHAL., ENTROP., HPRIME., and SPRIME. which compute the enthalpy and entropy as well as their temperature derivatives at constant pressure; EQUIL., the function which calculates the six equilibrium constants; and AMOUNT., the function which calculates the equilibrium composition, are listed in Appendix I and are not repeated here.

The program contains a number of variable names most of which are explained in Appendix I. *Those names pertaining to this program only are:

CARDS	number of combinations of compression ratio, manifold pressure and temperature, and exhaust pressure for which computations are to be made: C
NAME	whenever NAME is not blank, additional intermediate output is provided.
PH_i	an initial estimate of the value of $X = \sqrt{p_{O_2}}$ at Point 'i' (This is used in the computation of the equilibrium composition. In Appendix E it corresponds to X_1 and in the external function AMOUNT. it corresponds to PH.)
R2	gas constant in heat units
VB	clearance plus swept volumes, equal to r
VT	clearance volume, equal to 1

---

[*] Symbol after colon is an alternate designation.

```
$COMPILE MAD,PRINT OBJECT,PUNCH OBJECT,EXECUTE,DUMP             HOTEL001
           DIMENSION AL(87,ALDIM),AH(87,ALDIM),N(11),RE(12),K(11),P(11)
          1,X(50),SPACE(41)
           INTEGER I,I1,J1,J2,RE,CARDS,NFA,NAME
           VECTOR VALUES ALDIM = 2,0,8
           PROGRAM COMMON AL,AH,P,K,R2,NC,NH,NO,NN,R,J1,SPACE,ERROR2
           READ FORMAT SPHT1,NAME,AL(2,1)...AL(11,8),AH(2,1)...AH(11,8)
           VECTOR VALUES SPHT1 = $C6/(4E15.8)*$
START      READ FORMAT FUEL,RE(1)...RE(12),A,B,HCOMB,ERROR1,CARDS,AL(1,1
          1)...AL(1,8),AH(1,1)...AH(1,8)
           VECTOR VALUES FUEL = $12C6/4F10.5,I5/(4E15.8)*$
           PRINT FORMAT DUMP1,AL(1,1)...AL(7,8)
           VECTOR VALUES DUMP1 = $1H1,4HAL =/(8E15.8)*$
           PH3 = 1.
           PH4 = 1.
           T5 = 1200.
           ERROR2 = ERROR1/10.
           R = .08205
           R2 = 1.9872
           C = 3.764
           PRINT FORMAT DUMP2,AH(1,1)...AH(11,8)
           VECTOR VALUES DUMP2 = $1H0,4HAH =/(8E15.8)*$
           READ FORMAT FULAIR,NFA,X(1)...X(NFA)
           VECTOR VALUES FULAIR = $I10/(14F5.4)*$
           THROUGH LOOP1,FOR I1 = 1,1,I1.G.CARDS
           READ FORMAT ENGINE,CR,PMAN,PEXH,TMAN
           VECTOR VALUES ENGINE = $ 6F10.5*$
           PMAN = PMAN/14.696
           PEXH = PEXH/14.696
           TMAN = TMAN/1.8
           VT = 1./61.03
           VB = CR*VT
           THROUGH LOOP1,FORI=1,1,I.G.NFA
           X = X(I)
           WHENEVER NAME.NE.$      $
           PRINT FORMAT HEAD1,RE(1)...RE(12),PMAN*14.696,PEXH*14.696,X,T
          1MAN*1.8,CR,HCOMB,VT*61.03,(VB-VT)*61.03
           END OF CONDITIONAL
           VECTOR VALUES HEAD1 = $1H1    /1H0,S28,64HIDEALIZED THERMODYN
          1AMIC CYCLE FOR THE INTERNAL COMBUSTION ENGINE/1H0,10HTHIS IS
          2A C6,15H RUN EMPLOYING 2C6,37H AS A FUEL.  ADDITIONAL COMMENT
          3S ARE./1H0,9C6/                                      1H0,19HMANI
          4FOLD PRESSURE = F10.5,4H PSIS7,18HEXHAUST PRESSURE = F10.5,
          54H PSIS8,16HAIR-FUEL RATIO = F10.5/1H0,22HMANIFOLD TEMPERATUR
          6E = F10.5,2H KS6,19HCOMPRESSION RATIO = F10.5,S11,        17HH
          7 OF COMBUSTION = F10.2,9H CAL/MOLE/1H0,18HCLEARANCE VOLUME =
          8F10.5,7H CU.IN.,S5,14HSWEPT VOLUME = F10.5,7H CU.IN.*$
           T = T5
           J2 = 1
           N5 = PEXH*VT/R/T5
           F5 = N5/(A+B/2.+(A+B/4.)*(C*X+X-1.))
           N(2) = .ABS.(F5*(A+B/4.)*(X-1.))
           N2 = N(2)
           N(3) = F5*(A+B/4.)*C*X
           N3 = N(3)
           N(4) = F5*A
           N(5) = F5*B/2.
           N(6) = 0.
           N(7) = 0.
```

```
             ERROR1 = ERROR1*100.
             ERROR2 = ERROR2*100.
             TRANSFER TO LOC1
 LOOP        J2 = J2 + 1
             T5 = T4P
             T = T5
             N5 = PEXH*VT/R/T
             F5 = N5/(N(2)+N(3)+N(4)+N(5)+N(6)+N(7))
             N(2) = F5*N(2)
             N2 = N(2)
             N(3) = F5*N(3)
             N3 = N(3)
             N(4) = F5*N(4)
             N(5) = F5*N(5)
             N(6) = F5*N(6)
             N(7) = F5*N(7)
 LOC1        EXECUTE ENTROP.(2,7,S5,T,N5,PEXH,N)
             EXECUTE ENTHAL.(2,7,H5,T,N)
             U5 = H5 - N5*R2*T
             WHENEVER NAME.NE.$       $
             PRINT FORMAT HEAD2
             PRINT FORMAT OUT,5,T5,PEXH,H5,S5,U5,N5,F5,N(2)...N(7)
             END OF CONDITIONAL
             VECTOR VALUES HEAD2 =$1H0/8H0STATION,S5,6HT - *K,S5,8HP - ATM
            1.,S5,8HH - CAL.,S7,11HS - CAL./*KS8,8HU - CAL.S7,11HTOTAL MOL
            2ES,S7,1HF*$
             T0 = TMAN
             J = 0.
             WHENEVER J2.E.1,T1=T0
             NEXTT = T1
 LOOP4       T = NEXTT
             J = J + 1.
             N0 = PMAN*VB/R/T-N5
             F0 = N0/(1. +X*(A+B/4.)+C*X*(A+B/4.))
             N(1) = F0
             N(2) = F0*X*(A+B/4.)
             N(3) = N(2)*C
             EXECUTE ENTHAL.(1,3,H0,TMAN,N)
             EXECUTE HPRIME.(1,3,HPRIM,T,N)
             HPRIM = HPRIM - H0/T*(1. + N5/N0)
             H1 = H0 + U5 + PMAN*VT*24.2179
             N(2) = N(2) + N2
             N(3) = N(3) + N3
             EXECUTE ENTHAL.(1,7,HMIX,T,N)
             NEXTT = T - (HMIX-H1)/HPRIM
             WHENEVER .ABS.((HMIX-H1)/H1).G.ERROR1,TRANSFER TO LOOP4
             T1 = T
             N1 = N0 + N5
             EXECUTE ENTROP.(1,7,S1,T,N1,PMAN,N)
             U1 = H1-N1*R2*T
             WHENEVER NAME.NE.$       $
             PRINT FORMAT OUT, 0,T0,PMAN,H0,0,0,N0,F0,F0,F0*X*(A+B/4.),F0*
            1X*C*(A+B/4.),J
             PRINT FORMAT OUT,1,T1,PMAN,H1,S1,U1,N1,0,N(1)...N(7),J
             END OF CONDITIONAL
             WHENEVER J2.E.1, T2 = T1*CR.P..3
             N2 = N1
             J = 0.
```

```
            NEXTT = T2
LOOP5       T = NEXTT
            J = J + 1.
            P2 =  T*CR*PMAN/T1
            EXECUTE ENTROP.(1,7,S2,T,N2,P2,N)
            EXECUTE SPRIME.(1,7,SPRIM,T,N)
            SPRIM = SPRIM - N2*R2/T
            NEXTT = T - (S2 - S1)/SPRIM
            WHENEVER .ABS.((S2-S1)/S1).G.ERROR1,TRANSFER TO LOOP5
            EXECUTE ENTHAL.(1,7,H2,T,N)
            T2 = T
            U2 = H2 - N2*R2*T
            WHENEVER NAME.NE.$       $
            PRINT FORMAT OUT, 2,T2,P2,H2,S2,U2,N2,0.,N(1)...N(7),J
            END OF CONDITIONAL
            NC = F0*A + N(4) + N(6)
            NH = F0*B + (N(5) + N(7))*2.
            NO =(2.*NC+.5*NH)*X
            NN = NO*C
            WHENEVER J2.E.1,T3 = 4.*T2
            NEXTT = T3
            J = 0.
LOOP6       T = NEXTT
            J = J + 1.
            EXECUTE EQUIL.(T)
            EXECUTE AMOUNT.(T,VT,N3,PH3,N)
            EXECUTE ENTHAL.(2,11,H3,T,N)
            U3 = H3 - N3*R2*T
            WHENEVER J.G.5.,TRANSFER TO HALFIN
            EXECUTE HPRIME.(2,11,HPRIM,T,N)
            UPRIM = HPRIM - N3*R2
            Q = (U2-U3)/T/UPRIM
            WHENEVER .ABS.(Q).L..1
            NEXTT = T*EXP.(Q)
            OTHERWISE
            NEXTT = T + 100.*Q/.ABS.(Q)
            END OF CONDITIONAL
            DIF = .ABS.(T  - NEXTT)
            SAVE = DIF
            WHENEVER .ABS.((U3-U2)/U2).G.ERROR1,TRANSFER TO LOOP6
            TRANSFER TO END
HALFIN      QQ = U2 - U3
            WHENEVER Q/QQ .L.0.,DIF = DIF/2.
            NEXTT = T + DIF*QQ/.ABS.(QQ)
            Q = QQ
            WHENEVER .ABS.((U3-U2)/U2).G.ERROR1,TRANSFER TO LOOP6
END         P3 = N3*R*T/VT
            T3 = T
            EXECUTE ENTROP.(2,11,S3,T,N3,P3,N)
            WHENEVER NAME.NE.$       $
            PRINT FORMAT OUT,3,T3,P3,H3,S3,U3,N3,0.,N(1)...N(11),J,P(1)..
           1.P(11),SAVE
            END OF CONDITIONAL
            WHENEVER J2.E.1,T4 = T3*(1./CR).P..3
            NEXTT = T4
            J = 0.
LOOP7       T = NEXTT
            J = J + 1.
```

```
                EXECUTE EQUIL.(T)
                EXECUTE AMOUNT.(T,VB,N4,PH4,N)
                P4 = N4*R*T/VB
                EXECUTE ENTROP.(2,11,S4,T,N4,P4,N)
                EXECUTE SPRIME.(2,11,SPRIM,T,N)
                SPRIM = SPRIM - N4*R2/T
                NEXTT = T - (S4-S3)/SPRIM
                WHENEVER .ABS.((S4-S3)/S3).G.ERROR1,TRANSFER TO LOOP7
                T4 = T
                EXECUTE ENTHAL.(2,11,H4,T,N)
                U4 = H4 - N4*R2*T
                WHENEVER NAME.NE.$      $
                PRINT FORMAT OUT,4,T4,P4,H4,S4,U4,N4,0.,N(1)...N(11),J,P(1)..
               1.P(11)
                END OF CONDITIONAL
                WHENEVER J2 .E.1
                T4P = T4
                PH4P = PH4
                V4P = N4*R*T4P/PEXH
                END OF CONDITIONAL
                NEXTT = T4P
                J = 0.
                NEXTV = V4P
    LOOP8       T = NEXTT
                J = J + 1.
                EXECUTE EQUIL.(T)
                J3 = 0.
    BACK        V = NEXTV
                J3 =J3 + 1.
                EXECUTE AMOUNT.(T,V,N4P,PH4P,N)
                NEXTV = N4P*R*T/PEXH
                WHENEVER .ABS.((NEXTV-V  )/V  ).G.ERROR1,TRANSFER TO BACK
                EXECUTE ENTROP.(2,11,S4P,T,N4P,PEXH,N)
                EXECUTE SPRIME.(2,11,SPRIM,T,N)
                NEXTT = T - (S4P-S4)/SPRIM
                WHENEVER .ABS.((S4P-S4)/S4).G.ERROR1,TRANSFER TO LOOP8
                T4P = T
                V4P = V
                P4P = N4P*R*T/V
                EXECUTE ENTHAL.(2,11,H4P,T,N)
                U4P = H4P - N4P*R2*T
                WHENEVER NAME.NE.$      $
                PRINT FORMAT OUT,45, T4P,P4P, H4P,S4P,U4P,N4P,0.,N(1)...N(11)
               1,J,P(1)...P(11),J3
                PRINT FORMAT NOTICE ,J2,.ABS.(T5-T4P),NC,NH,NO,NN,VT,VB
                END OF CONDITIONAL
                VECTOR VALUES NOTICE = $1H0,23HAFTER ITERATION NUMBER I2,51H
               1 THE ABSOLUTE DIFFERENCE BETWEEN T5 AND T4PRIME IS F10.5/1H0,
               246HTHE MOLE ATOMS OF THE FOLLOWING SUBSTANCES ARE/9H CARBON =
               3E15.8,11H HYDROGEN = E15.8,9H OXYGEN = E15.8,11H NITROGEN = E
               415.8/5H VT = E15.8,12H L. AND VB = E15.8,3H L.*$
                N(2) = N(2)+.5*(N(8)+N(9)+N(10))
                N(3) = N(3) + .5*N(9)
                N(7) = N(7) + .5*(N(8)+N(11))
                WHENEVER J2 .E. 1
                ERROR1 = ERROR1/100.
                ERROR2 = ERROR2/100.
                TRANSFER TO LOOP
```

```
           END OF CONDITIONAL
           WHENEVER .ABS.((T5-T4P)/T5).G.ERROR1,TRANSFER TO LOOP
           PRINT FORMAT HEAD1,RE(1)...RE(12),PMAN*14.696,PEXH*14.696,X,T
          1MAN*1.8,CR,HCOMB,VT*61.03,(VB-VT)*61.03
           PRINT FORMAT HEAD3
           VECTOR VALUES HEAD3 = $1H0,S18,36HSUMMARY OF RESULTS IN ENGLI
          1SH SYSTEM/1H0, 7HSTATION,S5,6HT - *R,S5,8HP - PSI.,S5,
          2          8HH - BTU.,S5,11HS - BTU./*R,S6,8HU - CAL.*$
           PRINT FORMAT SUMMRY,0,T0*1.8,PMAN*14.696,H0/252.161,0.,0.,1,T
          11*1.8,PMAN*14.696,H1/252.161,S1/252.161/1.8,U1/252.161,2,T2*1
          2.8,P2*14.696,H2/252.161,S2/252.161/1.8,U2/252.161,3,T3*1.8,P3
          3*14.696,H3/252.161,S3/252.161/1.8,U3/252.161,4,T4*1.8,P4*14.6
          496,H4/252.161,S4/252.161/1.8,U4/252.161,45,T4P*1.8,P4P*14.696
          5,H4P/252.161,S4P/252.161/1.8,U4P/252.161,
          65,T5*1.8,PEXH*14.696,H5/252.161,S5/252.161/1.8,U5/252.161
           VECTOR VALUES SUMMRY = $1H ,I4,S6,2F10.3,3F15.8*$
           VECTOR VALUES OUT = $1H0,I4,S6,2F10.5,5E17.8/(6E20.8)*$
           WORK12 = (U2-U1)/252.161
           WORK43 = (U3-U4)/252.161
           WPUMP = ((VB-VT)*(PMAN-PEXH))*24.2179/252.161
           WNET = WORK43-WORK12+WPUMP
           PRINT FORMAT RESULT,WORK12,WORK43,WPUMP,WNET,WNET/HCOMB/F0*25
          1216.1,WNET*14.696/(VB-VT)/24.2179*252.161
           VECTOR VALUES RESULT = $1H0/1H0,S10,7HRESULTS/1H+,S10,7HRESUL
          1TS/1H0,31HUNDER THE FOLLOWING ASSUMPTIONS/40H 1) ISENTROPIC C
          2OMPRESSION AND EXPANSION/30H 2) CONSTANT VOLUME COMBUSTION/20
          3H 3) NO HEAT TRANSFER/1H0/1H0/
          4 S6,30HCOMPRESSION WORK             = E15.8,4H BTU/
          5 S6,30HEXPANSION WORK               = E15.8,4H BTU/
          6 S6,30HPUMPING WORK                 = E15.8,4H BTU/
          7 S6,30HNET CYCLE WORK               = E15.8,4H BTU/
          8 S6,30HINDICATED THERMAL EFFICIENCY= E15.8,8H PERCENT/
          9 S6,30HMEAN EFFECTIVE PRESSURE      = E15.8,4H PSI*$
LOOP1      PRINT FORMAT RESULL,VT/V4P,F0*(A+B/4.)*(C*X+X)/(VB-VT)*24.464
          1028
           VECTOR VALUES RESULL = $
          1 S6,30HRESIDUAL WEIGHT FRACTION     = E15.8,4H = F/
          2 S6,30HVOLUMETRIC EFFICIENCY        = E15.8,25H BASED ON 1 ATM
          3. AND 25*K *$
           TRANSFER TO START
           END OF PROGRAM
```

APPENDIX G

ITERATIVE METHODS FOR SOLUTION OF IMPLICIT FUNCTIONS OF A SINGLE VARIABLE

A. General

Consider a function of one variable,

$$f(x) = 0 \tag{G-1}$$

It is desired to find the value of x which will satisfy (G-1).

Assuming an initial value, x_1, in general the function $f(x_1)$ will not be equal to zero and must be corrected by some amount, $\Delta f(x_1)$, in order to equate it to zero. That is

$$f(x_1) + \Delta f(x_1) = 0 \tag{G-2}$$

It remains to find a correction to x_1, Δx_1, giving a new value x_2 which is closer to the correct answer.

B. Methods of Solution

1. Newton's Method

Newton's method proposes the following relation for determining x_2:

$$\Delta f(x_1) \approx \left(\frac{df(x)}{dx}\right)_1 \cdot \Delta x_1 = f'(x_1) \cdot \Delta x_1 \tag{G-3}$$

Substituting (G-3) in (G-2),

$$x_2 = x_1 + \Delta x_1 = x_1 - \frac{f(x_1)}{f'(x_1)} \tag{G-4}$$

In general, for the i-th trial,

$$x_{i+1} = x_i - \frac{f(x_i)}{f'(x_i)}$$

The interation is repeated until Δx_i is less than some prescibed value.

2. Half-Interval Method

The Half-Interval method proposes that an arbitrary initial step size, Δx_1, be used between successive trials for x. This step size is then reduced as the correct answer is approached. The following relation is used to find x_2:

$$x_2 = x_1 + \Delta x_1 \cdot \frac{-f(x_1)}{|f(x_1)|} \tag{G-5}$$

If $f(x_2)$ is different in sign than $f(x_1)$, $\Delta x_2 = \frac{\Delta x_1}{2}$. The negative sign is used in (G-5) since $f(x_2) > f(x_1)$ whenever $x_2 > x_1$, for all the functions considered.

In general, for the i-th trial,

$$x_{i+1} = x_i - \Delta x_i \cdot \frac{f(x_i)}{|f(x_i)|} \tag{G-6}$$

where $\Delta x_i = \frac{\Delta x_{i-1}}{2}$ whenever the ratio $\frac{f(x_{i-1})}{f(x_i)}$ is negative.

The iteration is repeated until Δx_i is less than some prescribed value.

APPENDIX H

CALCULATION OF THE RATE OF RADIANT HEAT TRANSFER

The rate of radiant heat transfer in an internal combustion engine will be calculated by the method of Hottel(87) and McAdams(68), Chapter IV. A sample calculation will be made to estimate the magnitude of the radiant heat transfer in a 10 to 1 compression ratio engine which will be taken to be representative of a present day high compression engine. This engine is assumed to run on the fuel-air-cycle (see Chapter III) which postulates an adiabatic combustion process at top center. If the radiation is calculated based on the state of the working fluid after this adiabatic combustion, the amount of radiant heat transfer found is expected to be considerably higher than that found in an actual engine where the maximum temperatures and pressures are appreciably lower. A normal combustion process is assumed for which the principal emitters are CO_2 and H_2O.

The following notation is used in connection with the calculations; the figure numbers refer to figures in McAdams:

ϵ_{gc}	emissivity of CO_2 from Figure 4-13
ϵ_{gw}	emissivity of H_2O from Figure 4-15
$\Delta\epsilon$	correction for overlapping emission spectra from Figure 4-17
C_c	pressure correction factor for CO_2 from Figure 4-16
C_w	pressure correction factor for H_2O from Figure 4-14
ϵ_g	emissivity of gas mixture
a	absorbtivity of wall
ϵ'	factor to account for the non-black body character of the enclosure

For the transfer of heat by radiation from hot gases whose principal emitters are CO_2 and H_2O, the following formula applies:

$$q/A = 1723\ \epsilon' \left[\epsilon_g \left(\frac{T_g}{100}\right)^4 - \left(\frac{T_w}{100}\right)^4 \right] \text{Btu/ft}^2\text{-sec} \qquad \text{(H-1)}$$

where

$$\epsilon_g = \epsilon_{gc}C_c + \epsilon_{gw}C_w - \Delta\epsilon_g$$

$$a = \epsilon_{sc}C_c + \epsilon_{gw}C_w - \Delta\epsilon_s$$

For the 10 to 1 compression ratio engine running on a stoiciometric mixture of iso-octane and air the following values were obtained from a fuel-air cycle analysis:

maximum cycle gas temperature	5000°R
maximum cycle gas pressure	100 atm
mole fraction of CO_2	0.1
mole fraction of H_2O	0.13

It is recognized that in an actual engine during normal combustion the pressures are never as high as those predicted by the fuel-air cycle analysis. A figure of 67 atm or 1000 psia seemed to be a more reasonable value for the pressure than 100 atm and thus was used in the calculations.

An average hydraulic radius is required for the calculations for which Hottel suggests

$$L = 3.4\ \frac{\text{volume of gas}}{\text{area of boundary surface}}\ \text{ft}$$

For an engine with a compact combustion chamber such as that used for the calculations reported in Chapter VII, 0.075 ft is an appropriate value.

Following the method of McAdams,

$$p_cL = 0.5 \text{ atm-ft}$$

$$p_wL = 0.65 \text{ atm-ft}$$

where p_c and p_w are the partial pressures of CO_2 and H_2O respectively. From the appropriate figures in Reference 68,

$$\epsilon_{gw} = 0.05$$

$$\epsilon_{gc} = 0.037$$

$$\Delta\epsilon_g = 0.046$$

$$a \cong 1.0$$

$$\left.\begin{aligned} C_c &= 1.75 \\ C_w &= 3.75 \end{aligned}\right\} \text{by extrapolation}$$

Then

$$\epsilon_g = 0.21$$

for $\epsilon_{surface} = 0.9$, $\epsilon' = 0.94$ (from Reference 87)

Substitution these values in (H-1)

$$q/A = 70 \text{ Btu/ft}^2\text{-sec}$$

The convective component of heat transfer can be calculated from Equation (5-18). If the speed is 3000 rpm and the stroke is 4 in., the average piston speed, w, is approximately 10 m/sec. For a wall temperature of 300°F,

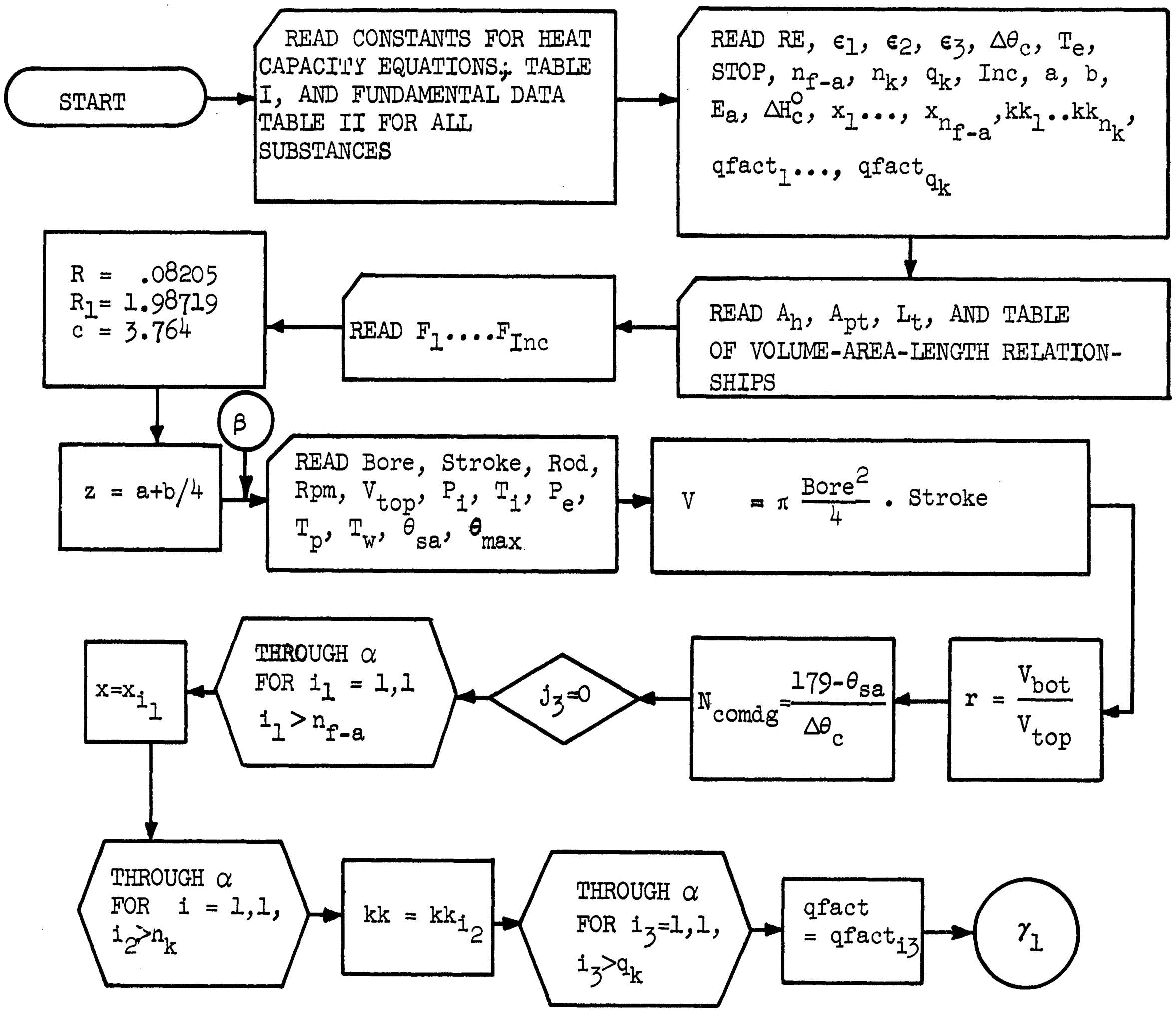
$$q/A = 490 \text{ Btu/ft}^2\text{-sec}$$

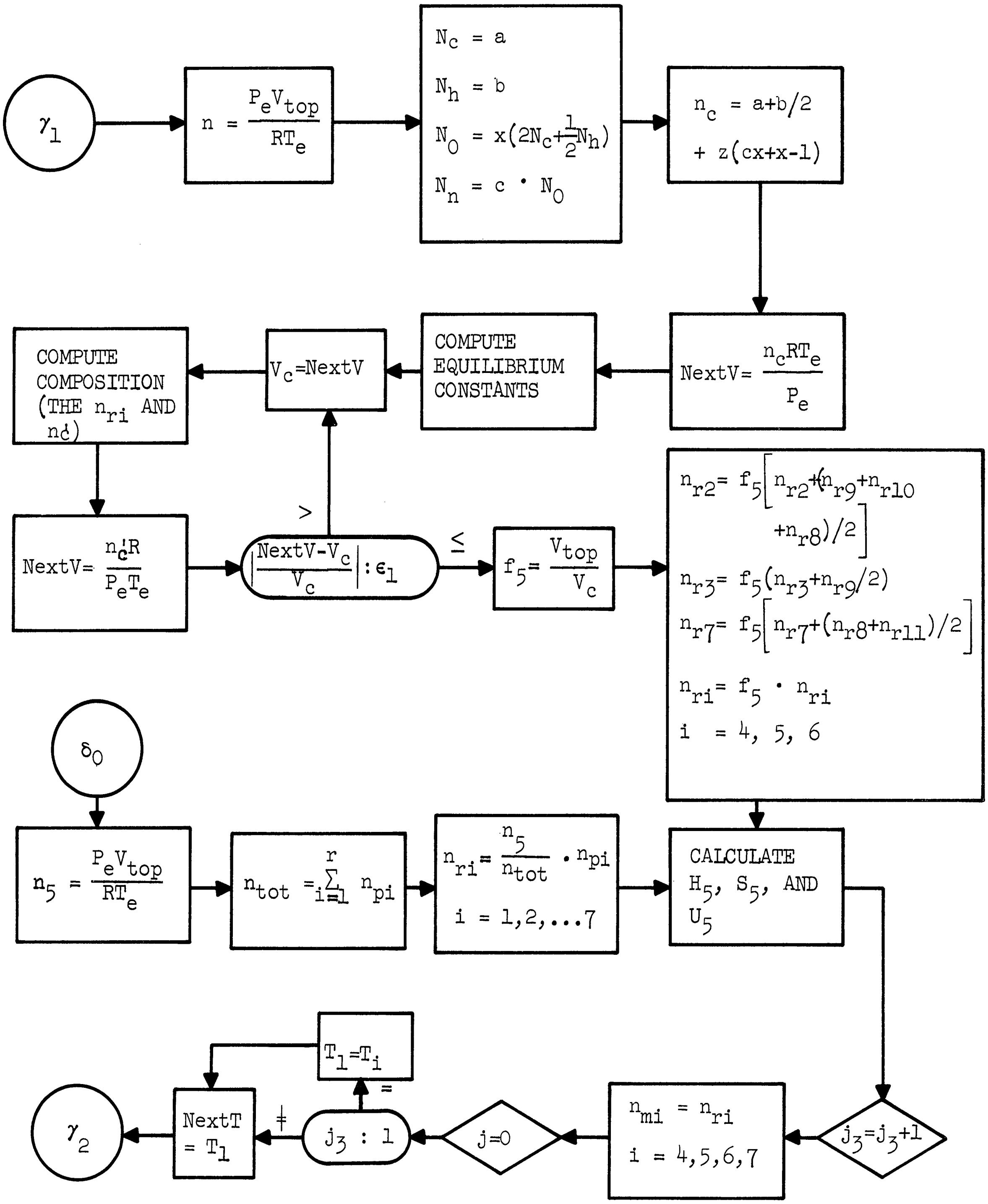
The total heat transfer is 560 Btu/ft^2-sec of which that due to radiation is about 12 percent. Because the assumptions and extrapolations used for this calculation always tended to overestimate the amount of radiant heat transfer it is felt that the percentage found is probably too high.

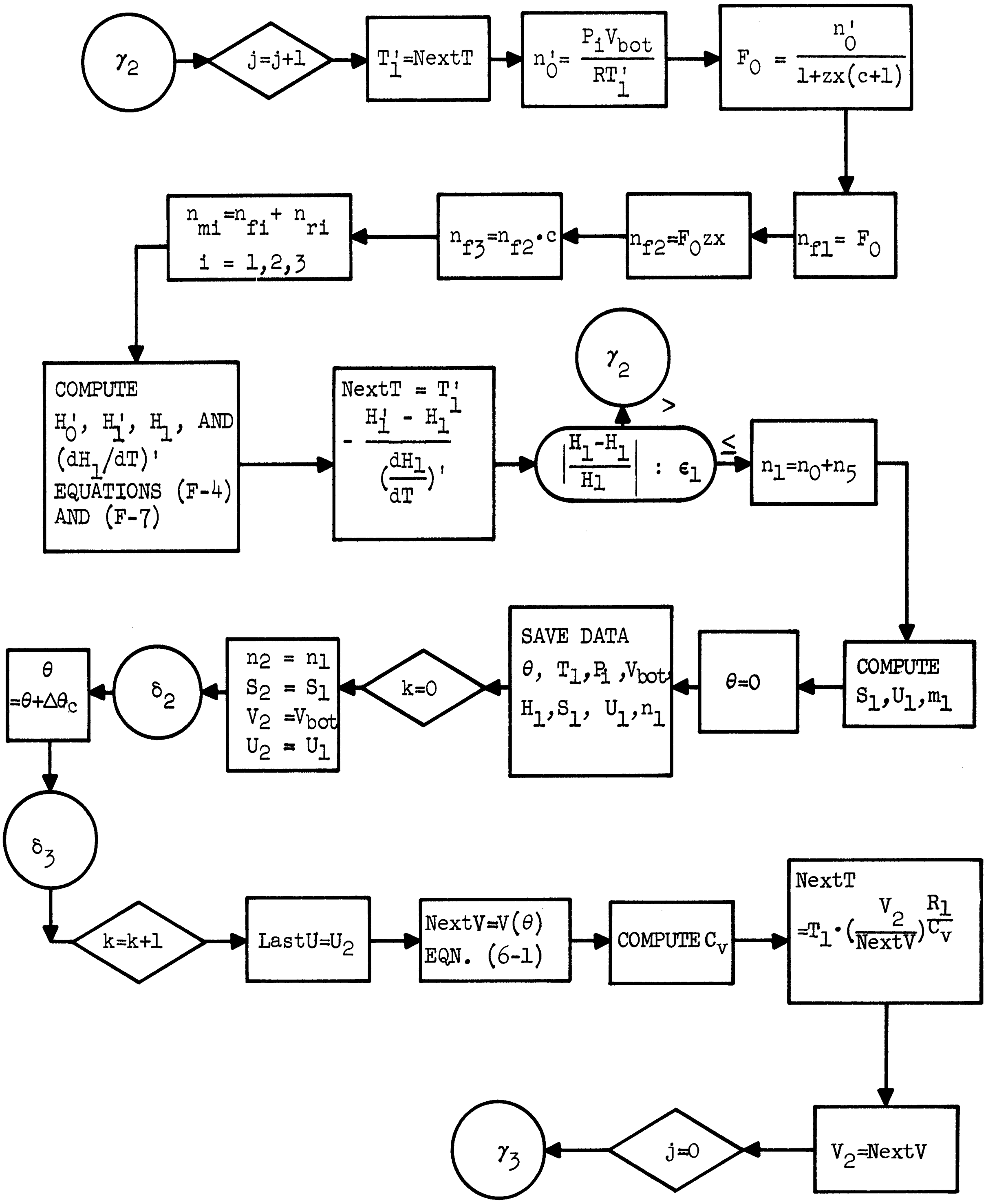
APPENDIX I

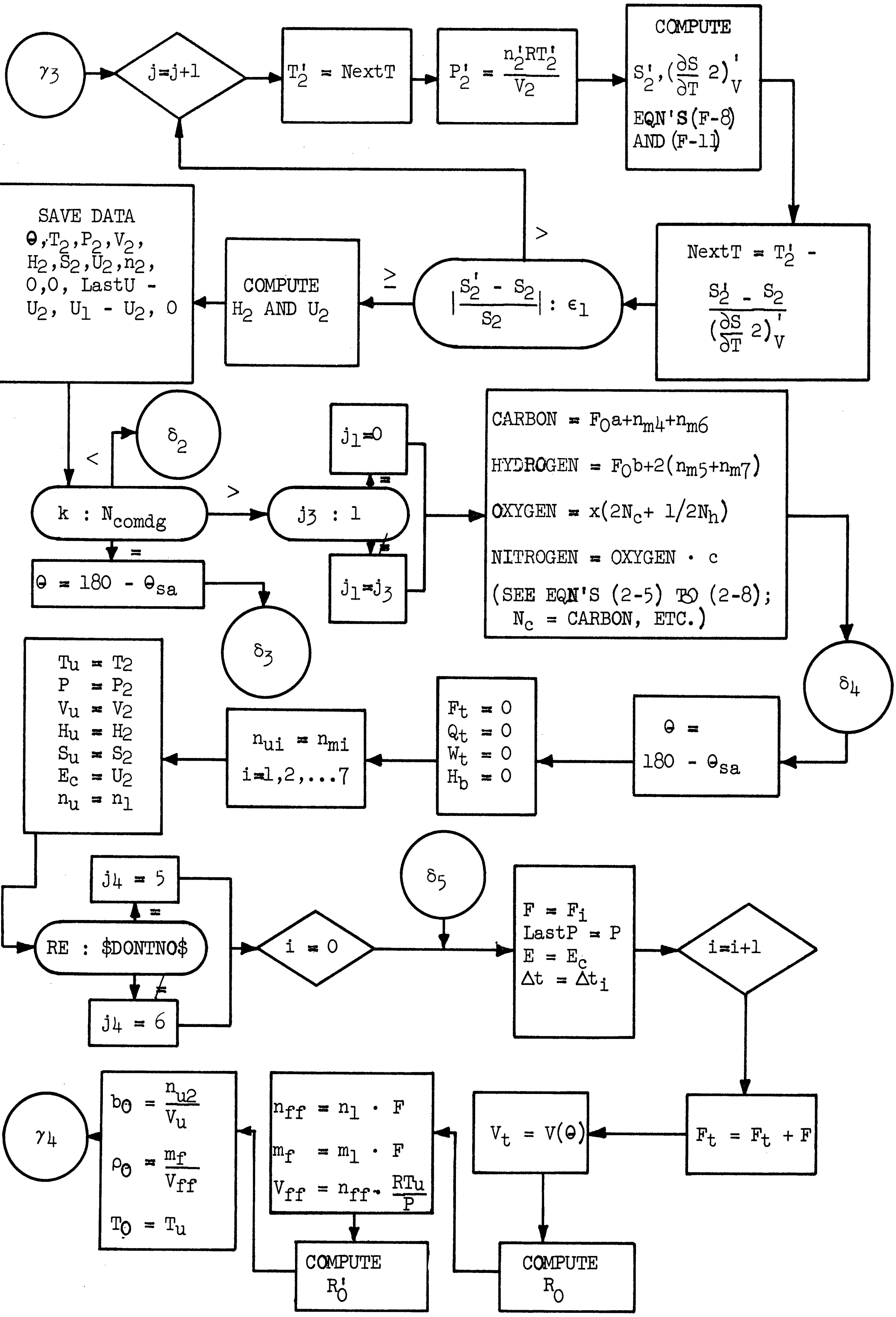
FLOW DIAGRAM AND PROGRAM LISTING FOR THE ANALYTICAL MODEL

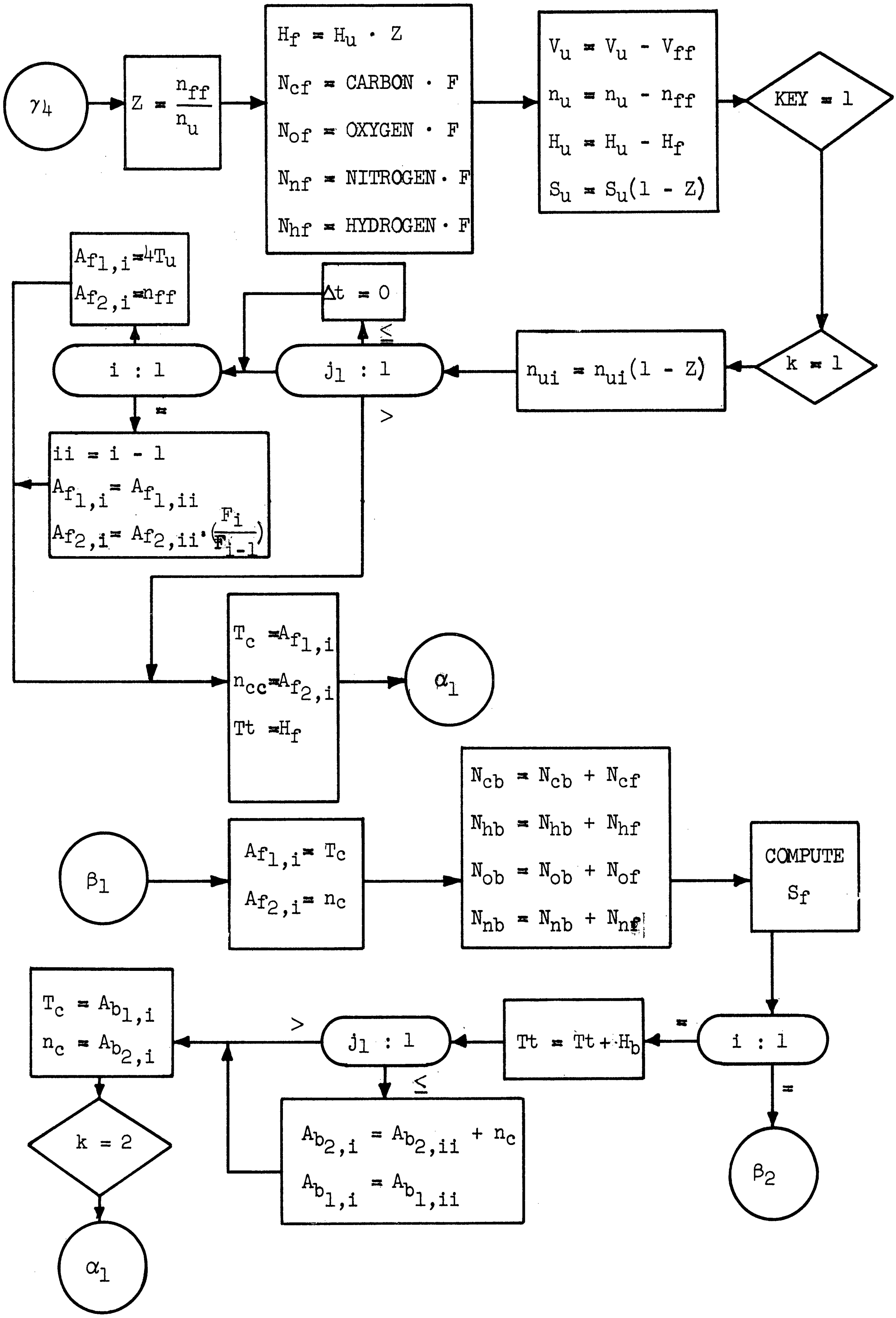
A. Flow Diagram

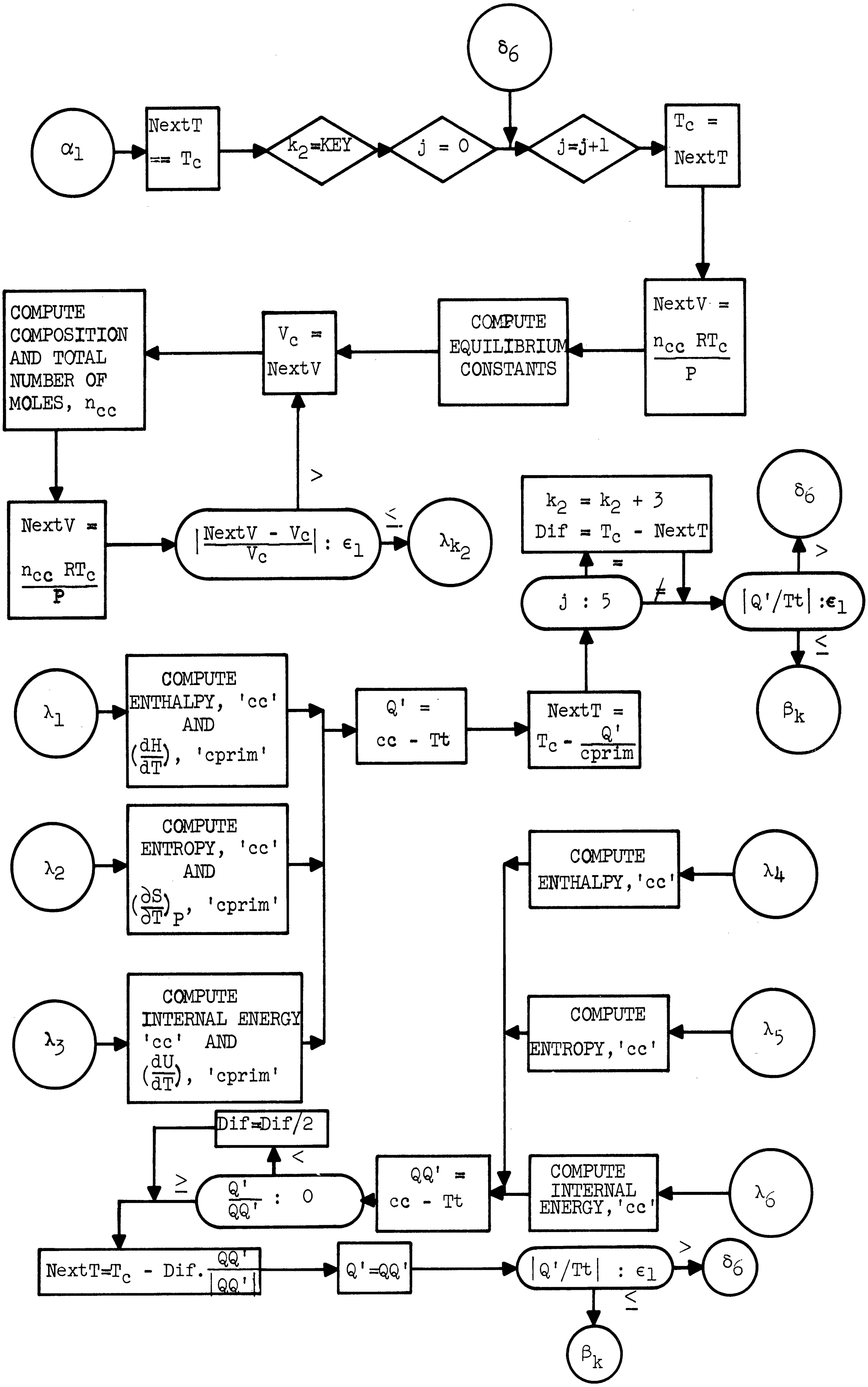


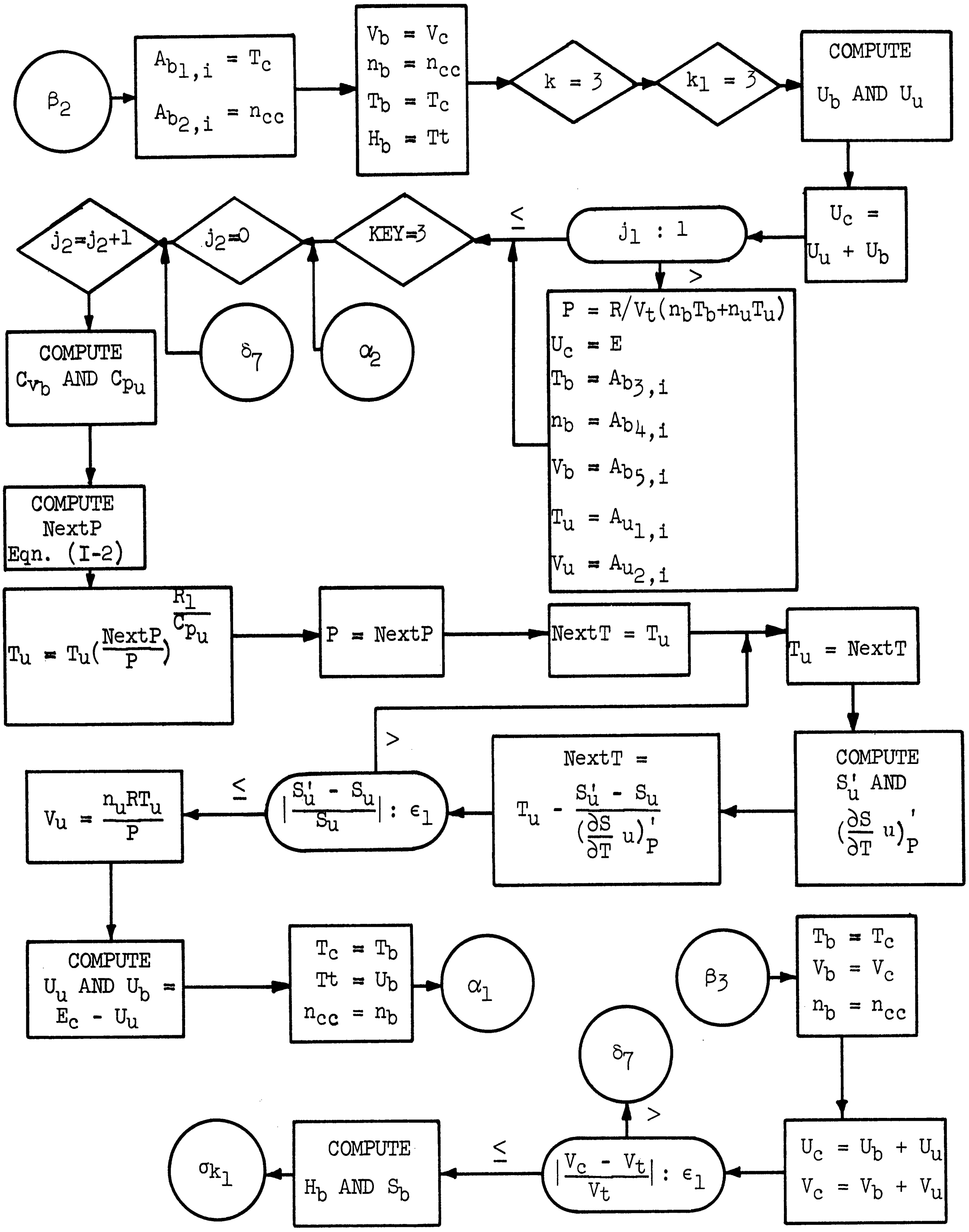

γ_1
$n = \frac{P_e V_{top}}{RT_e}$
$N_c = a$
$N_h = b$
$N_0 = x(2N_c + \frac{1}{2}N_h)$
$N_n = c \cdot N_0$
$n_c = a + b/2$
$+ z(cx + x - 1)$
$\text{NextV} = \frac{n_c RT_e}{P_e}$
COMPUTE EQUILIBRIUM CONSTANTS
$V_c = \text{NextV}$
COMPUTE COMPOSITION (THE n_{ri} AND n_c')
$\text{NextV} = \frac{n_c' R}{P_e T_e}$
$\left|\frac{\text{NextV} - V_c}{V_c}\right| : \epsilon_1$
>
≤
$f_5 = \frac{V_{top}}{V_c}$
$n_{r2} = f_5\left[n_{r2} + (n_{r9} + n_{r10} + n_{r8})/2\right]$
$n_{r3} = f_5(n_{r3} + n_{r9}/2)$
$n_{r7} = f_5\left[n_{r7} + (n_{r8} + n_{r11})/2\right]$
$n_{ri} = f_5 \cdot n_{ri}$
$i = 4, 5, 6$
δ_0
$n_5 = \frac{P_e V_{top}}{RT_e}$
$n_{tot} = \sum_{i=1}^{r} n_{pi}$
$n_{ri} = \frac{n_5}{n_{tot}} \cdot n_{pi}$
$i = 1, 2, \ldots 7$
CALCULATE H_5, S_5, AND U_5
$j_3 = j_3 + 1$
$n_{mi} = n_{ri}$
$i = 4, 5, 6, 7$
$j = 0$
$j_3 : 1$
=
≠
$T_1 = T_i$
$\text{NextT} = T_1$
γ_2

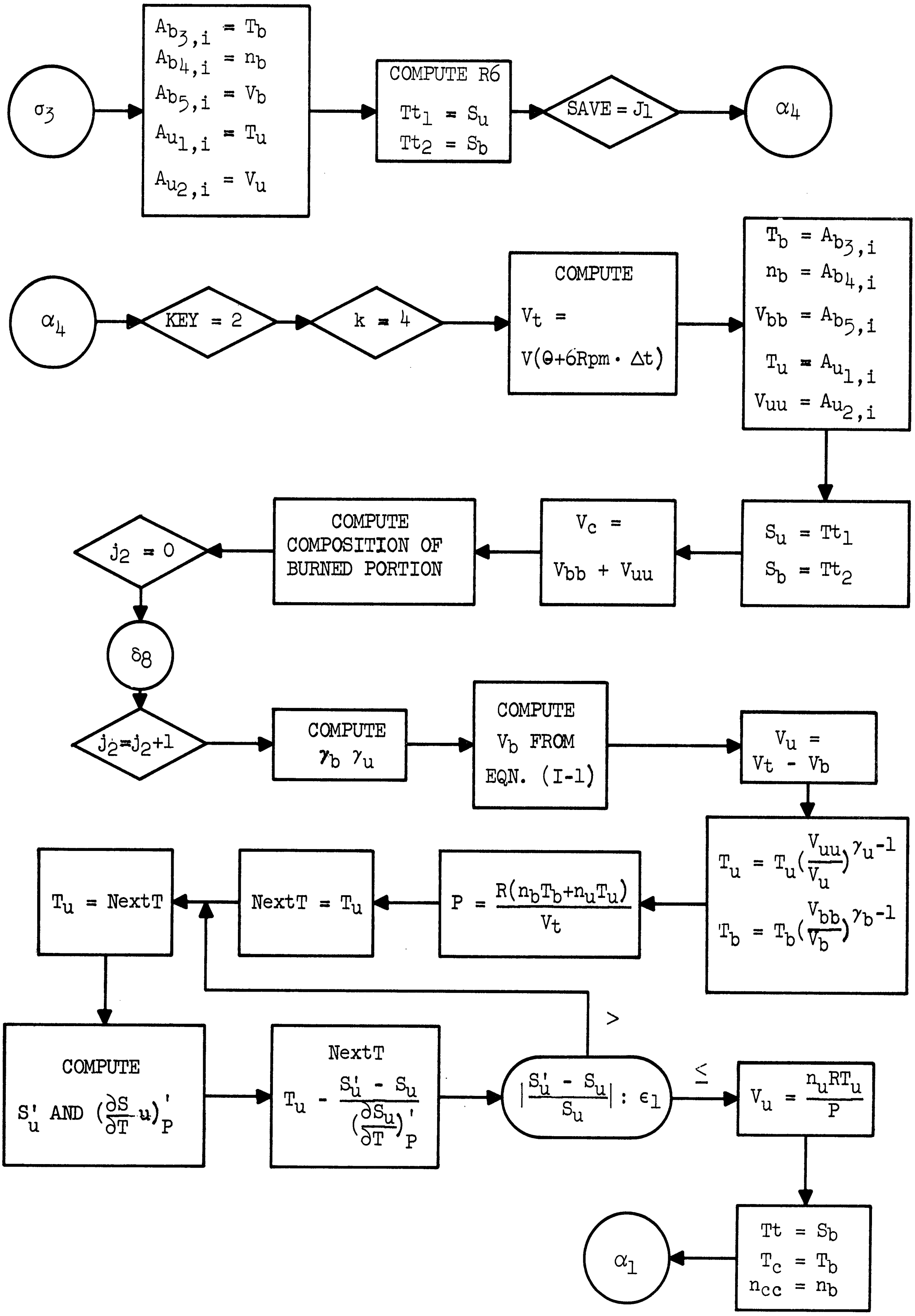

γ2
j=j+1
T'1=NextT
n'0= PiVbot / RT'1
F0 = n'0 / 1+zx(c+1)
nf1= F0
nf2=F0zx
nf3=nf2·c
nmi=nfi+ nri
i = 1,2,3
COMPUTE
H'0, H'1, H1, AND
(dH1/dT)'
EQUATIONS (F-4)
AND (F-7)
NextT = T'1 - H'1 - H1 / (dH1/dT)'
γ2
>
|H1-H1 / H1| : ε1
≤
n1=n0+n5
COMPUTE
S1,U1,m1
θ=0
SAVE DATA
θ, T1,P1 ,Vbot,
H1,S1, U1,n1
k=0
n2 = n1
S2 = S1
V2 =Vbot
U2 = U1
δ2
θ
=θ+Δθc
δ3
k=k+1
LastU=U2
NextV=V(θ)
EQN. (6-1)
COMPUTE Cv
NextT
=T1·(V2/NextV)^(R1/Cv)
V2=NextV
j=0
γ3

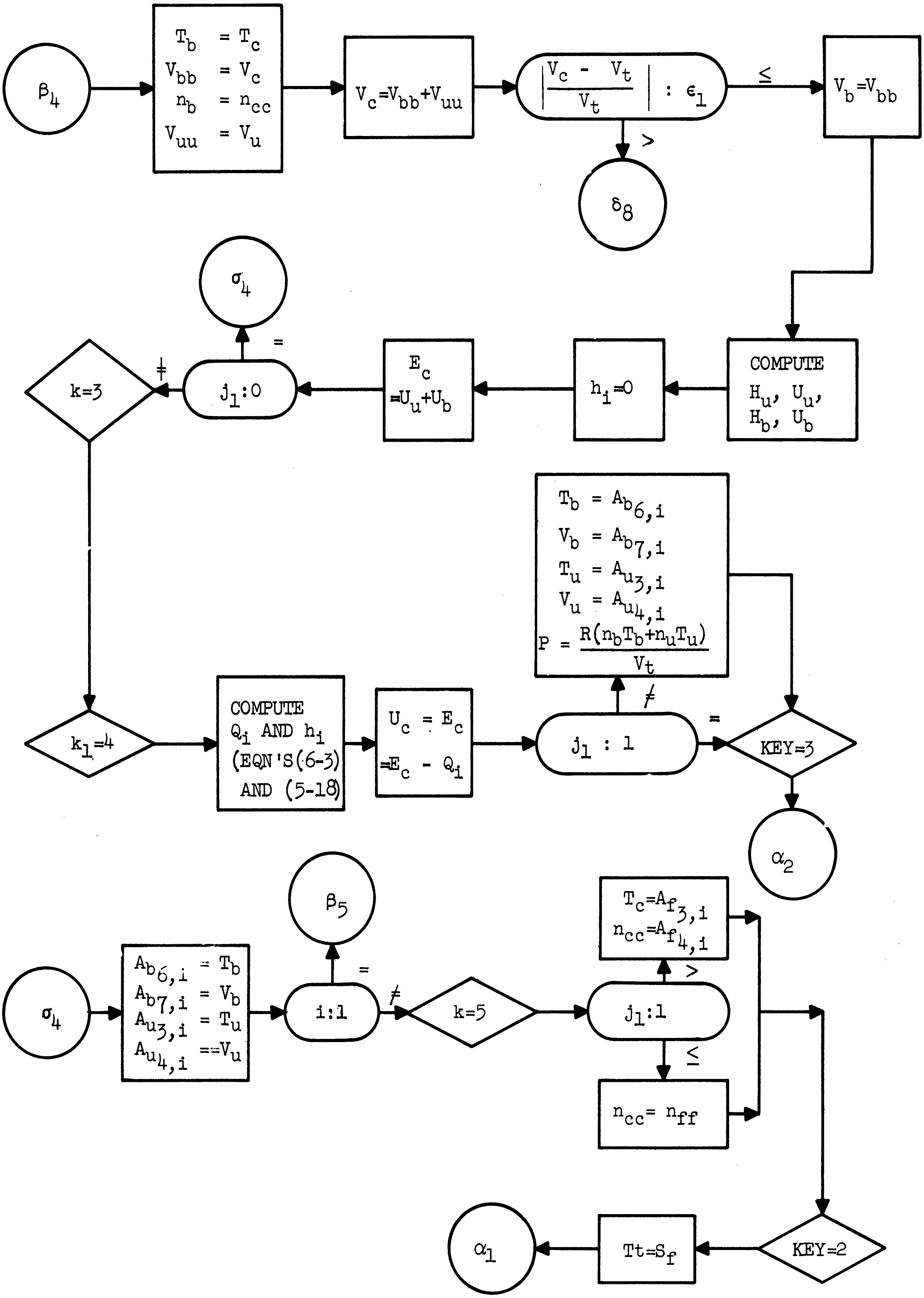

γ3
j=j+1
$T_2' = \text{NextT}$
$P_2' = \frac{n_2' R T_2'}{V_2}$
COMPUTE
$S_2', (\frac{\partial S}{\partial T} 2)_V'$
EQN'S (F-8) AND (F-11)
NextT = $T_2' - \frac{S_2' - S_2}{(\frac{\partial S}{\partial T} 2)_V'}$
$|\frac{S_2' - S_2}{S_2}| : \epsilon_1$
>
≥
COMPUTE H_2 AND U_2
SAVE DATA
$\Theta, T_2, P_2, V_2, H_2, S_2, U_2, n_2,$ 0,0, LastU - U_2, $U_1 - U_2$, 0
δ2
<
$k : N_{comdg}$
>
=
$\Theta = 180 - \Theta_{sa}$
δ3
$j_3 : 1$
$j_1 = 0$
=
≠
$j_1 = j_3$
CARBON = $F_0 a + n_{m4} + n_{m6}$
HYDROGEN = $F_0 b + 2(n_{m5} + n_{m7})$
OXYGEN = $x(2N_c + 1/2N_h)$
NITROGEN = OXYGEN · c
(SEE EQN'S (2-5) TO (2-8); N_c = CARBON, ETC.)
δ4
$\Theta = 180 - \Theta_{sa}$
$F_t = 0$
$Q_t = 0$
$W_t = 0$
$H_b = 0$
$n_{ui} = n_{mi}$
i=1,2,...7
$T_u = T_2$
$P = P_2$
$V_u = V_2$
$H_u = H_2$
$S_u = S_2$
$E_c = U_2$
$n_u = n_1$
RE : \$DONTNO\$
=
$j_4 = 5$
≠
$j_4 = 6$
i = 0
δ5
$F = F_i$
LastP = P
$E = E_c$
$\Delta t = \Delta t_i$
i=i+1
$F_t = F_t + F$
$V_t = V(\Theta)$
COMPUTE R_0
$n_{ff} = n_1 \cdot F$
$m_f = m_1 \cdot F$
$V_{ff} = n_{ff} \cdot \frac{RT_u}{P}$
COMPUTE R_0'
$b_0 = \frac{n_{u2}}{V_u}$
$\rho_0 = \frac{m_f}{V_{ff}}$
$T_0 = T_u$
γ4

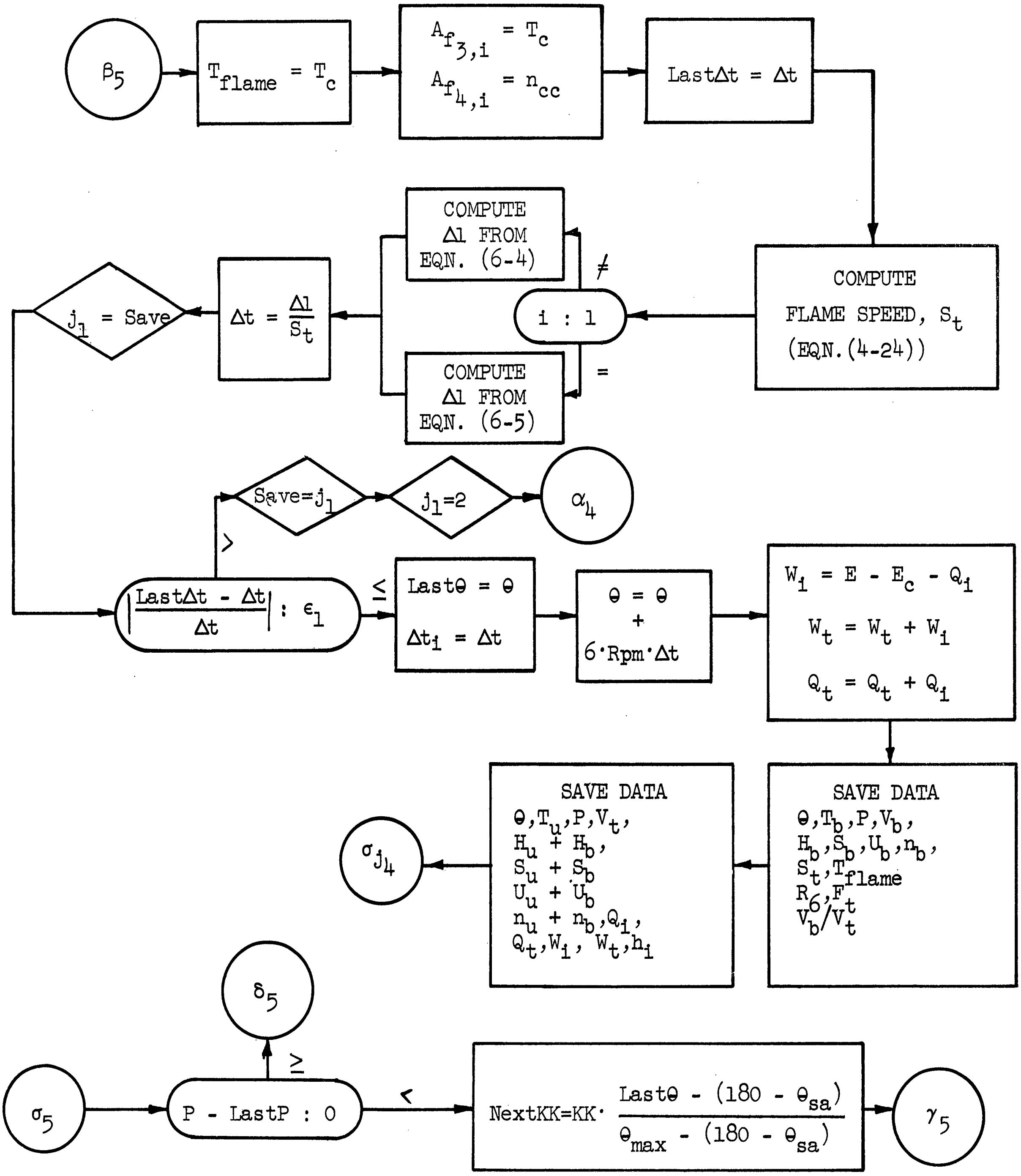

γ4
Z = n_ff / n_u
H_f = H_u · Z
N_cf = CARBON · F
N_of = OXYGEN · F
N_nf = NITROGEN · F
N_hf = HYDROGEN · F
V_u = V_u - V_ff
n_u = n_u - n_ff
H_u = H_u - H_f
S_u = S_u(1 - Z)
KEY = 1
k = 1
n_ui = n_ui(1 - Z)
j1 : 1
≤
>
Δt = 0
i : 1
=
Af1,i = 4Tu
Af2,i = nff
ii = i - 1
Af1,i = Af1,ii
Af2,i = Af2,ii · (Fi / Fi-1)
Tc = Af1,i
ncc = Af2,i
Tt = Hf
α1
β1
Af1,i = Tc
Af2,i = nc
Ncb = Ncb + Ncf
Nhb = Nhb + Nhf
Nob = Nob + Nof
Nnb = Nnb + Nnf
COMPUTE
Sf
i : 1
=
=
β2
Tt = Tt + Hb
j1 : 1
>
≤
Ab2,i = Ab2,ii + nc
Ab1,i = Ab1,ii
Tc = Ab1,i
nc = Ab2,i
k = 2
α1

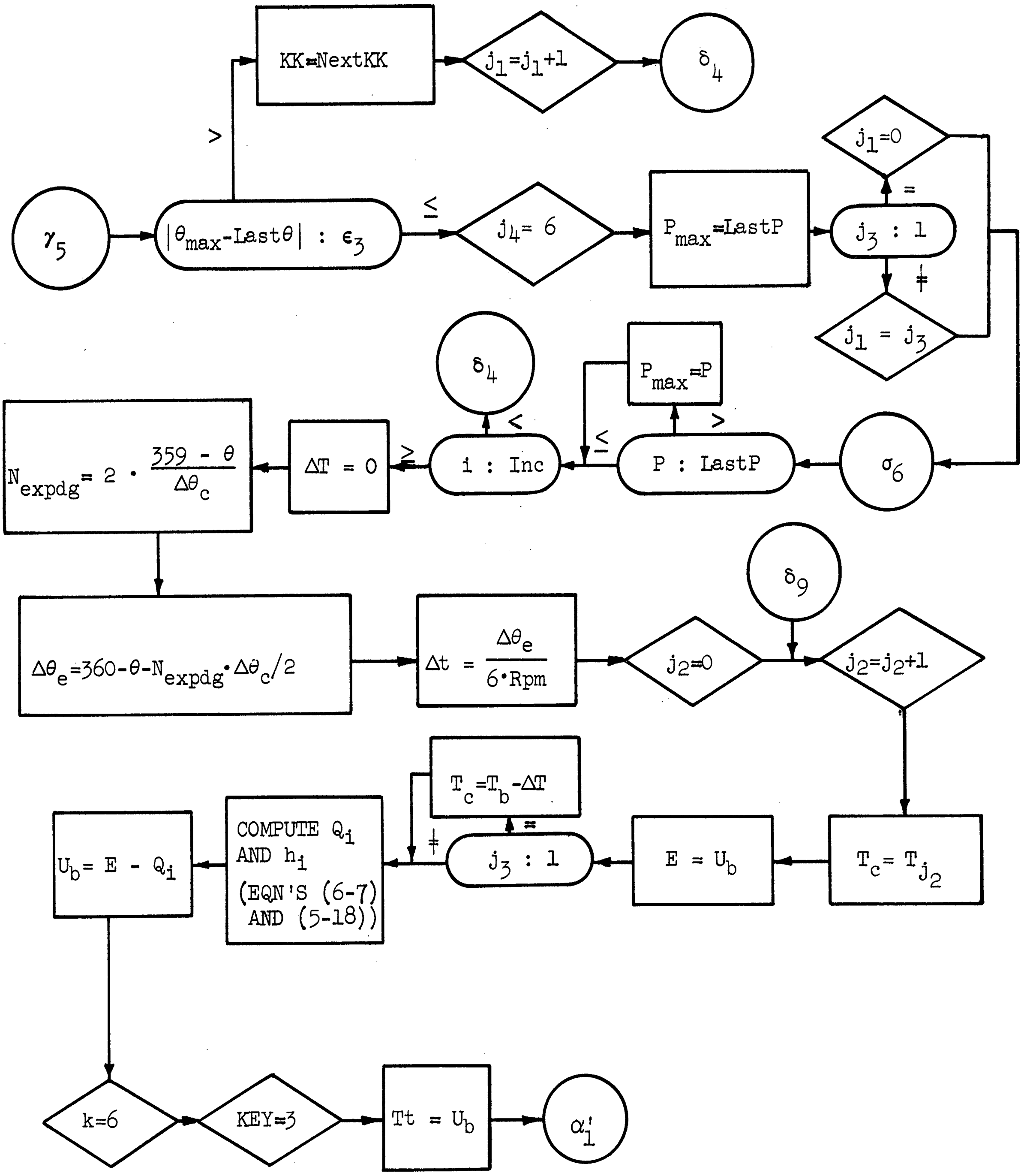

δ_6
α_1
NextT == T_c
k_2=KEY
j = 0
j=j+1
T_c = NextT
NextV = $\frac{n_{cc} RT_c}{P}$
COMPUTE EQUILIBRIUM CONSTANTS
V_c = NextV
COMPUTE COMPOSITION AND TOTAL NUMBER OF MOLES, n_{cc}
NextV = $\frac{n_{cc} RT_c}{P}$
$\left|\frac{NextV - V_c}{V_c}\right| : \epsilon_1$
>
≤
λ_{k_2}
$k_2 = k_2 + 3$
Dif = T_c - NextT
=
j : 5
≠
$|Q'/Tt| : \epsilon_1$
>
≤
δ_6
β_k
λ_1
COMPUTE ENTHALPY, 'cc' AND $(\frac{dH}{dT})$, 'cprim'
λ_2
COMPUTE ENTROPY, 'cc' AND $(\frac{\partial S}{\partial T})_P$, 'cprim'
λ_3
COMPUTE INTERNAL ENERGY 'cc' AND $(\frac{dU}{dT})$, 'cprim'
Q' = cc - Tt
NextT = $T_c - \frac{Q'}{cprim}$
λ_4
COMPUTE ENTHALPY,'cc'
λ_5
COMPUTE ENTROPY,'cc'
λ_6
COMPUTE INTERNAL ENERGY,'cc'
QQ' = cc - Tt
$\frac{Q'}{QQ'}$: 0
<
≥
Dif=Dif/2
NextT=T_c - Dif.$\frac{QQ'}{|QQ'|}$
Q'=QQ'
$|Q'/Tt| : \epsilon_1$
>
≤
δ_6
β_k

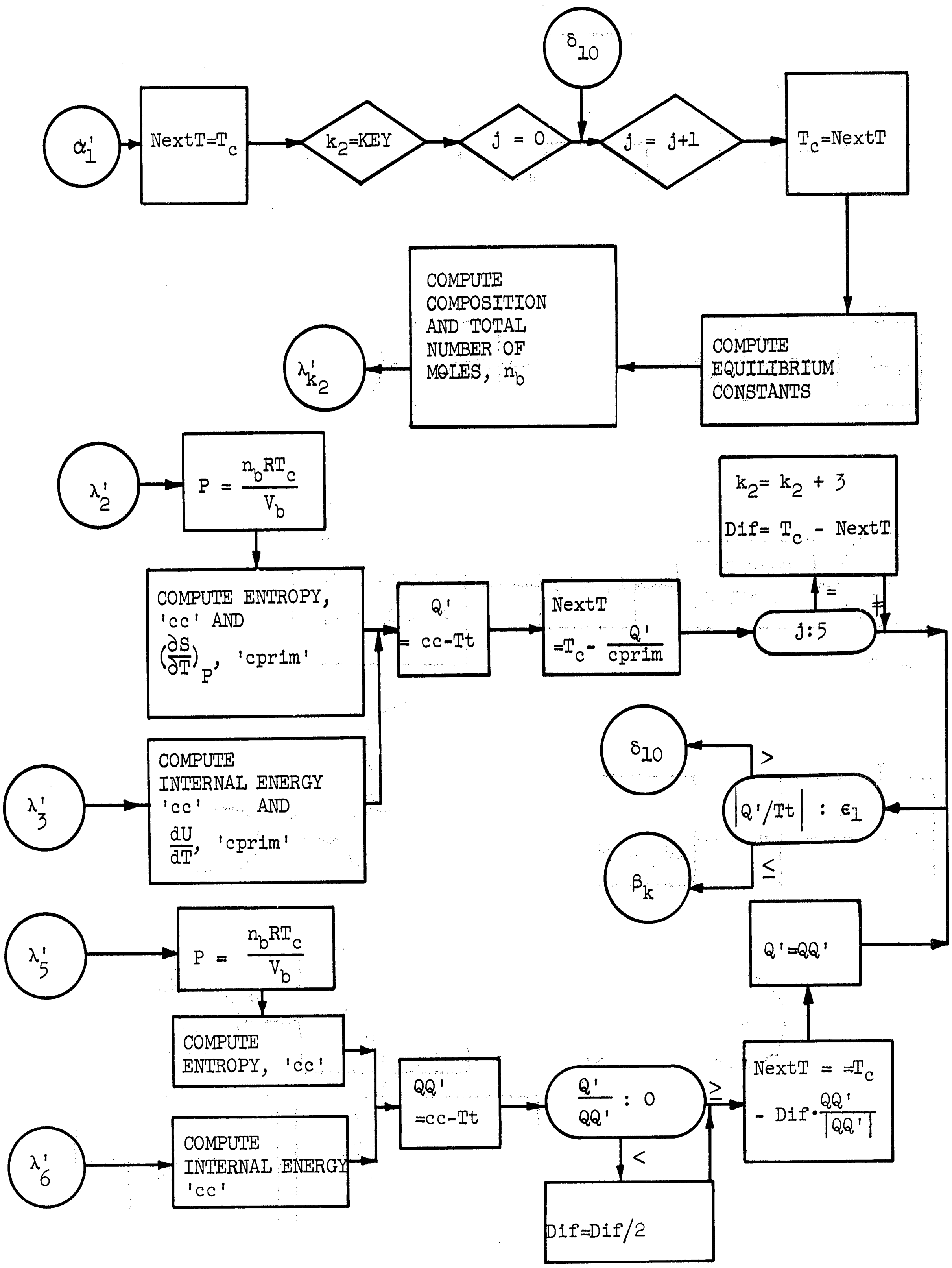

β_2
$A_{b1,i} = T_c$
$A_{b2,i} = n_{cc}$
$V_b = V_c$
$n_b = n_{cc}$
$T_b = T_c$
$H_b = Tt$
$k = 3$
$k_1 = 3$
COMPUTE U_b AND U_u
$U_c = U_u + U_b$
$j_1 : 1$
$\leq$
$>$
$P = R/V_t(n_bT_b+n_uT_u)$
$U_c = E$
$T_b = A_{b3,i}$
$n_b = A_{b4,i}$
$V_b = A_{b5,i}$
$T_u = A_{u1,i}$
$V_u = A_{u2,i}$
KEY=3
$j_2=0$
$j_2=j_2+1$
α_2
δ_7
COMPUTE C_{v_b} AND C_{p_u}
COMPUTE NextP Eqn. (I-2)
$T_u = T_u(\frac{NextP}{P})^{\frac{R_1}{C_{p_u}}}$
P = NextP
NextT = T_u
T_u = NextT
COMPUTE S'_u AND $(\frac{\partial S}{\partial T}u)'_P$
NextT = $T_u - \frac{S'_u - S_u}{(\frac{\partial S}{\partial T}u)'_P}$
$|\frac{S'_u - S_u}{S_u}| : \epsilon_1$
$>$
$\leq$
$V_u = \frac{n_uRT_u}{P}$
COMPUTE U_u AND $U_b = E_c - U_u$
$T_c = T_b$
$Tt = U_b$
$n_{cc} = n_b$
α_1
β_3
$T_b = T_c$
$V_b = V_c$
$n_b = n_{cc}$
$U_c = U_b + U_u$
$V_c = V_b + V_u$
$|\frac{V_c - V_t}{V_t}| : \epsilon_1$
$>$
δ_7
$\leq$
COMPUTE H_b AND S_b
σk_1

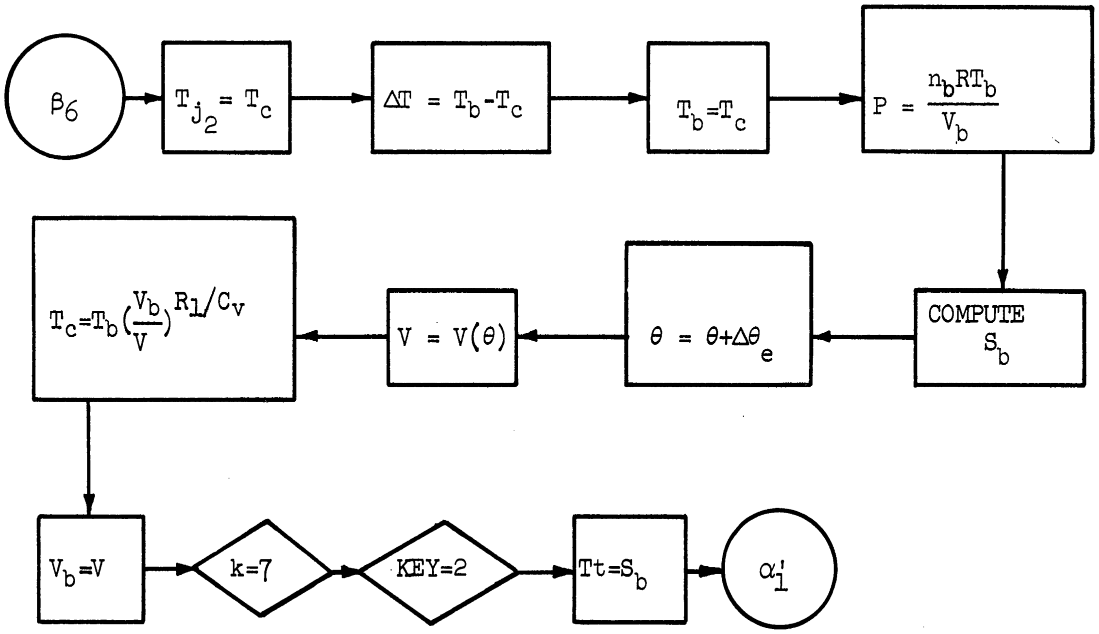

σ_3
$A_{b3,i} = T_b$
$A_{b4,i} = n_b$
$A_{b5,i} = V_b$
$A_{u1,i} = T_u$
$A_{u2,i} = V_u$
COMPUTE R6
$Tt_1 = S_u$
$Tt_2 = S_b$
SAVE = J1
α_4
α_4
KEY = 2
k = 4
COMPUTE
$V_t =$
$V(\Theta+6Rpm \cdot \Delta t)$
$T_b = A_{b3,i}$
$n_b = A_{b4,i}$
$V_{bb} = A_{b5,i}$
$T_u = A_{u1,i}$
$V_{uu} = A_{u2,i}$
$S_u = Tt_1$
$S_b = Tt_2$
$V_c =$
$V_{bb} + V_{uu}$
COMPUTE COMPOSITION OF BURNED PORTION
$j_2 = 0$
δ_8
$j_2 = j_2 + 1$
COMPUTE
$\gamma_b\ \gamma_u$
COMPUTE
V_b FROM
EQN. (I-1)
$V_u =$
$V_t - V_b$
$T_u = T_u\left(\frac{V_{uu}}{V_u}\right)^{\gamma_u - 1}$
$T_b = T_b\left(\frac{V_{bb}}{V_b}\right)^{\gamma_b - 1}$
$P = \frac{R(n_b T_b + n_u T_u)}{V_t}$
NextT = T_u
T_u = NextT
COMPUTE
S_u' AND $\left(\frac{\partial S}{\partial T}u\right)_P'$
NextT
$T_u - \frac{S_u' - S_u}{\left(\frac{\partial S_u}{\partial T}\right)_P'}$
$\left|\frac{S_u' - S_u}{S_u}\right| : \epsilon_1$
$>$
$\leq$
$V_u = \frac{n_u R T_u}{P}$
$Tt = S_b$
$T_c = T_b$
$n_{cc} = n_b$
α_1

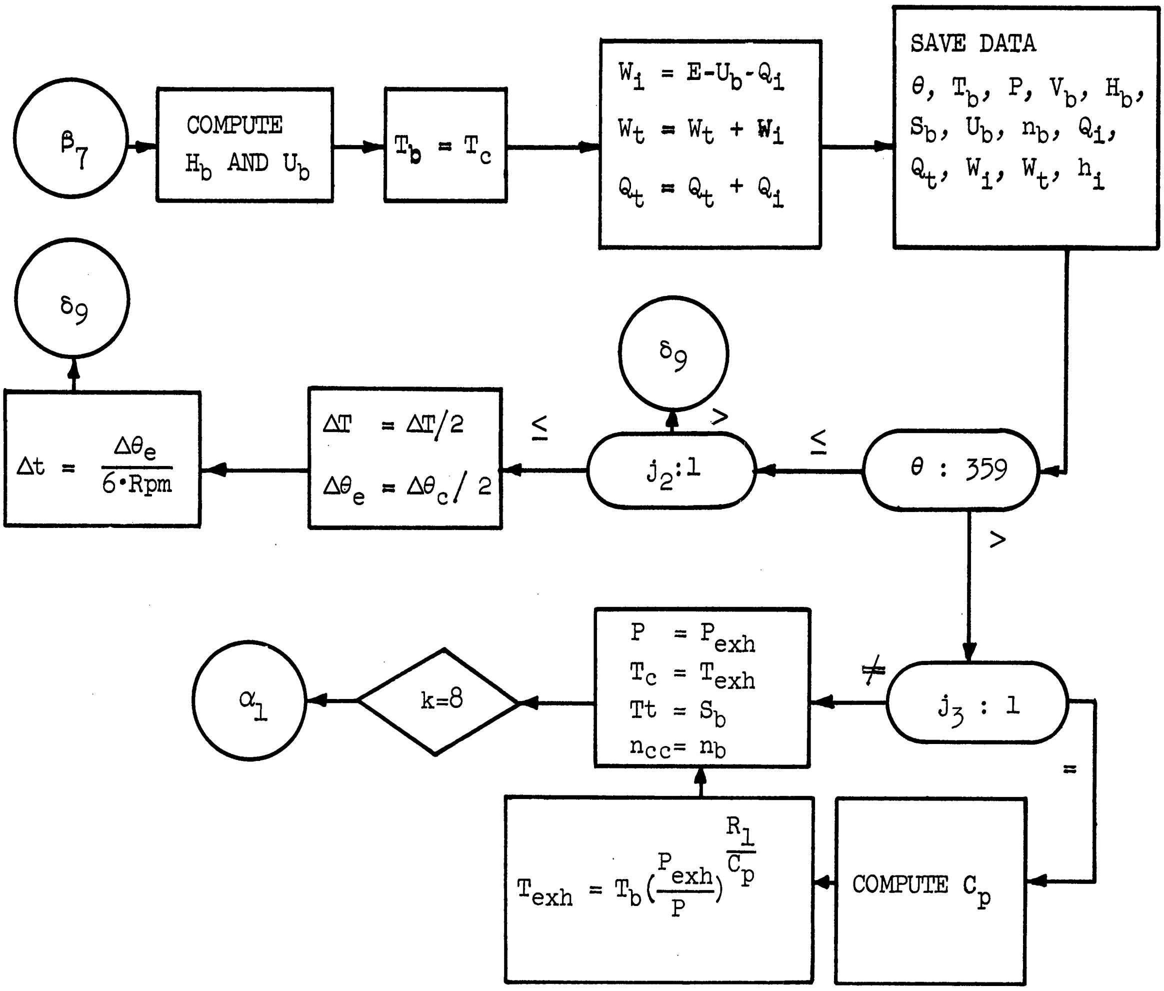

β4
Tb = Tc
Vbb = Vc
nb = ncc
Vuu = Vu
Vc=Vbb+Vuu
|(Vc - Vt)/Vt| : ε1
≤
>
δ8
Vb=Vbb
COMPUTE
Hu, Uu,
Hb, Ub
hi=0
Ec
=Uu+Ub
j1:0
=
σ4
≠
k=3
k1=4
COMPUTE
Qi AND hi
(EQN'S(6-3)
AND (5-18)
Uc = Ec
=Ec - Qi
j1 : 1
≠
Tb = Ab6,i
Vb = Ab7,i
Tu = Au3,i
Vu = Au4,i
P = R(nbTb+nuTu)/Vt
=
KEY=3
α2
σ4
Ab6,i = Tb
Ab7,i = Vb
Au3,i = Tu
Au4,i = Vu
i:1
=
β5
≠
k=5
j1:1
>
Tc=Af3,i
ncc=Af4,i
≤
ncc= nff
KEY=2
Tt=Sf
α1

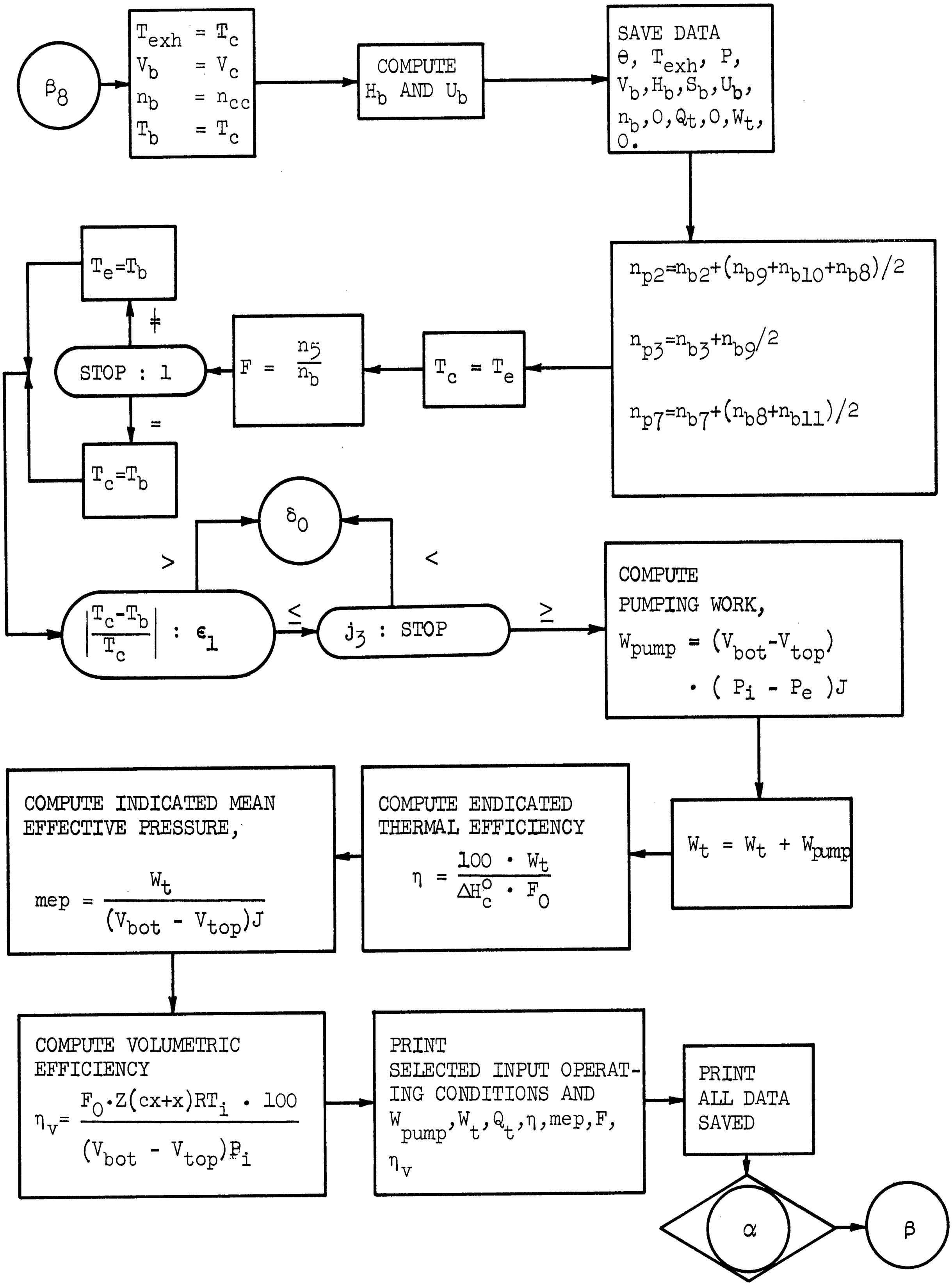

β_5
$T_{flame} = T_c$
$A_{f_{3,i}} = T_c$
$A_{f_{4,i}} = n_{cc}$
$Last\Delta t = \Delta t$
COMPUTE FLAME SPEED, S_t (EQN. (4-24))
$i : 1$
$\neq$
$=$
COMPUTE Δl FROM EQN. (6-4)
COMPUTE Δl FROM EQN. (6-5)
$\Delta t = \frac{\Delta l}{S_t}$
$j_1 = Save$
$\left|\frac{Last\Delta t - \Delta t}{\Delta t}\right| : \epsilon_1$
$>$
$Save = j_1$
$j_1 = 2$
α_4
$\leq$
$Last\theta = \theta$
$\Delta t_i = \Delta t$
$\theta = \theta + 6 \cdot Rpm \cdot \Delta t$
$W_i = E - E_c - Q_i$
$W_t = W_t + W_i$
$Q_t = Q_t + Q_i$
SAVE DATA
$\theta, T_b, P, V_b,$
$H_b, S_b, U_b, n_b,$
S_t, T_{flame}
R_6, F_t
V_b/V_t
SAVE DATA
$\theta, T_u, P, V_t,$
$H_u + H_b,$
$S_u + S_b$
$U_u + U_b$
$n_u + n_b, Q_i,$
Q_t, W_i, W_t, h_i
σ_{j_4}
δ_5
$\geq$
σ_5
$P - LastP : 0$
$<$
$NextKK = KK \cdot \frac{Last\theta - (180 - \theta_{sa})}{\theta_{max} - (180 - \theta_{sa})}$
γ_5


γ_5
$|\theta_{max}$-Last$\theta|$: ϵ_3
>
KK=NextKK
$j_1=j_1+1$
δ_4
≤
$j_4= 6$
P_{max}=LastP
j_3 : 1
=
$j_1=0$
≠
$j_1 = j_3$
σ_6
P : LastP
>
P_{max}=P
≤
i : Inc
<
δ_4
≥
$\Delta T = 0$
$N_{expdg}= 2 \cdot \frac{359 - \theta}{\Delta\theta_c}$
$\Delta\theta_e=360-\theta-N_{expdg}\cdot\Delta\theta_c/2$
$\Delta t = \frac{\Delta\theta_e}{6\cdot Rpm}$
$j_2=0$
δ_9
$j_2=j_2+1$
$T_c= T_{j_2}$
$E = U_b$
j_3 : 1
=
$T_c=T_b-\Delta T$
≠
COMPUTE Q_i AND h_i (EQN'S (6-7) AND (5-18))
$U_b= E - Q_i$
k=6
KEY=3
Tt = U_b
α_1'


α_1'
NextT=T_c
k_2=KEY
j = 0
δ_{10}
j = j+1
T_c=NextT
COMPUTE EQUILIBRIUM CONSTANTS
COMPUTE COMPOSITION AND TOTAL NUMBER OF MOLES, n_b
λ'_{k_2}
λ'_2
$P = \frac{n_b R T_c}{V_b}$
COMPUTE ENTROPY, 'cc' AND $(\frac{\partial S}{\partial T})_P$, 'cprim'
λ'_3
COMPUTE INTERNAL ENERGY 'cc' AND $\frac{dU}{dT}$, 'cprim'
Q' = cc-Tt
NextT =T_c- $\frac{Q'}{\text{cprim}}$
j:5
=
≠
k_2= k_2 + 3
Dif= T_c - NextT
δ_{10}
>
$|Q'/Tt| : \epsilon_1$
≤
β_k
Q'=QQ'
λ'_5
$P = \frac{n_b R T_c}{V_b}$
COMPUTE ENTROPY, 'cc'
λ'_6
COMPUTE INTERNAL ENERGY 'cc'
QQ' =cc-Tt
$\frac{Q'}{QQ'}$: 0
≥
<
Dif=Dif/2
NextT = T_c - Dif$\cdot\frac{QQ'}{|QQ'|}$


β6
T_{j2} = T_c
ΔT = T_b - T_c
T_b = T_c
P = n_b R T_b / V_b
COMPUTE S_b
θ = θ+Δθ_e
V = V(θ)
T_c = T_b (V_b/V)^{R1/Cv}
V_b = V
k=7
KEY=2
Tt=S_b
α'_1


β7
COMPUTE H_b AND U_b
T_b = T_c
W_i = E-U_b-Q_i
W_t = W_t + W_i
Q_t = Q_t + Q_i
SAVE DATA
θ, T_b, P, V_b, H_b, S_b, U_b, n_b, Q_i, Q_t, W_i, W_t, h_i
θ : 359
≤
>
j_2:1
≤
>
δ9
ΔT = ΔT/2
Δθ_e = Δθ_c/ 2
Δt = Δθ_e / 6·Rpm
δ9
j_3 : 1
≠
=
P = P_exh
T_c = T_exh
Tt = S_b
n_cc= n_b
k=8
α_1
COMPUTE C_p
T_exh = T_b (P_exh/P)^{R1/Cp}


β_8
$T_{exh} = T_c$
$V_b = V_c$
$n_b = n_{cc}$
$T_b = T_c$
COMPUTE H_b AND U_b
SAVE DATA θ, T_{exh}, P, V_b, H_b, S_b, U_b, n_b, 0, Q_t, 0, W_t, 0.
$n_{p2} = n_{b2} + (n_{b9} + n_{b10} + n_{b8})/2$
$n_{p3} = n_{b3} + n_{b9}/2$
$n_{p7} = n_{b7} + (n_{b8} + n_{b11})/2$
$T_c = T_e$
$F = \frac{n_5}{n_b}$
STOP : 1
$\neq$
$T_e = T_b$
=
$T_c = T_b$
δ_0
>
<
$\left|\frac{T_c - T_b}{T_c}\right| : \epsilon_1$
$\leq$
j_3 : STOP
$\geq$
COMPUTE PUMPING WORK,
$W_{pump} = (V_{bot} - V_{top}) \cdot (P_i - P_e) J$
$W_t = W_t + W_{pump}$
COMPUTE ENDICATED THERMAL EFFICIENCY
$\eta = \frac{100 \cdot W_t}{\Delta H_c^0 \cdot F_0}$
COMPUTE INDICATED MEAN EFFECTIVE PRESSURE,
$mep = \frac{W_t}{(V_{bot} - V_{top}) J}$
COMPUTE VOLUMETRIC EFFICIENCY
$\eta_v = \frac{F_0 \cdot Z(cx+x) RT_i \cdot 100}{(V_{bot} - V_{top}) P_i}$
PRINT SELECTED INPUT OPERATING CONDITIONS AND W_{pump}, W_t, Q_t, η, mep, F, η_v
PRINT ALL DATA SAVED
α
β

B. Explanation of Symbols Used in Flow Diagram and Computer Program

Symbol used in Flow Diagram	Meaning	Symbol used in Computer Program
A_L	matrix of constants for empirical heat capacity equations in temperature range 298.16 - 1500°K and fundamental data at 298.16°K (see Tables I and II)	AL
A_H	matrix of constants for empirical heat capacity equations in temperature range 1500 - 3500°K and fundamental data at 1500°K (see Tables I and II)	AH
A_h	surface area of combustion chamber head - cm^2	ATOT (1 or 2)
A_{pb}	piston head surface exposed to burned gas - cm^2	ANS (3)
A_{pu}	piston head surface exposed to unburned gas - cm^2	ANS (4)
A_{wb}	wall surface exposed to burned gas - cm^2	ANS (1)
A_{wu}	wall surface exposed to unburned gas - cm^2	ANS (2)
A_{pt}	total piston head surface area - cm^2	ATOT (3 or 4)
A_{wt}	total exposed wall area - cm^2	ARAA
$A_{f_{j,i}}, A_{b_{j,i}}, A_{u_{j,i}}$	three matrices in which are stored values of temperature, volume, and number of moles at selected points in each of the 'i' combustion increments	AF(j,i) AB(j,i) AU(j,i)
a	number of carbon atoms per molecule of fuel	A
Bore	engine bore - in	BORE
b	number of hydrogen atoms per molecule of fuel	B
b_0	density of oxygen molecules in flame element prior to combustion	BO

C_p	constant pressure heat capacity - cal/mole-°K	CP
C_v	constant volume heat capacity - cal mole-°K	CV
c	ratio of nitrogen to oxygen atoms in atmospheric air = 3.764	C
cc	trial value of a thermodynamic property	CC
cprime	trial value of the derivative of a thermodynamic property	CPRIM
Dif	an incremental change in temperature - °K	DIF
E	internal energy - cal	E
E_a	activation energy - cal/mole of fuel	EA
F	mass fraction of gas remaining in clearance volume - residual mass fraction	F
F_0	moles of fuel inducted	FO
F_t	total fraction of mass burned	FTOT
F_1-F_{Inc}	the Inc fractions into which the combustion process is divided	FR(1)...FR(INC)
H	enthalpy - cal	H
$\frac{dH}{dT}$	$\frac{dH}{dT} = C_p \cdot n$	HPRIM
h	convective heat transfer coefficient in portion - cal/cm^2-°K	COEF
Inc	number of increments into which the combustion process is divided	INC
j_3	number of times complete cycle has been executed	J3
KEY	type of process undergone during a given step by the burned portion or flame element Whenever KEY = 1, process is isenthalpic KEY = 2, process is isentropic and KEY = 3, process occurs at constant internal energy	KEY

kk_1-kk_{nk}	the n_k flame speed constants	KK(1)...KK(NK)
L_t	maximum extent of flame travel if combustion occurs at top center - cm	ATOT(5)
m_1	mass of charge in cylinder - gm	M1
m_f	mass of fresh charge inflamed - gm	MF
mep	indicated mean effective pressure - atm	IMEP
N_c, N_h, N_O, N_n or Carbon, Hydrogen, Oxygen, Nitrogen	mole atoms of carbon, hydrogen, oxygen, and nitrogen (see Equations (2-5) to (2-8))	NC,NH,NO,NN or CARBON,HYDRGN OXYGEN,NITRGN
N_{comdg}	number of compression increments	NCOMDG
N_{expdg}	number of expansion increments	NEXPDG
n	number of moles	N
n_b	total moles of burned gas	NB
n_u	total moles of unburned gas	NU
n_k	number of flame speed constants (K_1 Equation (4-24)) for which computations are to be made	NK
n_{bi}	moles of i-th component of burned mixture	N(i)
n_{fi}	moles of i-th component of flame element	NUN(i)
n_{mi}	moles of i-th component of unburned mixture prior to combustion	NUN(i)
n_{pi}	moles of i-th component of burned products during exhaust process	N(i)
n_{ri}	moles of i-th component of exhaust residual	N(i)
n_{ui}	moles of i-th component of unburned gas	NU(i)
n_{cc}	temporary designation of number of moles	NCC
n_{ff}	moles of fresh charge inflamed	NFF
n_{f-a}	number of air-fuel ratios for which computations are to be made	NFA
P	pressure - atm	P

P_e	exhaust pressure - atm	PEXH
P_i	intake manifold pressure - atm	PMAN
PH	an initial estimate of the value of $X = \sqrt{P_{O_2}}$ (This is used in the computation of the equilibrium composition)	PH
Q	heat transferred - cal	QB
Q_t	total heat transferred - cal	QTOT
q_k	number of heat transfer constants (by which the heat transfer coefficient, Equation (5-18), and subsequently the computed amount of heat transferred, Equation (5-19) are multiplied) for which computations are to be made	QK
$q_{fact_1} - q_{fact_{qk}}$	the q_k heat transfer constants	QFACT(1)... QFACT(QK)
R	gas constant in work units = 0.08205 l-atm/mole-°K	R
R_1	gas constant in heat units = 1.98719 cal/mole-°K	R1
R_0	flame front radius at end of (i-1)-st combustion increment	LASTL
R_0'	outer radius of reaction zone prior to combustion of i-th combustion increment	NEWL
R_6	flame front radius at end of i-th combustion increment	ANS(5)
Rod	connecting rod length - in	ROD
RE	remark - If RE is DONTNO it is assumed that the flame speed constant K_1, Equation (4-24), is not known	RE
r	compression ratio	CR
rpm	engine speed-rev/min	RPM
S	entropy - cal/°K	S
S_t	turbulent flame speed - cm/sec	ST

STOP	the maximum allowable number of times the complete cycle can be executed	STOP
Stroke	piston stroke - cm	STROKE
$(\frac{\partial S}{\partial T})_V$	$(\frac{\partial S}{\partial T})_V$	SPRIM
T	temperature - °K	T
T_e	exhaust temperature - °K	T5
T_{exh}	computed exhaust temperature - °K	TEXH
T_i	intake manifold temperature - °K	TMAN
T_{j_2}	temperature of the gas after the heat transfer step of the j_2-th expansion increment - °K	T(J1)
T_p	piston head surface temperature - °K	TPISTN
T_w	wall temperature - °K	TW
Tt	alternate designation of a thermodynamic property	TT
U	internal energy - cal	U
$\frac{dU}{dT}$	$\frac{dU}{dT} = C_v \cdot n$	HPRIM
V	volume - liters	V
V_t	total system volume - liters	VTOT
V_{ff}	volume of fresh charge inflamed - liters	VFF
V_{top}	clearance volume - liters	VTOP
V_{bot}	clearance plus swept volumes - liters	VBOT
W	work - cal	WORK
W_{pump}	pumping work - cal	WPUMP
W_t	total work performed - cal	WTOT
$x_1 - x_{n_{f-a}}$	the n_{f-a} air-fuel ratios (fraction chemically correct air)	X(1)...X(NFA)
Z	$Z = a + b/4$	Z

γ	ratio of heat capacity at constant pressure to that at constant volume	G
ΔH_c^o	enthalpy of combustion - cal/mole of fuel	HCOMB
Δl	extension of flame front due to chemical reaction	DS
Δt_i	time required for the combustion of the i-th increment	DT(i)
$\Delta\theta_c$	crank angle increments during the compression process	COMDG
$\Delta\theta_e$	crank angle increments during the expansion process	EXPDG
ϵ_1	allowable relative error in the thermodynamic properties	ERROR1
ϵ_2	allowable relative error in the composition of the products	ERROR2
ϵ_3	allowable absolute error between the calculated and experimental crank angles where maximum pressure occurs	ERROR3
η	indicated thermal efficiency - percent	EFF
η_v	volumetric efficiency - percent	VOLEFF
θ_{max}	crank angle where maximum pressure occurs ($\theta = 0°$ at bottom center and 180° at top center)	PIMAX
θ_{sa}	spark advance - degrees	PI
ρ_0	density of flame element prior to combustion - gr/liter	RH0

SUPERSCRIPTS

'	designates a trial value of a property	c

SUBSCRIPTS

b	burned	B
u	unburned	U

f	flame element	F
i	intake manifold	MAN
e	exhaust manifold	EXH

STATEMENT LABELS

α	end of computation for one data set	END
α_1	entry to section which finds $T = T(H \text{ or } S \text{ or } U \text{ and } P)$	ENTRY1
α_2	section which finds the pressure of the system with known volume and internal energy and known entropy in the burned portion	ENTRY2
α_4	entry point for change of volume due to piston motion	ENTRY4
α'_1	entry to section which finds $T = T\ (H \text{ or } S \text{ or } U \text{ and } V)$	ENTCY1
β	entry point for consideration of a second data set	BEGIN
β_1	end of constant pressure combustion of i-th flame element - Step 1	LOC(1)
β_2	end of constant pressure mixing	LOC(2)
β_3	end of recompression to original volume	LOC(3)
β_4	end of change of volume due to piston motion	LOC(4)
β_5	end of recompression of flame element to final pressure - Step 7	LOC(5)
β_6	end of constant volume heat transfer of j_2-th expansion increment	LCC(6)
β_7	end of isentropic change of volume due to piston motion	LCC(7)
γ_2	beginning of induction and mixing process	LOOOP3

δ_0	entry point for recomputation of cycle using a newly computed exhaust temperature	LOOOP1
δ_2	end of induction and beginning of stepwise compression process	LOOOP5
δ_4	end of compression process and entry to combustion process	RETURN
δ_5	beginning of combustion	ANOTHR
δ_9	beginning of j_2-th expansion increment	LCC1
λ_{1-3}	finds T using Newton's method	ENTRY(1-3)
λ'_{2-3}	finds T using Newton's method	ENTCY(2-3)
λ_{3-6}	finds T using half interval convergence method	ENTRY(4-6)
λ'_{5-6}	finds T using half interval convergence	ENTCY(5-6)
σ_4	end of heat transfer and constant volume readjustment of the i-th combustion increment - Step 5 and 6	SPT(4)
σ_5	entry to section which computes the flame speed constant	SPT(5)
σ_6	completion of the i-th combustion increment	SPT(6)

```
 $COMPILE MAD,PRINT OBJECT,PUNCH OBJECT,EXECUTE,DUMP                  3-ICE001
           PROGRAM COMMON AL,AH,P,K,R1,NC,NH,NO,NN,R,J2,RE,KK,X,TW,
          1QFACT,EA,RATIO,BO,RHO,SPEED,ERROR2,CPF,TPISTN,ATOT,XX,XNUM,
          2BORE,STROKE,ROD,VTOP,VBOT,PMAN,PEXH,TMAN,RPM,N,THETA,ERROR1,
          3J3,STOP,T5,H5,S5,U5,N5,QTOT,WTOT,F0,NEXTV,HCOMB,INC,Z,C,
          4  TZ,TX,COMDG, PMAX,NAME,CR,PI
           INTEGER RE,I,I1,I2,I3,J,J1,J2,J3,J4,L,L1,L2,JC,NK,NFA,INC,QK,
          1NAME,XNUM,NCOMDG,         II,SAVE,KEY,STOP,TZSAVE,TZZERO,TXZERO
           DIMENSION AL(87,ALDIM),AH(87,ALDIM),RE(12),X(10),KK(5),QFACT
          1(5),NUN(7),P(11),N(11),K(11),XX(105,XDIM),NAME(2),
          2FR( 60),ANS(5),NU(7),ATOT(5),TZ(1980),     TX( 780),
          3              AB(420,DIM),AU(240,DIM),AF(240,DIM),PHF(120,DIM),
          4PHB(120,DIM),DT( 60),TT(2)
           EQUIVALENCE (CPRIM,SPRIM),(HPRIM,CV),(HMIX,TT),(TZ,TZZERO),
          1(TX,TXZERO)
           VECTOR VALUES DIM = 2,0,60
           VECTOR VALUES ALDIM = 2,0,8
           VECTOR VALUES XDIM = 2,0,21
           READ FORMAT SPHT,AL(1,1)...AL(11,8),AH(1,1)...AH(11,8)
           VECTOR VALUES SPHT = $4E15.8*$
           READ FORMAT REMARK,RE...RE(12),ERROR1,ERROR2,ERROR3,COMDG,T5,
          1STOP,NFA,NK,QK,INC,A,B,EA,HCOMB,SPEED,NAME...NAME(2),X(1)...X
          2(NFA),KK(1)...KK(NK),QFACT(1)...QFACT(QK)
           PRINT FORMAT DUMP1,$1AL = $,AL(1,1)...AL( 7,8)
           Z = A+B/4.
           PRINT FORMAT DUMP1,$ AH = $,AH(1,1)...AH(11,8)
           VECTOR VALUES DUMP1 = $C6/(8E15.8)*$
           VECTOR VALUES REMARK =$13C6/5F10.5,5I2/5F10.1,3C6/(7F10.2)*$
           READ FORMAT FRACTN,XDIM(2),ATOT(1)...ATOT(5),FR(1)...FR(INC)
           VECTOR VALUES FRACTN = $I10,5F10.5/(14F5.5)*$
           R = .08205
           R1 = 1.98719
           C = 3.764
           READ FORMAT FRAT,XX(1,1)...XX(5,XDIM(2))
           VECTOR VALUES FRAT = $14F5.5*$
           XNUM = XDIM(2)
           DIM(2) = INC
           PRINT FORMAT REMARK,RE...RE(12),ERROR1,ERROR2,ERROR3,COMDG,T5
          1,STOP,NFA,NK,QK,INC,A,B,EA,HCOMB,SPEED,NAME...NAME(2),X(1)...
          2X(NFA),KK(1)...KK(NK),QFACT(1)...QFACT(QK)
           PRINT FORMATFRACTB,XDIM(2),ATOT(1)...ATOT(5),FR(1)...FR(INC),
          1XX(1,1)...XX(5,XDIM(2))
           VECTOR VALUES FRACTB = $ I10,5F10.5/(14F8.5)*$
           PH51 = 1.
 BEGIN     READ FORMAT ENGINE,BORE,STROKE,ROD,RPM,VTOP,PMAN,PEXH,TMAN,TP
          1ISTN,TW,PI,PIMAX,D1,D2
           VECTOR VALUES ENGINE = $7F10.5*$
           BORE = BORE  *2.54
           STROKE=STROKE*2.54
           ROD = ROD*2.54
           VTOP = VTOP/61.03
           VBOT = VTOP+3.1416*BORE/4000.*BORE*STROKE
           CR = VBOT/VTOP
           NCOMDG = (179.-PI)/COMDG
           J3 = 0
           THROUGH END, FOR I1 = 1,1,I1.G.NFA
           X = X(I1)
           THROUGH END, FOR I2 = 1,1,I2.G.NK
           KK = KK(I2)
```

```
            THROUGH END, FOR I3 = 1,1,I3.G.QK
            QFACT = QFACT(I3)
            PRINT FORMAT INTRO, NAME...NAME(2),X,BORE/2.54,EA,TPISTN,STRO
           1KE/2.54,TW,ROD/2.54,HCOMB,TMAN,VTOP*61.03,PMAN,61.03*(VBOT-VT
           2OP),PEXH,CR,PI
            N5 = PEXH/R*VTOP/T5
            NC = A
            NH = B
            NO = X*(2.*NC+.5*NH)
            NN = C*NO
            NCC = A+B/2.+Z*(C*X+X-1.)
            NEXTV = NCC*R/PEXH*T5
            EXECUTE EQUIL.(T5)
            PRINTFORMATINTOR1,RPM,INC,ERROR1*100.,KK,QFACT,RE(4)...RE(12)
 BACK       VC = NEXTV
            EXECUTE AMOUNT.(T5,VC,NCC,PH51,N)
            NEXTV = NCC*R/PEXH*T5
            WHENEVER .ABS.((NEXTV-VC)/VC).G.ERROR1,TRANSFER TO BACK
            F5 = VTOP/VC
            N(2) = F5*(N(2)+(N(9)+N(10)+N(8))/2.)
            N(3) = F5*(N(3)+N(9)/2.)
            N(4) = F5*N(4)
            N(5) = F5*N(5)
            N(6) = F5*N(6)
            N(7) = F5*(N(7)+(N(8)+N(11))/2.)
            TRANSFER TO LOOC1
 LOOOP1     N5 = PEXH/R*VTOP/T5
            F5 = N5/(N(2)+N(3)+N(4)+N(5)+N(6)+N(7))
            THROUGH LOOOP2,FORL1 = 2,1,L1.G.7
 LOOOP2     N(L1) = F5*N(L1)
 LOOC1      EXECUTE ENTHAL.(2,7,H5,T5,N)
            J3 = J3 + 1
            U5 = H5 - N5*R1*T5
            PRINT FORMAT HEAD3
            VECTOR VALUES HEAD3 = $4H0LOC,S2,1HJS2,3HINCS4,5HTHETAS4, 6HT
           1 - *K,S4,8HP - ATM.S7,6HV - L.S4,8HH - CAL.S6,11HS - CAL./*KS
           26,8HU - CAL.S5,11HTOTAL MOLES*$
            EXECUTE ENTROP.(2,7.S5,T5,N5,PEXH,N)
            PRINTFORMAT OUT,5,0,1,540.,T5,PEXH,VTOP,H5,S5,U5,N5,N(2)...N(
           17)
            NUN(4) = N(4)
            NUN(5) = N(5)
            NUN(6) = N(6)
            NUN(7) = N(7)
            J = 0
            WHENEVER J3.E.1,T1 = TMAN
            NEXTT = T1
 LOOOP3     T = NEXTT
            J = J + 1
            N0 = PMAN/R*VBOT/T - N5
            F0 = N0/(1. + Z*X*(C+1.))
            NUN(1) = F0
            NUN(2) = F0*Z*X
            NUN(3) = NUN(2)*C
            EXECUTE ENTHAL.(1,3,H0,TMAN,NUN)
            EXECUTE HPRIME.(1,3,HPRIM,T,NUN)
            HPRIM = HPRIM - H0/T*(1. + N5/N0)
            H  = H0 + U5 + PMAN*VTOP*24.2179
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```
                NUN(2) = NUN(2) + N(2)
                NUN(3) = NUN(3) + N(3)
                EXECUTE ENTHAL.(1,7,HMIX,T,NUN)
                NEXTT = T - (HMIX-H )/HPRIM
                WHENEVER .ABS.((HMIX-H )/H ).G.ERROR1,TRANSFER TO LOOOP3
                N1 = NO + N5
                EXECUTE ENTROP.(1,7,S1,T,N1,PMAN,NUN)
                U  = H -N1*R1*T
                U1 = U
                M1 = NUN(1)*(12.01*A+1.008*B)+NUN(2)*32.+NUN(3)*28.02+NUN(4)*
               144.01+NUN(5)*18.016+NUN(6)*28.01+NUN(7)*2.016
                T1 = T
                PRINT FORMATOUT,0,J,1,0.,TMAN,PMAN,VBOT,HO,0.,0.,NO,FO*X*Z,FO
               1*C*X*Z
                THETA = 0.
                JC = 0
                TZZERO = 1
                TZ(TZZERO     ) = 0.
                TZ(TZZERO + 1 ) = T
                TZ(TZZERO + 2 ) = PMAN
                TZ(TZZERO + 3 ) = VBOT
                TZ(TZZERO + 4 ) = H
                TZ(TZZERO + 5 ) = S1
                TZ(TZZERO + 6 ) = U
                TZ(TZZERO + 7 ) = N1
                TZZERO = TZZERO + 13
                PRINT FORMAT OUT,1,J,1,0.,T,PMAN,VBOT,H,S1,U,N1,NUN(1)...
               1NUN(7),M1
                V = VBOT
LOOOP5          THETA = THETA + COMDG
LOOC2           JC = JC + 1
                LASTU = U
                NEXTV = VOLUME.(THETA)
                EXECUTE HPRIME.(1,7,CV,T,NUN)
                CV = CV/N1 - R1
                NEXTT = T*(V/NEXTV).P.(R1/CV)
                V = NEXTV
                J = 0
LOOOP4          J = J + 1
                T = NEXTT
                P = T*R/V*N1
                EXECUTE ENTROP.(1,7,S,T,N1,P,NUN)
                EXECUTE SPRIME.(1,7,SPRIM,T,NUN)
                SPRIM = SPRIM - N1/T*R1
                NEXTT = T -(S-S1)/SPRIM
                WHENEVER .ABS.((NEXTT-T)/T).G.ERROR1,TRANSFER TO LOOOP4
                EXECUTE ENTHAL.(1,7,H,T,NUN)
                U = H - N1*R1*T
                TZ(TZZERO     ) = THETA
                TZ(TZZERO + 1 ) = T
                TZ(TZZERO + 2 ) = P
                TZ(TZZERO + 3 ) = V
                TZ(TZZERO + 4 ) = H
                TZ(TZZERO + 5 ) = S
                TZ(TZZERO + 6 ) = U
                TZ(TZZERO + 7 ) = N1
                TZ(TZZERO + 8 ) = 0.
                TZ(TZZERO + 9 ) = 0.
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```
               TZ(TZZERO + 10) = LASTU - U
               TZ(TZZERO + 11) = U1 - U
               TZ(TZZERO + 12) = 0.
               TZZERO = TZZERO + 13
               PRINT FORMAT OUT,2,J,JC,THETA,T,P,V,H,S,U
               WHENEVER JC.L.NCOMDG, TRANSFER TO LOOOP5
               WHENEVER JC.E.NCOMDG
               THETA = 180.-PI
               TRANSFER TO LOOC2
               END OF CONDITIONAL
               V2 = V
               T2 = T
               H2 = H
               U2 = U
               P2 = P
               THROUGH END1, FOR L1=1,1,L1.G.7
   END1        NU(L1) = NUN(L1)
               WHENEVER J3.E.1
               J1 = 0
               OTHERWISE
               J1 = J3
               END OF CONDITIONAL
               CARBON = F0*A +NU(4) +NU(6)
               HYDRGN = F0*B + 2.*(NU(5) +NU(7))
               OXYGEN = X*(2.*CARBON+.5*HYDRGN'
               NITRGN = C*OXYGEN
               TZSAVE = TZZERO
   RETURN      THETA = 180.-PI
               TZZERO = TZSAVE
               TXZERO = 1
               QB =
               LASTL = 0.
               FTOT = 0.
               QTOT = 0.
               WTOT = U1-U2
               SEC = 0.
               THROUGH HERE, FOR L1 = 1,1,L1.G.7
   HERE        NUN(L1) = NU(L1)
               TU = T2
               P = P2
               VU = V2
               HU = H2
               SU = S1
               EC = U2
               NU = N1
               HB = 0.
               VB = 0.
               WHENEVER RE(0).E.$DONTNOS$
               J4 = 5
               OTHERWISE
               J4 = 6
               END OF CONDITIONAL
               I = 0
   ANOTHR      LASTP = P
               I = I + 1
               E = EC
               DT = DT(I)
               FR = FR(I)
```

```
                  FTOT = FTOT + FR
                  VTOT = VOLUME.(THETA)
                  NFF = N1*FR
                  MF = M1*FR
                  VFF = NFF*R/P*TU
                  EXECUTE AREA.(VB,VTOT,ANS,D1,D2)
                  LASTL = ANS(5)
                  EXECUTE AREA.(VB+VFF,VTOT,ANS,D1,D2)
                  NEWL = ANS(5)
                  DS = NEWL - LASTL
                  BO = NUN(2)/VU
                  RHO = MF/VFF
                  TO = TU
                  Z1= NFF/NU
                  HF = HU*Z1
                  VU = VU-VFF
                  NU = NU-NFF
                  HU = HU-HF
                  SU = SU*(1.-Z1)
                  NFC = CARBON*FR
                  NFH = HYDRGN*FR
                  NFO = OXYGEN*FR
                  NFN = NITRGN*FR
                  KEY = 1
                  L = 1
                  THROUGH LOC, FOR L1 = 1,1,L1.G.7
     LOC          NUN(L1) = NUN(L1)*(1.-Z1)
                  WHENEVER J1.G.1, TRANSFER TO SKIP
                  DT(I) = 0.
                  WHENEVER I.G.1
                  II = I-1
                  MQ = FR(I)/FR(II)
                  AF(1,I) = AF(1,II)
                  AF(2,I) = AF(2,II)*MQ
                  PHF(1,I) = PHF(1,II)*MQ
                  OTHERWISE
                  PHF(1,I) = 1.
                  AF(1,I) = 4.*TU
                  AF(2,I) = NFF
                  END OF CONDITIONAL
     SKIP         TC = AF(1,I)
                  NCC = AF(2,I)
                  PH = PHF(1,I)
                  TT = HF
                  NC = NFC
                  NO = NFO
                  NH = NFH
                  NN = NFN
     ENTRY1       J = 0
                  L2 = KEY
                  NEXTT = TC
     LOC1         TC = NEXTT
                  J = J+1
                  NEXTV = NCC*R/P*TC
                  EXECUTE EQUIL.(TC)
     LOC2         VC = NEXTV
                  EXECUTE AMOUNT.(TC,VC,NCC,PH,N)
                  NEXTV = NCC*R/P*TC
```

```
                WHENEVER .ABS.((NEXTV-VC)/VC).G.ERROR1,TRANSFER TO LOC2
                TRANSFER TO ENTRY(L2)
  ENTRY(1)      EXECUTE ENTHAL.(2,11,CC,TC,N)
                EXECUTE HPRIME.(2,11,CPRIM,TC,N)
                TRANSFER TO LESS
  ENTRY(2)      EXECUTE ENTROP.(2,11,CC,TC,NCC,P,N)
                EXECUTE SPRIME.(2,11,CPRIM,TC,N)
                TRANSFER TO LESS
  ENTRY(3)      EXECUTE ENTHAL.(2,11,CC,TC,N)
                CC = CC-NCC*R1*TC
                EXECUTE HPRIME.(2,11,CPRIM,TC,N)
                CPRIM = CPRIM-NCC*R1
  LESS          Q = CC-TT
                NEXTT = TC-Q/CPRIM
                WHENEVER J.E.5
                L2 = L2+3
                DIF = .ABS.(TC - NEXTT)
                END OF CONDITIONAL
                WHENEVER .ABS.(Q/TT).G.ERROR1,TRANSFER TO LOC1
                TRANSFER TO LOC(L)
  ENTRY(4)      EXECUTE ENTHAL.(2,11,CC,TC,N)
                TRANSFER TO MORE
  ENTRY(5)      EXECUTE ENTROP.(2,11,CC,TC,NCC,P,N)
                TRANSFER TO MORE
  ENTRY(6)      EXECUTE ENTHAL.(2,11,CC,TC,N)
                CC = CC-NCC*R1*TC
  MORE          QQ = CC-TT
                WHENEVER Q/QQ.L.0.,DIF = DIF/2.
                NEXTT = TC - DIF*QQ/.ABS.(QQ)
                Q = QQ
                WHENEVER .ABS.(Q/TT).G.ERROR1,TRANSFER TO LOC1
                TRANSFER TO LOC(L)
  LOC(1)        AF(1,I) = TC
                AF(2,I) = NCC
                PHF(1,I) = PH
                EXECUTE ENTROP.(2,11,SF,TC,NCC,P,N)
                WHENEVER I.E.1
                TRANSFER TO  LOC(2)
                END OF CONDITIONAL
                TT = HB + TT
                NC = NBC + NC
                NO = NBO + NO
                NH = NBH + NH
                NN = NBN + NN
                WHENEVER J1 .L.2
                AB(1,I) = AB(1,II)
                AB(2,I) = AB(2,II)+NCC
                PHB(1,I) = 1.
                END OF CONDITIONAL
                TC = AB(1,I)
                NCC = AB(2,I)
                PH = PHB(1,I)
                L = 2
                TRANSFER TO ENTRY1
  LOC(2)        AB(1,I) = TC
                AB(2,I) = NCC
                PHB(1,I) = PH
                VB = VC
```

```
            NB = NCC
            TB = TC
            HB = TT
            NBC = NC
            NBH = NH
            NBO = NO
            NBN = NN
            L = 3
            L1 = 3
            UB = HB - NB*R1*TB
            UU = HU -NU*R1*TU
            UC = UB + UU
            WHENEVER J1.G.1
            TB = AB(3,I)
            NB = AB(4,I)
            VB = AB(5,I)
            TU = AU(1,I)
            VU = AU(2,I)
            PH = PHB(2,I)
            UC = E
            P = R/VTOT*(NB*TB+NU*TU)
            END OF CONDITIONAL
            KEY = 3
ENTRY2      JC = 0
LOC3        JC = JC + 1
            EXECUTE HPRIME.(2,11,CP,TB,N)
            CP = CP/NB-R1
            NEXTP = R/VTOT*((EC-UC)/CP + NB*TB + NU*TU)
            EXECUTE HPRIME.(1,7,CP,TU,NUN)
            TU = TU*(NEXTP/P).P.(R1/CP*NU)
            P = NEXTP
            NEXTT = TU
LOC4        TU = NEXTT
            EXECUTE ENTROP.(1,7,TT,TU,NU,P,NUN)
            EXECUTE SPRIME.(1,7,CPRIM,TU,NUN)
            NEXTT = TU-((TT-SU)/CPRIM)
            WHENEVER .ABS.((NEXTT-TU)/TU).G.ERROR1,TRANSFER TO LOC4
            VU = NU*R/P*TU
            EXECUTE ENTHAL.(1,7,HU,TU,NUN)
            UU = HU - NU*R1*TU
            UB = EC- UU
            TC = TB
            TT = UB
            NCC = NB
            TRANSFER TO ENTRY1
LOC(3)      TB= TC
            VB = VC
            NB = NCC
            UC = UB + UU
            VC = VU + VB
            WHENEVER .ABS.((VC-VTOT)/VTOT).G.ERROR1,TRANSFER TO LOC3
            EXECUTE ENTHAL.(2,11,HB,TB,N)
            PRINT FORMAT OUT,L1,J,I,THETA,TU,P,VU,HU,SU,UU,NU,NUN(1)...NU
           1N(7)
            EXECUTE ENTROP.(2,11,SB,TB,NB,P,N)
            PRINT FORMAT OUT,L1,JC,I,THETA,TB,P,VB,HB,SB,UB,NB,N(2)...N(1
           11)
            TRANSFER TO SPT(L1)
```

```
 SPT(3)       AB(3,I) = TB
              AB(4,I) = NB
              AB(5,I) = VB
              AU(1,I) = TU
              AU(2,I) = VU
              PHB(2,I) = PH
              TT(1) = SU
              TT(2) = SB
              PRINT FORMAT HEAD3
              SAVE = J1
              EXECUTE AREA.(VB,VTOT,ANS,D1,D2)
 ENTRY4       KEY = 2
              PHETA = 6.*RPM*DT+THETA
              VTOT = VOLUME.(PHETA)
              L = 4
              TB = AB(3,I)
              NB = AB(4,I)
              VBB = AB(5,I)
              TU = AU(1,I)
              VUU = AU(2,I)
              PH = PHB(2,I)
              SU = TT(1)
              SB = TT(2)
              VC = VBB + VUU
              EXECUTE EQUIL.(TB)
              EXECUTE AMOUNT.(TB,VBB,NB,PH,N)
              JC = 0
                3  + +
              GB = CP/(CP-R1*NB)
              WHENEVER I.E.INC
              VB = VTOT
              TB = TB*(VBB/VB).P.(GB-1.)
              P = P*(VBB/VB).P.GB
              J4 = 6
              TRANSFER TO SPT1
              END OF CONDITIONAL
              EXECUTE HPRIME.(1,7,CP,TU,NUN)
              GU = CP/(CP-R1*NU)
              VB = VTOT/(1.+VUU/VBB*(VC/VTOT).P.((GU-GB)/GB))
              VU = VTOT - VB
              TU = TU*(VUU/VU).P.(GU-1.)
              TB = TB*(VBB/VB).P.(GB-1.)
              P = R/VTOT*(NB*TB+NU*TU)
              NEXTT = TU
 LOC6         TU = NEXTT
              EXECUTE ENTROP.(1,7,SC,TU,NU,P,NUN)
              EXECUTE SPRIME.(1,7,SPRIM,TU,NUN)
              NEXTT = TU-((SC-SU)/SPRIM)
              WHENEVER .ABS.((NEXTT-TU)/TU).G.ERROR1,TRANSFER TO LOC6
              VU = NU*R/P*TU
 SPT1         TT = SB
              TC = TB
              NCC = NB
              TRANSFER TO ENTRY1
 LOC(4)       TB = TC
              VBB =VC
              NB = NCC
              VUU = VU
```

```
          VC = VBB + VUU
          WHENEVER .ABS.((VC-VTOT)/VTOT).G.ERROR1,TRANSFER TO LOC5
          VB = VBB
          EXECUTE ENTHAL.(1,7,HU,TU,NUN)
          EXECUTE ENTHAL.(2,11,HB,TB,N)
          UU = HU-NU*R1*TU
          PRINT FORMAT OUT,L,JC,I,PHETA,TU,P,VU,HU,SU,UU,NU,NUN(1)...NU
         1N(7)
          UB = HB-NB*R1*TB
          COEF = 0.
          EC = UU + UB
          PRINT FORMAT OUT,L,J,I,PHETA,TB,P,VB,HB,SB,UB,NB,N(2)...N(11)
          WHENEVER J1.E.0,TRANSFER TO SPT(4)
          WHENEVER FTOT .LE. .02, TRANSFER TO SPT(4)
          L = 3
          L1 = 4
          QB = QTRAN2.(TB,TU,P,DT,ANS,COEF)
          EC = EC-QB
          UC = EC
          WHENEVER J1.NE.1
          TB = AB(6,I)
          VB = AB(7,I)
          TU = AU(3,I)
          VU = AU(4,I)
          P = R/VTCT*(NB*TB+NU*TU)
          END OF CONDITIONAL
          KEY = 3
          TRANSFER TO ENTRY2
SPT(4)    AB(6,I) = TB
          AB(7,I) = VB
          AU(3,I) = TU
          AU(4,I) = VU
          WHENEVER I.E.1,TRANSFER TO LOC(5)
          L = 5
          WHENEVER J1.G.1
          PH = PHF(2,I)
          TC = AF(3,I)
          NCC= AF(4,I)
          OTHERWISE
          PH = 1.
          NCC= NFF
          END OF CONDITIONAL
          TT = SF
          NC = NFC
          NH = NFH
          NO = NFO
          NN = NFN
          KEY = 2
          TRANSFER TO ENTRY1
LOC(5)    TFLAME = TC
          PHF(2,I) = PH
          AF(3,I) = TC
          AF(4,I) = NCC
          RATIO = NFF/NCC
          EXECUTE HPRIME.(2,11,CPF,TC,N)
          CPF = CPF/MF
          R2 = R1*NCC/MF
          EXECUTE STURB.(TO,TFLAME,ST,R2)
          DT = DS/ST
```

```
           NC = NBC
           NH = NBH
           NO = NBO
           NN = NBN
           J1 = SAVE
           WHENEVER .ABS.((PHETA-THETA-6.*RPM*DT)/PHETA).G.ERROR1
           SAVE = J1
           J1 = 2
           TRANSFER TO ENTRY4
           END OF CONDITIONAL
           PRINT FORMAT VOLU,ST,TFLAME,COEF,FTOT
           VECTOR VALUES VOLU =$14HOVOLUMES AGREE,S5,13HFLAME SPEED =
          1F10.5,S5,8HTFLAME = F10.5,S5,20HHEAT TRANSFER COEF = E15.8/
          219H FRACTION BURNED = F10.8*$
           WORK = E-EC-QB
           WTOT = WTOT+WORK
           QTOT = QTOT+QB
           SEC = SEC + DT
           LSTTH = THETA
           THETA = PHETA
           DT(I) = DT
           PRINT FORMAT INTRI,THETA,TU,P,VTOT,HU+HB,SU+SB,UU+UB,NU+NB,QB
          1,QTOT,WORK,WTOT,  SEC,TB,P,VB,HB,SB,UB,NB,ANS...ANS(5),NEWL,
          2LASTL
           VECTOR VALUES INTRI=$S6,4HTIMES5,1HTS9,1HPS9,1HVS9,1HHS9,1HS
          1S9,1HUS9,1HNS9,2HQBS8,4HQTOTS6,4HWORKS6,4HWTOT/(12F10.5)*$
           TX(TXZERO      ) = THETA
           TX(TXZERO + 1 ) = TB
           TX(TXZERO + 2 ) = P
           TX(TXZERO + 3 ) = VB
           TX(TXZERO + 4 ) = HB
           TX(TXZERO + 5 ) = SB
           TX(TXZERO + 6 ) = UB
           TX(TXZERO + 7 ) = NB
           TX(TXZERO + 8 ) = ST
           TX(TXZERO + 9 ) = TFLAME
           TX(TXZERO + 10) = ANS(5)
           TX(TXZERO + 11) = FTOT
           TX(TXZERO + 12) = VB/VTOT
           TXZERO = TXZERO + 13
           TZ(TZZERO      ) = THETA
           TZ(TZZERO + 1 ) = TU
           TZ(TZZERO + 2 ) = P
           TZ(TZZERO + 3 ) = VTOT
           TZ(TZZERO + 4 ) = HU+HB
           TZ(TZZERO + 5 ) = SU+SB
           TZ(TZZERO + 6 ) = UU+UB
           TZ(TZZERO + 7 ) = NU+NB
           TZ(TZZERO + 8 ) = QB
           TZ(TZZERO + 9 ) = QTOT
           TZ(TZZERO + 10) = WORK
           TZ(TZZERO + 11) = WTOT
           TZ(TZZERO + 12) = COEF
           TZZERO = TZZERO + 13
           PRINT FORMAT HEAD3
           TRANSFER TO SPT(J4)
 SPT(5)    WHENEVER (P-LASTP).GE.0.,TRANSFER TO ANOTHR
           NEXTK = KK*(LSTTH-(180.-PI))/(PIMAX-(180.-PI))
```

```
                WHENEVER .ABS.(PIMAX-LSTTH).G.ERROR3
                J1 = J1 + 1
                KK = NEXTK
                PRINT FORMAT OUTPOT,KK
                VECTOR VALUES OUTPOT = $5H0KK = E15.8*$
                TRANSFER TO RETURN
                END OF CONDITIONAL
                J4 = 6
                PMAX = LASTP
                WHENEVER J3.E.1
                J1 = 0
                OTHERWISE
                J1 = J3
                END OF CONDITIONAL
SPT(6)          WHENEVER P.G.LASTP,PMAX = P
                WHENEVER I.L.INC,TRANSFER TO ANOTHR
                EXECUTE FINISH.(EC,TB,VB,PH,BACK,LOOOP1,F,D1)
                EXECUTE OUTPUT.(F)
END             CONTINUE
                TRANSFER TO BEGIN
                VECTOR VALUES INTRO = $1H1,S35,49HA MODEL SIMULATING THE INTE
               1RNAL-COMBUSTION ENGINE/7H0ENGINES33,4HFUELS36,20HOPERATING CO
               2NDITIONS/28H0FOUR STROKE AUTOMOTIVE TYPES12,3C6,S22,14HAIR-FU
               3EL RATIO F9.2/5H BORES8,F10.2,4H IN.S13,17HACTIVATION ENERGY
               4F10.2,24H CAL/MOLE     PISTON TEMP F12.2,2H K/7H STROKES6,F10.
               52,4H IN.S13,11HENTHALPY OFS29,9HWALL TEMPF14.2,2H K/4H RODS9,
               6F10.2,4H IN.S13,10HCOMBUSTIONF17.2,22H CAL/MOLE    MAN. TEMP
               7F14.2,2H K/12H CLEAR. VOL.F11.2,7H CU.IN.S50,8HMAN. PR.F15.2,
               84H ATM/11H SWEPT VOL.F12.2,7H CU.IN.S50,8HEXH. PR.F15.2,4H AT
               9M/18H COMPRESSION RATIOF5.2,7H TO ONES50,10HSPARK ADV.F13.2*$
                VECTOR VALUES INTOR1 = $S80,5HSPEEDS10,F8.2,4H RPM/ 21H0COMBU
               1STION OCCURS IN I3,34H INCREMENTS.  ERRORS ARE LESS THAN F10.
               25,33H PERCENT.  FLAME SPEED FACTOR IS E15.8/24H HEAT TRANSFER
               3 FACTOR IS F10.5,S3,10C6*$
                VECTOR VALUES OUT =$1H0,3I3,S2,3F10.3,F15.8,4E15.8/(6E20.8)*$
                INTERNAL FUNCTION VOLUME.(ZETA) = .0007854*BORE*BORE*(STROKE/
               12.*(1.+COS.(ZETA*.01745))+ROD*(1.-SQRT.(1.-(STROKE/2.*SIN.(
               2ZETA*.01745)/ROD).P.2)))+ VTOP
                END OF PROGRAM

                                                                                 C.C.     0156
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$COMPILE MAD, PRINT OBJECT,PUNCH OBJECT                          4FNSH001
           EXTERNAL FUNCTION(ENERGY,TEMPT,VOL,PHP,BACK,LOOOP1,F,D1)
           PROGRAM COMMON AL,AH,P,K,R1,NC,NH,NO,NN,R,J2,RE,KK,X,TW,
          1QFACT.EA,RATIO,BO,RHO,SPEED,ERROR2,CPF,TPISTN,ATOT,XX,XNUM,
          2BORE,STROKE,ROD,VTOP,VBOT,PMAN,PEXH,TMAN,RPM,N,THETA,ERROR1,
          3J3,STOP,T5,H5,S5,U5,N5,QTOT,WTOT,F0,NEXTV,HCOMB,INC,Z,C,
          4  TZ,TX,COMDG, PMAX,NAME,CR,PI
           STATEMENT LABEL BACK,LOOOP1
           INTEGER RE,I,II,I2,I3,J,J1,J2,J3,G,L2,N1,N2,INC,NAME,XNUM,
          2NEXPDG,      KEY,STOP,TZZERO
           DIMENSION AL(87,ALDIM),AH(87,ALDIM),RE(12),X(10),KK(5),QFACT
          1(5),P(11),N(11),K(11),XX(105,XDIM),NAME(2),RT(40),ATOT(5),B(7
          2),TZ(1980),TX(780)
           EQUIVALENCE (TZ,TZZERO)
           VECTOR VALUES XDIM = 2,0,21
           VECTOR VALUES ALDIM = 2,0,8
           ENTRY TO FINISH.
           UB = ENERGY
           TB = TEMPT
           VB = VOL
           PH = PHP
           DELTAT = 0.
           NEXPDG = (359.-THETA)/COMDG*2.
           DTHETA = 360.-THETA-NEXPDG*COMDG/2.
           DT = DTHETA/6./RPM
           J1 = 0
LCC1       J1 = J1 + 1
           TC =RT(J1)
           E = UB
           WHENEVER J3.E.1,TC=TB-DELTAT
           ARAA = ARREA.(THETA)
           QB = QTRANS.(P,ARAA,COEF)
           QTOT = QTOT + QB
           UB = E-QB
           G = 6
           KEY = 3
           TT = UB
ENTCY1     J = 0
           L2 = KEY
           NEXTT = TC
LCC(2)     TC = NEXTT
           J = J + 1
           EXECUTE EQUIL.(TC)
           EXECUTE AMOUNT.(TC,VB,NB,PH,N)
           TRANSFER TO ENTCY(L2)
ENTCY(2)   P = NB*R/VB*TC
           EXECUTE ENTROP.(2,11,CC,TC,NB ,P,N)
           EXECUTE SPRIME.(2,11,CPRIM,TC,N)
           CPRIM = CPRIM - NB*R1/TC
           TRANSFER TO LESSC
ENTCY(3)   EXECUTE ENTHAL.(2,11,CC,TC,N)
           CC = CC- NB*R1*TC
           EXECUTE HPRIME.(2,11,CPRIM,TC,N)
           CPRIM = CPRIM- NB*R1
LESSC      Q = CC-TT
           NEXTT = TC-Q/CPRIM
           WHENEVER J.E.5
           L2 = L2+3
           DIF = .ABS.(TC - NEXTT)
```

```
            END OF CONDITIONAL
            WHENEVER .ABS.(Q/TT).G.ERROR1,TRANSFER TO LCC(2)
            TRANSFER TO COMMOC
ENTCY(5)    P = NB*R/VB*TC
            EXECUTE ENTROP.(2,11,CC,TC,NB ,P,N)
            TRANSFER TO MOREC
ENTCY(6)    EXECUTE ENTHAL.(2,11,CC,TC,N)
            CC = CC- NB*R1*TC
MOREC       QQ = CC-TT
            WHENEVER Q/QQ.L.0.,DIF = DIF/2.
            NEXTT = TC - DIF*QQ/.ABS.(QQ)
            Q = QQ
            WHENEVER .ABS.(Q/TT).G.ERROR1,TRANSFER TO LCC(2)
COMMOC      PRINTFORMATOUT,G,J,I,THETA,TC,P,VB,TT,0.,CC,NB
            TRANSFER TO LCC(G)
LCC(6)      RT(J1)= TC
            DELTAT = TB-TC
            TB = TC
            P = NB*R/VB*TB
            EXECUTE ENTROP.(2,11,SB,TB,NB,P,N)
            THETA = THETA+DTHETA
            V = VOLUME.(THETA)
            TC = TB*(VB/V).P.(NB*R1/CPRIM)
            VB = V
            G = 7
            KEY = 2
            TT = SB
            TRANSFER TO ENTCY1
LCC(7)      EXECUTE ENTHAL.(2,11,HB,TC,N)
            TB = TC
            UB = HB-NB*R1*TB
            WORK = E-UB-QB
            WTOT = WTOT+WORK
            PRINT FORMAT OUT,G,J,J1,THETA,TB,P,VB,HB,SB,UB,NB,N(2)...N(11
           1),0.,QB,QTOT,WORK,WTOT,COEF,ARAA
            TZ(TZZERO      ) = THETA
            TZ(TZZERO + 1 ) = TB
            TZ(TZZERO + 2 ) = P
            TZ(TZZERO + 3 ) = VB
            TZ(TZZERO + 4 ) = HB
            TZ(TZZERO + 5 ) = SB
            TZ(TZZERO + 6 ) = UB
            TZ(TZZERO + 7 ) = NB
            TZ(TZZERO + 8 ) = QB
            TZ(TZZERO + 9 ) = QTOT
            TZ(TZZERO + 10) = WORK
            TZ(TZZERO + 11) = WTOT
            TZ(TZZERO + 12) = COEF
            TZZERO = TZZERO + 13
            WHENEVER THETA.G.359.,TRANSFER TO LCC3
            WHENEVER J1.G.1,TRANSFER TO LCC1
            DELTAT = DELTAT/2.
            DTHETA = COMDG/2.
            DT = DTHETA/6./RPM
            TRANSFER TO LCC1
LCC3        WHENEVER J3.E.1
            EXECUTE HPRIME.(2,11,CPRIM,TC,N)
            TEXH = TB*(PEXH/P).P.(R1*NB/CPRIM)
```

```
           END OF CONDITIONAL
           NEXTT = TEXH
           P = PEXH
           NEXTV = NB*R/PEXH*TEXH
           J = 0
LCC(3)     TC = NEXTT
           J = J + 1
           EXECUTE EQUIL.(TC)
LCC5       VB = NEXTV
           EXECUTE AMOUNT.(TC,VB,NB,PH,N)
           NEXTV = NB*R/PEXH*TC
           WHENEVER .ABS.((NEXTV-VB)/VB).G.ERROR1,TRANSFER TO LCC5
           EXECUTE ENTROP.(2,11,CC,TC,NB,P,N)
           Q = CC - TT
           EXECUTE SPRIME.(2,11,CPRIM,TC,N)
           NEXTT = TC-Q/CPRIM
           WHENEVER .ABS.(Q/TT).G.ERROR1,TRANSFER TO LCC(3)
           TB = TC
           TEXH = TC
           EXECUTE ENTHAL.(2,11,HB,TB,N)
           UB = HB-NB*R1*TB
           TZ(TZZERO      ) = THETA
           TZ(TZZERO + 1 ) = TB
           TZ(TZZERO + 2 ) = PEXH
           TZ(TZZERO + 3 ) = VB
           TZ(TZZERO + 4 ) = HB
           TZ(TZZERO + 5 ) = SB
           TZ(TZZERO + 6 ) = UB
           TZ(TZZERO + 7 ) = NB
           TZ(TZZERO + 8 ) = 0.
           TZ(TZZERO + 9 ) = QTOT
           TZ(TZZERO + 10) = 0.
           TZ(TZZERO + 11) = WTOT
           TZ(TZZERO + 12) = 0.
           TZZERO = TZZERO + 13
           PRINT FORMAT OUT,9,J1,J,360.,TB,P,VB,HB,SB,UB,NB,N(2)...N(11)
           N(2) = N(2) +(N(9)+N(10)+N(8))/2.
           N(3) = N(3) + N(9)/2.
           N(7) = N(7)+(N(8)+N(11))/2.
           TC = T5
           F = N5/NB
           TZ(TZZERO      ) = 540.
           TZ(TZZERO + 1 ) = T5
           TZ(TZZERO + 2 ) = PEXH
           TZ(TZZERO + 3 ) = VTOP
           TZ(TZZERO + 4 ) = H5
           TZ(TZZERO + 5 ) = S5
           TZ(TZZERO + 6 ) = U5
           TZ(TZZERO + 7 ) = N5
           TZ(TZZERO + 8 ) = 0.
           TZ(TZZERO + 9 ) = QTOT
           TZ(TZZERO + 10) = 0.
           TZ(TZZERO + 11) = WTOT
           TZ(TZZERO + 12) = 0.
           TZZERO = TZZERO + 12
           WHENEVER STOP.G.1,T5=TB
           WHENEVER .ABS.((TC-TB)/TC).G.ERROR1.AND.J3.L.STOP,TRANSFER TO
          1LOOOP1
```

```
                 FUNCTION RETURN
                 INTERNAL FUNCTION ARREA.(ZETA) = 3.1416*BORE*(STROKE/2.*(1.+
                1COS.(ZETA*.01745))+ROD*(1.-SQRT.(1.-(SIN.(ZETA*.01745)*STROKE
                2/2./ROD).P.2))+D1)+ATOT(1)
                 INTERNAL FUNCTION VOLUME.(ZETA) = .0007854*BORE*BORE*(STROKE/
                12.*(1.+COS.(ZETA*.01745))+ROD*(1.-SQRT.(1.-(STROKE/2.*SIN.(
                2ZETA*.01745)/ROD).P.2)))+ VTOP
                 VECTOR VALUES OUT =$1H0,3I3,S2,3F10.3,F15.8,4E15.8/(6E20.8)*$
                 INTERNAL FUNCTION(PR,AREA,S)
                 ENTRY TO QTRANS.
                 S = RPM/3000.*STROKE
                 S = 2.1*SQRT.(PR*TB)*S.P..33/36000.
                 FUNCTION RETURN DT*S*(AREA*(TB-TW)+ATOT(3)*(TB-TPISTN))*QFACT
                 END OF FUNCTION
                 INTERNAL FUNCTION(TEMP)
                 ENTRY TO EQUIL.
                 WHENEVER TEMP.LE. 1500.,FUNCTION RETURN
                 TR = TEMP/1500.
                 RT = 1./TR
                 B(1) = (ELOG.(TR)+RT-1.)/1.9872
                 B(2) = 750.00*(TR+RT-2.)/1.9872
                 B(3) = 375000.00*(TR*TR+2.*RT-3.)/1.9872
                 B(4) =281250000.*(TR*TR*TR+3.*RT-4.)/1.9872
                 B(7) = (1.-RT)/2980.785
                 K(4) = 0.
                 THROUGH LOOP7,FOR VALUES OF I = 1,2,3,4,7
 LOOP7           K(4) = K(4)+(AH(6,I)+.5*AH(2,I)-AH(4,I)  )*B(I)
                 K(4) = EXP.(AH(4,8)  +K(4))
                 K(5) = 0.
                 THROUGH LOOP8,FOR VALUES OF I = 1,2,3,4,7
 LOOP8           K(5) = K(5)+(AH(7,I)+.5*AH(2,I)-AH(5,I))*B(I)
                 K(5) = EXP.(AH(5,8)  +K(5))
                 K(8) = 0.
                 THROUGH LOOP9,FOR VALUES OF I = 1,2,3,4,7
 LOOP9           K(8) = K(8)+(.5*(AH(2,I)+AH(7,I))-AH(8,I))*B(I)
                 K(8) = EXP.(AH(8,8)  +K(8))
                 K(7) = 0.
                 THROUGH LOOP10,FOR VALUES OF I = 1,2,3,4,7
 LOOP10          K(7) = K(7)+(.5*AH(7,I)-AH(11,I))*B(I)
                 K(7) = EXP.(AH(7,8)  +K(7))
                 K(9) = 0.
                 THROUGH LOOP11,FOR VALUES OF I = 1,2,3,4,7
 LOOP11          K(9) = K(9)+(.5*(AH(2,I)+AH(3,I))-AH(9,I))*B(I)
                 K(9) = EXP.(AH(9,8)  +K(9))
                 K(2) = 0.
                 THROUGH LOOP12,FOR VALUES OF I = 1,2,3,4,7
 LOOP12          K(2) = K(2)+(.5*AH(2,I)-AH(10,I))*B(I)
                 K(2) = EXP.(AH(2,8)  +K(2))
                 FUNCTION RETURN
                 END OF FUNCTION
                 INTERNAL FUNCTION(N1,N2,PROPTY,TEMP,BLANK)
                 ENTRY TO SPRIME.
                 B(1) = 1./TEMP
                 B(2) = 1.
                 B(3) = TEMP
                 B(4) = TEMP*TEMP
                 TRANSFER TO MATRIX
                 ENTRY TO HPRIME.
```

```
           B(1) = 1.
           B(2) = TEMP
           B(3) = TEMP*TEMP
           B(4) = TEMP*TEMP*TEMP
           TRANSFER TO MATRIX
           ENTRY TO ENTHAL.
           I = 5
           PROPTY = 0.
           WHENEVER TEMP.G.1500., TRANSFER TO HIGHT
           TR = TEMP/298.16
           B(1) = 298.16*(TR - 1.)
           B(2) = 44449.693*(TR*TR - 1.)
           B(3) = 8835413.6*(TR*TR*TR - 1.)
           B(4) = 1975775200.*(TR*TR*TR*TR - 1.)
           B(5) = 1.
           TRANSFER TO LOW
HIGHT      TR = TEMP/1500.
           B(1) = 1500.*(TR - 1.)
           B(2) = 1125000.*(TR*TR -1.)
           B(3) = 1125000000.*(TR*TR*TR - 1.)
           B(4) = .1265625E13*(TR*TR*TR*TR -1.)
           B(5) = 1.
           TRANSFER TO HIGH
MATRIX     I = 4
           PROPTY = 0.
           WHENEVER TEMP .G. 1500., TRANSFER TO HIGH
LOW        THROUGH SUMB, FOR I2 = N1,1,I2.G.N2
           TA = 0.
           THROUGH SUMA, FOR I3 = 1,1,I3.G.I
SUMA       TA     = TA      + B(I3)*AL(I2,I3)
SUMB       PROPTY = PROPTY + N(I2)*TA
           FUNCTION RETURN
HIGH       THROUGH ADDA, FOR I2 = N1,1,I2.G.N2
           TA = 0.
           THROUGH ADDB, FOR I3 = 1,1,I3.G.I
ADDB       TA     = TA      + B(I3)*AH(I2,I3)
ADDA       PROPTY = PROPTY + N(I2)*TA
           FUNCTION RETURN
           END OF FUNCTION
           INTERNAL FUNCTION (N1,N2,PROPTY,TEMP,MOLES,PTOTAL,BLANK)
           ENTRY TO ENTROP.
           PROPTY = 0.
           WHENEVER TEMP.G.1500., TRANSFER TO BIGHT
           TR = TEMP/298.16
           B(1) = ELOG.(TR)
           B(2) = 298.16*(TR - 1.)
           B(3) = 44449.693*(TR*TR - 1.)
           B(4) = 8835413.6*(TR*TR*TR - 1.)
           B(6) = 1.
           THROUGH BUMB, FOR I2 = N1,1,I2.G.N2
           WHENEVER N(I2) .E. 0.,TRANSFER TO BUMB
           TA = 0.
           THROUGH BUMA, FOR VALUES OF I3 = 1,2,3,4,6
BUMA       TA = TA + B(I3)*AL(I2,I3)
           PROPTY = PROPTY + N(I2)*(TA    -1.9872*ELOG.(N(I2)*PTOTAL/MOL
          1ES))
BUMB       CONTINUE
           FUNCTION RETURN
```

```
 BIGHT      TR = TEMP/1500.
            B(1) = ELOG.(TR)
            B(2) = 1500.*(TR - 1.)
            B(3) = 1125000.*(TR*TR -1.)
            B(4) = 1125000000.*(TR*TR*TR - 1.)
            B(6) = 1.
            THROUGH BDDA, FOR I2 = N1,1,I2.G.N2
            WHENEVER N(I2) .E. 0.,TRANSFER TO BDDA
            TA = 0.
            THROUGH BDDB, FOR VALUES OF I3 = 1,2,3,4,6
 BDDB       TA = TA + B(I3)*AH(I2,I3)
            PROPTY = PROPTY + N(I2)*(TA    -1.9872*ELOG.(N(I2)*PTOTAL/MOL
           1ES))
 BDDA       CONTINUE
            FUNCTION RETURN
            END OF FUNCTION
            INTERNAL FUNCTION(TEMP,VOL,MOLES,PHH,BLANK)
            ENTRY TO AMOUNT.
            P(1) = 0.
            FA = TEMP*R/VOL
            WHENEVER TEMP .LE.1500.,TRANSFER TO H2OGAS
            WHENEVER PHH.LE.0.,PHH = 1.
            NEXTL = PHH
 LOOP1      L = NEXTL
            S1 = L/K(8) + 1./K(7)
            S2 = 4.*(1. + L/K(5))
            S3 = SQRT.(L*L/K(9)/K(9)+8.*FA*NN)
            S4 = SQRT.(S1*S1 + 2.*S2*FA*NH)
            M = (S4 - S1)/S2
            S = S3/4. - L/4./K(9)
            DNWRL = (L/K(9)/S3-1.)/4./K(9)
            DMWRL = -(S2*(1./K(8)-(S1/K(8)+4.*FA*NH/K(5))/S4)+(S4-S1)*4./
           1K(5))/S2/S2
            P(2) = L*L
            P(3) = S*S
            P(4) = NC*FA/(K(4)/L + 1.)
            P(5) = L*M*M/K(5)
            P(6) = P(4,*K(4)/L
            P(7) = M*M
            P(8) = L*M/K(8)
            P(9) = S*L/K(9)
            P(10) = L/K(2)
            P(11) = M/K(7)
            FL = 2.*(P(2) + P(4))+P(5) + P(6)+P(9)+P(8)+P(10) - FA*NO
            FPRIML  = FA*NC*K(4)/(L+K(4))/(L+K(4))+4.*L+M*M/K(5)+ M/K(8)+
           1S/K(9)+1./K(2)+DMWRL*(L/K(8)+2.*L*M/K(5)) +DNWRL/K(9)*L
            M = -FL/L/FPRIML
            WHENEVER .ABS.(M) .L.16.
            NEXTL = L*EXP.(M)
            OTHERWISE
            NEXTL = L*EXP.(M/.ABS.(M))
            END OF CONDITIONAL
            WHENEVER .ABS.((NEXTL-L)/L).G.ERROR2,TRANSFER TO LOOP1
            PHH = L
            TRANSFER TO LOC2
 H2OGAS     WHENEVER (NC+NH/4.)/NO.LE..5,TRANSFER TO SIMPLE
            S1 = NO/NC-1.
            S3 = (1.+NH/NC/.7494)/S1-1.6688
            L = (S3+SQRT.(S3*S3+6.6752/S1))/2.
            P(2) = 0.
            P(4) = FA*NC/L
            P(5) = FA*(NO-NC)-P(4)
            P(6) = .ABS.(FA*NC-P(4))
            P(7) = .ABS.(FA*NH/2. -P(5))
            TRANSFER TO HERR
 SIMPLE     P(2) = .ABS.(FA*(NO/2.-NC-NH/4.))
            P(4) = FA*NC
            P(5) = FA*NH/2.
            P(6) = 0.
            P(7) = 0.
 HERR       P(8) = 0.
            P(9) = 0.
            P(10) = 0.
            P(11) = 0.
            P(3) = FA*NN/2.
            PHH = 1.
 LOC2       MOLES = 0.
            THROUGH LOOP2, FOR I = 1,1,I.G.11
            N(I) = P(I)/FA
 LOOP2      MOLES = MOLES + N(I)
            FUNCTION RETURN
            END OF FUNCTION
            END OF FUNCTION
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```
$COMPILE MAD,PRINT OBJECT ,PUNCH OBJECT                        3OUTP201
        EXTERNAL FUNCTION (F)
        PROGRAM COMMON AL,AH,P,K,R1,NC,NH,NO,NN,R,J2,RE,KK,X,TW,
       1QFACT,EA,RATIO,B0,RHO,SPEED,ERROR2,CPF,TPISTN,ATOT,XX,XNUM,
       2BORE,STROKE,ROD,VTOP,VBOT,PMAN,PEXH,TMAN,RPM,N,THETA,ERROR1,
       3J3,STOP,T5,H5,S5,U5,N5,QTOT,WTOT,F0,NEXTV,HCOMB,INC,Z,C,
       4  TZ,TX,COMDG, PMAX,NAME,CR,PI
        INTEGER NUM2,INC,RE,NAME,TZZERO
        DIMENSION AL(87,ALDIM),AH(87,ALDIM),RE(12),X(10),KK(5),QFACT
       1(5),P(11),N(11),K(11),XX(105,XDIM),NAME(2),      ATOT(5),
       2  TZ(1980,TDIM),TX(  780,TDIM)
        EQUIVALANCE (TZZERO,TZ)
        VECTOR VALUES TDIM = 2,1,13
        VECTOR VALUES ALDIM = 2,0,8
        VECTOR VALUES XDIM = 2,0,21
        ENTRY TO OUTPUT.
        PRINT FORMAT INTRO, NAME...NAME(2),X,BORE/2.54,EA,TPISTN,STRO
       1KE/2.54,TW,ROD/2.54,HCOMB,TMAN,VTOP*61.03,PMAN,61.03*(VBOT-VT
       2OP),PEXH,CR,PI
        WPUMP = (VBOT-VTOP)*(PMAN-PEXH)*24.2179
        WTOT = WTOT + WPUMP
        EFF = WTOT/HCOMB*100./F0
        PRINT FORMAT INTOR1,RPM,INC,ERROR1*100.,KK,QFACT, RE(4)...RE(
       112)
        IMEP = WTOT/(VBOT-VTOP)/24.2179
        VOLEFF = F0*Z*(C*X+X)/(VBOT-VTOP)*R/PMAN*TMAN
        PRINT FORMAT RESULT,WPUMP,WTOT,QTOT,EFF,IMEP,F,VOLEFF
        VECTOR VALUES RESULT = $1H2,S20,18HSUMMARY OF RESULTS/1H0/S6,
       112HPUMPING WORKS18,E15.8,4H CAL/S6,14HNET CYCLE WORKS16,E15.8
       2,4H CAL/S6,19HNET HEAT TRANSFEREDS11,E15.8,4H CAL/S6,28HINDIC
       3ATED THERMAL EFFICIENCYS2,E15.8,8H PERCENT/S6,23HMEAN EFFECTI
       4VE PRESSURES7,E15.8,4H ATM/S6,24HRESIDUAL WEIGHT FRACTION,S6,
       5E15.8/S6,21HVOLUMETRIC EFFICIENCYS9,E15.8,8H PERCENT*$
        NUM2 = TZZERO/13
        PRINT FORMAT HEADER
        VECTOR VALUES HEADER = $1H1/6H0THETAS5,1HTS6,1HPS5,1HVS9,1HH,
       1 S9,1HSS9,1HUS9,1HNS9,1HQS8,4HQTOTS7,1HWS8,4HWTOTS7,2HHB*$
        PRINT FORMAT TABLE1,TZ(1,1)...TZ(NUM2,13)
        VECTOR VALUES TABLE1 = $1H F6.2,F8.2,F7.2,F8.5,9F10.5*$
        PRINT FORMAT HEADR1
        VECTOR VALUES HEADR1 = $1H1/6H0THETAS5,1HTS6,1HPS5,1HVS9,1HH,
       1 S9,1HSS9,1HUS9,1HNS5,50HFLAME SPEED, TEMP., AND EXTENT MASS-
       2FR. BURN.-VOL.*$
        PRINT FORMAT TABLE1,TX(1,1)...TX(INC,13)
        FUNCTION RETURN
        VECTOR VALUES INTRO = $1H1,S35,49HA MODEL SIMULATING THE INTE
       1RNAL-COMBUSTION ENGINE/7H0ENGINES33,4HFUELS36,20HOPERATING CO
       2NDITIONS/28H0FOUR STROKE AUTOMOTIVE TYPES12,3C6,S22,14HAIR-FU
       3EL RATIO F9.2/5H BORES8,F10.2,4H IN.S13,17HACTIVATION ENERGY
       4F10.2,24H CAL./MOLE   PISTON TEMP F12.2,2H K/7H STROKES6,F10.
       52,4H IN.S13,11HENTHALPY OFS29,9HWALL TEMPF14.2,2H K/4H RODS9,
       6F10.2,4H IN.S13,10HCOMBUSTIONF17.2,22H CAL/MOLE    MAN. TEMP
       7F14.2,2H K/12H CLEAR. VOL.F11.2,7H CU.IN.S50,8HMAN. PR.F15.2,
       84H ATM/11H SWEPT VOL.F12.2,7H CU.IN.S50,8HEXH. PR.F15.2,4H AT
       9M/18H COMPRESSION RATIOF5.2,7H TO ONES50,10HSPARK ADV.F13.2*$
        VECTOR VALUES INTOR1 = $S80,5HSPEEDS10,F8.2,4H RPM/ 21H0COMBU
       1STION OCCURS IN I3,34H INCREMENTS.  ERRORS ARE LESS THAN F10.
       25,33H PERCENT.  FLAME SPEED FACTOR IS E15.8/24H HEAT TRANSFER
       3 FACTOR IS F10.5,S3,10C6*$

$COMPILE MAD,PRINT OBJECT,PUNCH OBJECT                         4QTRAN01
        EXTERNAL FUNCTION(TB,TU,PR,DT,ANS,HB)
        DIMENSION AL(87,ALDIM),AH(87,ALDIM),RE(12),X(10),KK(5),QFACT
       1(5),P(11),K(11),XX(105,XDIM),A(5)
        PROGRAM COMMON AL, AH,P,K,R1,NC,NH,NO,NN,R,J2,RE,KK,X,TW,QFAC
       1T,EA,RATIO,B0,RHO,SPEED,ERROR2,CPF,TPISTN,A,XX,XNUM,BORE,STRO
       2KE,ROD,VTOP,VBOT,PMAN,PEXH,TMAN,RPM
        VECTOR VALUES ALDIM = 2,0,8
        VECTOR VALUES XDIM = 2,0,21
        ENTRY TO QTRAN2.
        S = RPM/3000.*STROKE
        HB = 2.1*SQRT.(PR*TB)*S.P..33/36000.
        HU = 2.1*SQRT.(PR*TU)*S.P..33/36000.
        FUNCTION RETURN DT*(HB*(ANS(1)*(TB-TW)+ANS(3)*(TB-TPISTN)) +
       1HU*(ANS(2)*(TU-TW)+ANS(4)*(TU-TPISTN)))*QFACT
        END OF FUNCTION
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$COMPILE MAD,PRINT OBJECT,PUNCH OBJECT                            6ANS0001
           EXTERNAL FUNCTION (VB,VTOT,ANS,D1,D2)
           PROGRAM COMMON AL, AH,P,K,R1,NC,NH,NO,NN,R,J2,RE,KK,X,TW,QFAC
          1T,EA,RATIO,BO,RHO,SPEED,ERROR2,CPF,TPISTN,A,XX,XNUM,BORE,
          2STROKE,ROD,VTOP,VBOT,PMAN,PEXH,TMAN,RPM,N,THETA,ERROR1
           ERASABLE LOP,L1P,L2P,DER,DVWRF,NEXTF,I0,XMUM,F,DL,I1,I2,I3,
          1L0,L1,L2,AW,AWB,AWU,S,Q,QQ,DIF
           INTEGER I,I0,I1,I2,XNUM,I3,J2
           DIMENSION AL(87,ALDIM),AH(87,ALDIM),RE(12),X(10),KK(5),QFACT
          1(5),P(11),K(11),XX(105,XDIM),A(5),N(11)
           VECTOR VALUES ALDIM = 2,0,8
           VECTOR VALUES XDIM = 2,0,21
           ENTRY TO AREA.
           J2 = 0
           XDIM(2) = XNUM
           XMUM = XNUM - 1
           DL = STROKE/2.*(1.+COS.(THETA*.01745)) + ROD*(1.-SQRT.(1.-
          1(STROKE/2.*SIN.(THETA*.01745)/ROD).P.2))
           WHENEVER THETA .G. 180.,TRANSFER TO DOWN
           F = VB/VTOT*XMUM
           WHENEVER VB/VTOT .L..03
           ANS(5) = (VB/.0041888).P..33
           OTHERWISE
           I1 = F + .5
           WHENEVER I1.LE.1,I1 = 2
           WHENEVER I1.GE.XNUM-1,I1 = I1 - 1
           I2 = I1 + 1
           I3 = I2 + 1
           I0 = I1 - 1
           L0 = (F-I1)*(F-I2)/2.
           L1 = (I0-F)*(F-I2)
           L2 = (F-I0)*(F-I1)/2.
           ANS(5) = A(5)*(L0*XX(5,I1) + L1*XX(5,I2) + L2*XX(5,I3))
           END OF CONDITIONAL
           ANS = VB
           F = ANS(5)/A(5)*XMUM
           TRANSFER TO FINISH
DOWN       NEXTF = ANS(5)/A(5)*XMUM
BACK       F = NEXTF
           J2 = J2 + 1
           ANS(5) = F*A(5)/XMUM
           I1 = F + .5
           WHENEVER I1.LE.0,I1 = 1
           WHENEVER I1.GE.XNUM-1,I1 = XNUM-2
           I2 = I1 + 1
           I3 = I2 + 1
           I0 = I1 - 1
           L0 = (F-I1)*(F-I2)/2.
           L1 = (I0-F)*(F-I2)
           L2 = (F-I0)*(F-I1)/2.
           WHENEVER J2.LE.5
           L0P = F-(I1+I2)/2.
           L1P = I0+I2-2.*F
           L2P = F-(I0+I1)/2.
           ANS = VTOP*(L0*XX(4,I1) + L1*XX(4,I2) + L2*XX(4,I3))
           WHENEVER ANS(5).LE.D2
           ANS = ANS + .0031416*ANS(5)*ANS(5)*DL
           DER = .0062832*F*DL*(A(5)/XMUM).P.2
           OTHERWISE
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```
                 ANS = ANS + DL*.ABS.(A(1)*(L0*XX(1,I1)+L1*XX(1,I2)+L2*XX(1,I3
                1))))/1000.
                 DER = DL*A(1)*(L0P*XX(1,I1)+L1P*XX(1,I2)+L2P*XX(1,I3))/1000.
                 END OF CONDITIONAL
                 DVWRF = VTOP*(L0P*XX(4,I1)+L1P*XX(4,I2)+L2P*XX(4,I3))
                 Q = VB-ANS
                 NEXTF = F + Q/(DVWRF+DER)
                 DIF = .ABS.(NEXTF - F)
                 OTHERWISE
                 ANS = VTOP*(L0*XX(4,I1) + L1*XX(4,I2) + L2*XX(4,I3))
                 WHENEVER ANS(5).LE.D2
                 ANS = ANS + .0031416*ANS(5)*ANS(5)*DL
                 OTHERWISE
                 ANS = ANS + DL*.ABS.(A(1)*(L0*XX(1,I1)+L1*XX(1,I2)+L2*XX(1,I3
                1))))/1000.
                 END OF CONDITIONAL
                 QQ = VB-ANS
                 WHENEVER Q/QQ.L.0.,DIF = DIF/2.
                 NEXTF = F+DIF*QQ/.ABS.(QQ)
                 Q = QQ
                 END OF CONDITIONAL
                 WHENEVER .ABS.((NEXTF-F)/F).G..0001,TRANSFER TO BACK
    FINISH       I1 = F + 1.
                 I2 = I1 + 1
                 I0 = I1 - 1
                 L0 = I1 - F
                 L1 = F - I0
                 AW = 3.1416*BORE*(DL + D1)
                 WHENEVER ANS(5).G..99*A(5)
                 AWB = AW
                 AWU = 0.
                 TRANSFER TO END
                 END OF CONDITIONAL
                 WHENEVER ANS(5) .G.D2
                 S = (BORE - D2 + ANS(5))/2.
                 AWB = AW*2./3.1416*ATAN.(SQRT.(      (S-BORE/2.)*(S-BORE/2.+D2
                1)/S/(S-ANS(5))))
                 AWU = AW - AWB
                 OTHERWISE
                 AWU = AW
                 AWB = 0.
                 END OF CONDITIONAL
    END          ANS(1) = A(1)*(L0*XX(1,I1) + L1*XX(1,I2))
                 ANS(2) = A(1) - ANS(1)
                 ANS(1) = ANS(1 ) + AWB
                 ANS(2) = ANS(2) + AWU
                 ANS(3) = A(3)*(L0*XX(3,I1) + L1*XX(3,I2))
                 ANS(4) = A(3) - ANS(3)
                 FUNCTION RETURN
                 END OF FUNCTION


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$COMPILE MAD,PRINT OBJECT,PUNCH OBJECT                          4ENTHL01
           EXTERNAL FUNCTION(N1,N2,PROPTT,TEMP,N)
           DIMENSION AL(87,ALDIM),AH(87,ALDIM),X(10),K(11),P(11),B(5),
          1RE(12),KK(5),QFACT(5)
           ERASABLE B,I,I2,I3,TR,TA,PROPTY
           PROGRAM COMMON AL,AH,P,K,R1,NC,NH,NO,NN,R,J2,RE,KK,X,TW,QFACT
          1,EA,RATIO,B0,RHO,SPEED,ERROR2
           VECTOR VALUES ALDIM = 2,0,8
           ENTRY TO SPRIME.
           B(1) = 1./TEMP
           B(2) = 1.
           B(3) = TEMP
           B(4) = TEMP*TEMP
           TRANSFER TO MATRIX
           ENTRY TO HPRIME.
           B(1) = 1.
           B(2) = TEMP
           B(3) = TEMP*TEMP
           B(4) = TEMP*TEMP*TEMP
           TRANSFER TO MATRIX
           ENTRY TO ENTHAL.
           I = 5
           PROPTY = 0.
           WHENEVER TEMP.G.1500., TRANSFER TO HIGHT
           TR = TEMP/298.16
           B(1) = 298.16*(TR - 1.)
           B(2) = 44449.693*(TR*TR - 1.)
           B(3) = 8835413.6*(TR*TR*TR - 1.)
           B(4) = 1975775200.*(TR*TR*TR*TR - 1.)
           B(5) = 1.
           TRANSFER TO LOW
HIGHT      TR = TEMP/1500.
           B(1) = 1500.*(TR - 1.)
           B(2) = 1125000.*(TR*TR -1.)
           B(3) = 1125000000.*(TR*TR*TR - 1.)
           B(4) = .1265625E13*(TR*TR*TR*TR -1.)
           B(5) = 1.
           TRANSFER TO HIGH
MATRIX     I = 4
           PROPTY = 0.
           WHENEVER TEMP .G. 1500., TRANSFER TO HIGH
LOW        THROUGH SUMB, FOR I2 = N1,1,I2.G.N2
           TA = 0.
           THROUGH SUMA, FOR I3 = 1,1,I3.G.I
SUMA       TA     = TA     + B(I3)*AL(I2,I3)
SUMB       PROPTY = PROPTY + N(I2)*TA
           PROPTT = PROPTY
           FUNCTION RETURN
HIGH       THROUGH ADDA, FOR I2 = N1,1,I2.G.N2
           TA = 0.
           THROUGH ADDB, FOR I3 = 1,1,I3.G.I
ADDB       TA     = TA     + B(I3)*AH(I2,I3)
ADDA       PROPTY = PROPTY + N(I2)*TA
           PROPTT = PROPTY
           FUNCTION RETURN
           INTEGER  I2,I3,N1,N2,I
           END OF FUNCTION
```

```
$COMPILE MAD,PRINT OBJECT, PUNCH OBJECT                           4ENTRP01
          EXTERNAL FUNCTION (N1,N2,PROPTT,TEMP,MOLES,PTOTAL,N)
          DIMENSION AL(87,ALDIM),AH(87,ALDIM),X(10),B(6),K(11),P(11),
         1RE(12),KK(5),QFACT(5),SPACE(5)
          PROGRAM COMMON AL,AH,P,K,R1,NC,NH,NO,NN,R,J2,RE,KK,X,TW,QFACT
         1,EA,RATIO,BO,RHO,SPEED,ERROR1
          ERASABLE SPACE,B,I2,I3,TR,TA,PROPTY
          VECTOR VALUES ALDIM = 2,0,8
          ENTRY TO ENTROP.
          PROPTY = 0.
          WHENEVER TEMP.G.1500., TRANSFER TO BIGHT
          TR = TEMP/298.16
          B(1) = ELOG.(TR)
          B(2) = 298.16*(TR - 1.)
          B(3) = 44449.693*(TR*TR - 1.)
          B(4) = 8835413.6*(TR*TR*TR - 1.)
          B(6) = 1.
          THROUGH BUMB, FOR I2 = N1,1,I2.G.N2
          WHENEVER N(I2) .E. 0.,TRANSFER TO BUMB
          TA = 0.
          THROUGH BUMA, FOR VALUES OF I3 = 1,2,3,4,6
BUMA      TA = TA + B(I3)*AL(J2,I3)
          PROPTY = PROPTY + N(I2)*(TA    -1.9872*ELOG.(N(I2)*PTOTAL/MOL
         1ES))
BUMB      CONTINUE
          PROPTT = PROPTY
          FUNCTION RETURN
BIGHT     TR = TEMP/1500.
          B(1) = ELOG.(TR)
          B(2) = 1500.*(TR - 1.)
          B(3) = 1125000.*(TR*TR -1.)
          B(4) = 1125000000.*(TR*TR*TR - 1.)
          B(6) = 1.
          THROUGH BDDA, FOR I2 = N1,1,I2.G.N2
          WHENEVER N(I2) .E. 0.,TRANSFER TO BDDA
          TA = 0.
          THROUGH BDDB, FOR VALUES OF I3 = 1,2,3,4,6
BDDB      TA = TA + B(I3)*AH(I2,I3)
          PROPTY = PROPTY + N(I2)*(TA    -1.9872*ELOG.(N(I2)*PTOTAL/MOL
         1ES))
BDDA      CONTINUE
          PROPTT = PROPTY
          FUNCTION RETURN
          INTEGER  I2,I3,N1,N2
          END OF FUNCTION

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$COMPILE MAD,PRINT OBJECT,PUNCH OBJECT                        4EQUIL01
           EXTERNAL FUNCTION(TEMP)
           DIMENSION AL(87,ALDIM),AH(87,ALDIM),X(10),K(11),P(11),B(7),
          1RE(12),KK(5),QFACT(5),SPACE(5)
           PROGRAM COMMON AL,AH,P,K,R1,NC,NH,NO,NN,R,J2,RE,KK,X,TW,QFACT
          1,EA,RATIO,BO,RHO,SPEED,ERROR1
           VECTOR VALUES ALDIM = 2,0,8
           ERASABLE SPACE,B,TR,RT,I
           ENTRY TO EQUIL.
           WHENEVER TEMP.LE. 1500.,FUNCTION RETURN
           TR = TEMP/1500.
           RT = 1./TR
           B(1) = (ELOG.(TR)+RT-1.)/1.9872
           B(2) = 750.00*(TR+RT-2.)/1.9872
           B(3) = 375000.00*(TR*TR+2.*RT-3.)/1.9872
           B(4) =281250000.*(TR*TR*TR+3.*RT-4.)/1.9872
           B(7) = (1.-RT)/2980.785
           K(4) = 0.
           THROUGH LOOP7,FOR VALUES OF I = 1,2,3,4,7
LOOP7      K(4) = K(4)+(AH(6,I)+.5*AH(2,I)-AH(4,I)   )*B(I)
           K(4) = EXP.(AH(4,8)  +K(4))
           K(5) = 0.
           THROUGH LOOP8,FOR VALUES OF I = 1,2,3,4,7
LOOP8      K(5) = K(5)+(AH(7,I)+.5*AH(2,I)-AH(5,I))*B(I)
           K(5) = EXP.(AH(5,8)  +K(5))
           K(8) = 0.
           THROUGH LOOP9,FOR VALUES OF I = 1,2,3,4,7
LOOP9      K(8) = K(8)+(.5*(AH(2,I)+AH(7,I))-AH(8,I))*B(I)
           K(8) = EXP.(AH(8,8)  +K(8))
           K(7) = 0.
           THROUGH LOOP10,FOR VALUES OF I = 1,2,3,4,7
LOOP10     K(7) = K(7)+(.5*AH(7,I)-AH(11,I))*B(I)
           K(7) = EXP.(AH(7,8)  +K(7))
           K(9) = 0.
           THROUGH LOOP11,FOR VALUES OF I = 1,2,3,4,7
LOOP11     K(9) = K(9)+(.5*(AH(2,I)+AH(3,I))-AH(9,I))*B(I)
           K(9) = EXP.(AH(9,8)  +K(9))
           K(2) = 0.
           THROUGH LOOP12,FOR VALUES OF I = 1,2,3,4,7
LOOP12     K(2) = K(2)+(.5*AH(2,I)-AH(10,I))*B(I)
           K(2) = EXP.(AH(2,8)  +K(2))
           FUNCTION RETURN
           INTEGER I
           END OF FUNCTION
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$COMPILE MAD,PUNCH OBJECT,PRINT OBJECT                          3AMONT01
              EXTERNAL FUNCTION(TEMP,VOL,MOLES,PHH,N)
              DIMENSION AL(87,ALDIM),AH(87,ALDIM),X(10),K(11),P(11),
             1RE(12),KK(5),QFACT(5),SPACE(5)
              PROGRAM COMMON AL,AH,P,K,R1,NC,NH,NO,NN,R,J1,RE,KK,X,TW,QFACT
             1,EA,RATIO,BO,RHO,SPEED,ERROR1
              ERASABLE SPACE,I,M,S,DNWRL,DMWRL,FL,Q,FPRIML,S4,S3,S2,S1,L,
             1NEXTL,FA
              VECTOR VALUES ALDIM = 2,0,8
              ENTRY TO AMOUNT.
              P(1) = 0.
              FA = TEMP*R/VOL
              WHENEVER TEMP .LE.1500.,TRANSFER TO H2OGAS
              WHENEVER PHH.LE.0.,PHH = 1.
              NEXTL = PHH
              J1 = 0
LOOP1         L = NEXTL
              J1 = J1 +1
              S1 = L/K(8) + 1./K(7)
              S2 = 4.*(1. + L/K(5))
              S3 = SQRT.(L*L/K(9)/K(9)+8.*FA*NN)
              S4 = SQRT.(S1*S1 + 2.*S2*FA*NH)
              M = (S4 - S1)/S2
              S = S3/4. - L/4./K(9)
              DNWRL = (L/K(9)/S3-1.)/4./K(9)
              DMWRL = -(S2*(1./K(8)-(S1/K(8)+4.*FA*NH/K(5))/S4)+(S4-S1)*4./
             1K(5))/S2/S2
              P(2) = L*L
              P(3) = S*S
              P(4) = NC*FA/(K(4)/L + 1.)
              P(5) = L*M*M/K(5)
              P(6) = P(4)*K(4)/L
              P(7) = M*M
              P(8) = L*M/K(8)
              P(9) = S*L/K(9)
              P(10) = L/K(2)
              P(11) = M/K(7)
              FL = 2.*(P(2) + P(4))+P(5) + P(6)+P(9)+P(8)+P(10) - FA*NO
              FPRIML  = FA*NC*K(4)/(L+K(4))/(L+K(4))+4.*L+M*M/K(5)+ M/K(8)+
             1S/K(9)+1./K(2)+DMWRL*(L/K(8)+2.*L*M/K(5)) +DNWRL/K(9)*L
              Q = -FL/L/FPRIML
              WHENEVER .ABS.(Q) .L.16.
              NEXTL = L*EXP.(Q)
              OTHERWISE
              NEXTL = L*EXP.(Q/.ABS.(Q))
              END OF CONDITIONAL
              WHENEVER .ABS.((NEXTL-L)/L).G.ERROR1,TRANSFER TO LOOP1
              PHH = L
              TRANSFER TO LOC2
H2OGAS        WHENEVER (NC+NH/4.)/NO.LE..5,TRANSFER TO SIMPLE
              S1 = NO/NC-1.
              S3 = (1.+NH/NC/.7494)/S1-1.6688
              L = (S3+SQRT.(S3*S3+6.6752/S1))/2.
              P(2) = 0.
              P(4) = FA*NC/L
              P(5) = FA*(NO-NC)-P(4)
              P(6) = .ABS.(FA*NC-P(4))
              P(7) = .ABS.(FA*NH/2. -P(5))
              TRANSFER TO HERR
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SIMPLE     P(2) = .ABS.(FA*(NO/2.-NC-NH/4.))
           P(4) = FA*NC
           P(5) = FA*NH/2.
           P(6) = 0.
           P(7) = 0.
HERR       P(8) = 0.
           P(9) = 0.
           P(10) = 0.
           P(11) = 0.
           P(3) = FA*NN/2.
           PHH = 1.
LOC2       MOLES = 0.
           THROUGH LOOP2, FOR I = 1,1,I.G.11
           N(I) = P(I)/FA
LOOP2      MOLES = MOLES + N(I)
           FUNCTION RETURN
           INTEGER I,J1
           END OF FUNCTION
$COMPILE MAD ,PUNCH OBJECT,PRINT OBJECT                              4FLAME01
           EXTERNAL FUNCTION (T0,TF,ST,R2)
           DIMENSION AL(87,ALDIM),AH(87,ALDIM),X(10),K(11),P(11),
          1RE(12),KK(5),QFACT(5),LOC(3)
           VECTOR VALUES ALDIM = 2,0,8
           PROGRAM COMMON AL,AH,P,K,R1,NC,NH,NO,NN,R,J2,RE,KK,X,TW,QFACT
          1,EA,RATIO,B0,RHO,SPEED,ERROR1,CPF
           ENTRY TO STURB.
           WHENEVER .ABS.(X-1.).GE..05
           J = 1
           OTHERWISE
           J = 2
           S2 = X
           X = .95
           END OF CONDITIONAL
LOC1       WHENEVER X.GE.1.05
           PHI = 1./X
           OTHERWISE
           PHI = X
           END OF CONDITIONAL
           S1 = R1*TF/EA*TF/(TF-T0)
           AE = S1*T0/TF
           BE = B0*T0/TF*(1.-PHI*(1.-S1))
           LAMDA = (TF.P..67)*(CPF+1.25*R2)
           WDT = AE*BE*SQRT.(TF)*S1* EXP.(-EA/R1/TF)
           BRAKT = 1.+1.25*R2/CPF
           ST = KK*BRAKT*RATIO*SQRT.(LAMDA*WDT/RHO/CPF)
           TRANSFER TO LOC(J)
LOC(1)     WHENEVER RE(7).E.$HELP  $
           KK(1) = SPEED/ST
           KK = KK(1)
           ST = SPEED
           RE(7) = 0
           END OF CONDITIONAL
           FUNCTION RETURN
LOC(2)     J = 3
           X = 1.05
           Z = ST
           TRANSFER TO LOC1
LOC(3)     X = S2
           ST = Z+10.*(X-.95)*(ST-Z)
           TRANSFER TO LOC(1)
           INTEGER J,RE
           END OF FUNCTION
```

APPENDIX J

SPECIAL THERMODYNAMIC CONSIDERATIONS ASSOCIATED WITH INTER-RELATED STATE CHANGES OF TWO DISTINCT GASEOUS REGIONS

A. Isentropic Change of Volume of Each Region

Step 4 of the combustion process involves an isentropic change of volume of each of two gaseous regions. The two regions (burned and unburned) initially occupy a volume V and finally a volume V'. Pressure equilibrium is maintained between the regions. The fraction of the total volume occupied initially by each portion is known. It is desired to find what part of the total volume is occupied by the burned portion after the volume change.

The burned gas is presumed to be initially at P, T_b, V_b, and S_b whereas the unburned gas is at P, T_u, V_u, and S_u. After the volume change the burned gas is at P', T_b', V_b', and S_b' and the unburned gas at P', T_u', V_u', and S_u'. Let the ratio of the heat capacity at constant pressure to that at constant volume be k_u and k_b for the two regions at the initial volume and the difference between them $k_u - k_b = \delta$.

In the unburned gas, for this isentropic volume change,

$$\left(\frac{V_u'}{V_u}\right)^{k_u} = \frac{P}{P'}$$

and in the burned,

$$\left(\frac{V_b'}{V_b}\right)^{k_b} = \frac{P}{P'}$$

Equation these

$$\left(\frac{V_u'}{V_u}\right)^{k_u} = \left(\frac{V_b'}{V_b}\right)^{k_u+\delta} = \left(\frac{V_b'}{V_b}\right)^{k_u} \cdot \left(\frac{V_b'}{V_b}\right)^{\delta}$$

or

$$\frac{V'_u}{V_u} = \frac{V'_b}{V_b} \cdot \left(\frac{V'_b}{V_b}\right)^{\delta/k_u} = \frac{V'_b}{V_b} \cdot \kappa$$

where κ can be thought of as a correction factor to account for the differences in the heat capacity ratios.

Solving the above expression for V'_b and substitution $V' = V'_b + V'_u$

$$V'_b = \frac{V'}{1 + V_u/V_b \cdot \kappa}$$

The correction factor κ can be approximated by assuming that $\frac{V'_b}{V_b} = \frac{V'}{V}$. Thus the final expression for the volume of the burned portion after the isentropic change of volume is

$$V'_b \cong \frac{V'}{1 + \left(\frac{V_u}{V_b}\right) \cdot \left(\frac{V'}{V}\right)^{\delta/k_u}} \qquad \text{(J-1)}$$

B. Change of Volume with Known Values of Internal Energy and Entropy

Step 3 of the combustion process involves the recompression of the system to a specified final volume and internal energy while maintaining the entropy of the unburned portion constant. Pressure equilibrium is maintained between both portions. It is desired to estimate the pressure of the system after this compression.

The n_b moles of burned gas are presumed to be initially at P, T_b, V_b, and U_b and have heat capacity C_{p_b}. The n_u moles of unburned gas are presumed to be initially at P, T_u, V_u, and U_u and have heat capacity C_{p_u}. After the change in volume the burned gas has properties P, T'_b, V'_b, and U'_b and the unburned gas properties P, T'_u, V'_u, and U'_u. The initial total internal energy is $U = U_u + U_b$ and volume $V = V_u + V_b$. The final internal energy is $U' = U'_u + U'_b$ and volume is $V' = V'_u + V'_b$. These four quantities are known.

The change in internal energy of the unburned portion for this isentropic process is

$$U'_u - U_u = n_u C_{v_u} T_u \left[\left(\frac{P}{P'}\right)^{R/C_{p_u}} - 1 \right]$$

The change of internal energy in the burned portion is

$$U'_b - U_b = n_b C_{v_b} \left[T'_b - T_b \right] = n_b C_{v_b} \left[\frac{P'V'_b}{n_b R} - T_b \right]$$

$$= \frac{C_{v_b} P'}{R} (V' - V'_u) - n_b C_{v_b} T_b$$

The total change of internal energy for the system is the sum of the changes in each portion and is

$$U' - U = U'_b - U_b + U'_u - U_u$$

$$= n_u C_{v_u} T_u \left(\frac{P}{P'}\right)^{R/C_{p_u}} - n_u T_u (C_{v_u} + C_{v_b}) - n_b T_b C_{v_b} + C_{v_b} \frac{P'V'}{R}$$

Rearranging

$$P' = \frac{R}{V'} \left\{ \frac{U'-U}{C_{v_b}} + n_b T_b + n_u T_u + \frac{C_{v_u}}{C_{v_b}} n_u T_u \left[1 - \left(\frac{P}{P'}\right)^{R/C_{p_u}} \right] \right\}$$

Neglecting the bracketted term as being small compared to the other terms the expression for the final pressure becomes:

$$P' \cong \frac{R}{V'} \left\{ \frac{U' - U}{C_{v_b}} + n_b T_b + n_u T_u \right\} \qquad \text{(J-2)}$$

Neglecting this term amounts to assuming that the entire internal energy decrease occurs in the burned portion.

APPENDIX K

CALCULATED DATA

The data sets presented are separated into three groups according to whether the flame propagation rate is normal, rapid, or reduced. These are referred to as Data Set A, B, and C respectively.

Each set of data presented consists of four pages. The first page describes the current operating conditions of the engine and presents the results of the calculations. The second and third pages present the total system thermodynamic properties and other information as a function of crank angle. The fourth page presents the thermodynamic properties of the burned gas region and other information during the course of the combustion process only as a function of crank angle. The data following are given in the following notation and units:

THETA	crank angle degrees, 0° = BDC
T	gas temperature, °K
P	cylinder pressure, atm
V	volume, liters
H	enthalpy, cal
S	entropy, cal/°K
U	internal energy, cal
N	moles
Q	incremental heat transfer, cal
QTOT	total heat transfer, cal
W	incremental work, cal
WTOT	total work, cal

HB	heat transfer coefficient in burned gas region, cal/cm^2-°K (from Equation (5-18))
FLAME SPEED	flame propagation rate, cm/sec (from Equation (4-24))
FLAME TEMPERATURE	effective flame temperature, °K (calculated in Step 7 of the combustion process)
EXTENT OF FLAME PROPAGATION	radius of spherical flame front, cm (corresponds to R'_0 in Figure 10-a)
MASS-FR. BURNED	mass fraction burned
VOL.-FR. BURNED	volume fraction occupied by burned gas

For all the data calculated using the analytical model in Data Sets A, B, and C, the exhaust temperature is 1000°K. During each cycle 0.00033 moles of fuel are inducted together with 0.0038 moles of O_2 and 0.0143 moles of N_2. For the number of increments considered in the calculations about 25 minutes of computer time are required on the IBM 709 for each set of operating conditions.

DATA SET A

NORMAL FLAME PROPAGATION RATES

```
                              A MODEL SIMULATING THE INTERNAL-COMBUSTION ENGINE

 ENGINE                                 FUEL                                    OPERATING CONDITIONS

 FOUR STROKE AUTOMOTIVE TYPE            OCTANE C8H18                            AIR-FUEL RATIO       .92
 BORE                3.94 IN.           ACTIVATION ENERGY  39000.00 CAL./MOLE   PISTON TEMP       500.00 K
 STROKE              2.46 IN.           ENTHALPY OF                             WALL TEMP         420.00 K
 ROD                 7.06 IN.           COMBUSTION        1222770.00 CAL/MOLE   MAN. TEMP         320.00 K
 CLEAR. VOL.         3.33 CU.IN.                                                MAN. PR.             .99 ATM
 SWEPT VOL.         30.00 CU.IN.                                                EXH. PR.            1.03 ATM
 COMPRESSION RATIO10.00 TO ONE                                                  SPARK ADV.         16.00
                                                                                SPEED            2800.00 RPM

 COMBUSTION OCCURS IN 39 INCREMENTS.  ERRORS ARE LESS THAN    .00100 PERCENT.  FLAME SPEED FACTOR IS   .13550000E 06
 HEAT TRANSFER FACTOR IS    1.00000   NORMAL RUN

                      SUMMARY OF RESULTS

      PUMPING WORK                    -.47611947E 00 CAL
      NET CYCLE WORK                   .14767102E 03 CAL
      NET HEAT TRANSFERED              .70592567E 02 CAL
      INDICATED THERMAL EFFICIENCY     .36569741E 02 PERCENT
      MEAN EFFECTIVE PRESSURE          .12406213E 02 ATM
      RESIDUAL WEIGHT FRACTION         .33289108E-01
      VOLUMETRIC EFFICIENCY            .97627462E 00 PERCENT
```

THETA	T	P	V	H	S	U	N	Q	QTOT	W	WTOT	HB
.00	344.84	.99	.54611	-22.58769	.95518	-35.68175	.01911	.00000	.00000	.00000	.00000	.00000
10.00	345.51	1.00	.54302	-22.48808	.95518	-35.60766	.01911	.00000	.00000	-.07409	-.07409	.00000
20.00	347.55	1.02	.53380	-22.18514	.95518	-35.38210	.01911	.00000	.00000	-.22555	-.29965	.00000
30.00	351.01	1.06	.51855	-21.66938	.95518	-34.99796	.01911	.00000	.00000	-.38415	-.68380	.00000
40.00	356.02	1.12	.49750	-20.92281	.95518	-34.44157	.01911	.00000	.00000	-.55639	-1.24019	.00000
50.00	362.73	1.21	.47096	-19.91986	.95518	-33.69353	.01911	.00000	.00000	-.74803	-1.98822	.00000
60.00	371.37	1.33	.43941	-18.62534	.95518	-32.72705	.01911	.00000	.00000	-.96649	-2.95471	.00000
70.00	382.23	1.49	.40348	-16.99272	.95518	-31.50656	.01911	.00000	.00000	-1.22048	-4.17519	.00000
80.00	395.67	1.70	.36400	-14.96164	.95518	-29.98581	.01911	.00000	.00000	-1.52076	-5.69595	.00000
90.00	412.16	2.01	.32199	-12.45483	.95518	-28.10524	.01911	.00000	.00000	-1.88057	-7.57652	.00000
100.00	432.28	2.43	.27867	-9.37447	.95518	-25.78904	.01911	.00000	.00000	-2.31620	-9.89272	.00000
110.00	456.74	3.04	.23542	-5.59927	.95518	-22.94252	.01911	.00000	.00000	-2.84652	-12.73924	.00000
120.00	486.33	3.94	.19371	-.98560	.95518	-19.45242	.01911	.00000	.00000	-3.49010	-16.22933	.00000
130.00	521.84	5.28	.15510	4.61714	.95518	-15.19795	.01911	.00000	.00000	-4.25447	-20.48381	.00000
140.00	563.67	7.30	.12106	11.31073	.95518	-10.09294	.01911	.00000	.00000	-5.10500	-25.58881	.00000
150.00	610.94	10.30	.09296	18.99131	.95518	-4.20704	.01911	.00000	.00000	-5.88590	-31.47471	.00000
160.00	659.41	14.36	.07199	26.99693	.95518	1.95803	.01911	.00000	.00000	-6.16508	-37.63979	.00000
164.00	677.09	16.13	.06580	29.94867	.95518	4.23851	.01911	.00000	.00000	-2.28048	-39.92026	.00000
166.95	688.74	17.40	.06209	31.90476	.95521	5.74418	.01911	.00000	.00000	-1.50567	-41.42593	.00000
169.07	696.63	18.30	.05987	33.23635	.95547	6.70610	.01911	.00000	.00000	-.96192	-42.38785	.00000
171.43	705.94	19.41	.05785	34.82764	.95664	7.63212	.01912	.00000	.00000	-.92602	-43.31387	.00000
172.60	711.73	20.13	.05704	35.83153	.95808	8.02685	.01912	.00000	.00000	-.39473	-43.70860	.00000
174.20	720.72	21.29	.05611	37.42886	.96096	8.50117	.01914	.00000	.00000	-.47432	-44.18292	.00000
176.53	734.82	23.22	.05515	39.91459	.96663	8.89990	.01917	.13470	.13470	-.53343	-44.71635	.02559
177.99	746.13	24.87	.05480	42.02377	.97225	9.01625	.01920	.09865	.23335	-.21499	-44.93134	.02651
179.06	756.12	26.41	.05465	43.98577	.97785	9.02613	.01923	.08185	.31520	-.09173	-45.02308	.02737
179.91	765.28	27.89	.05461	45.87238	.98341	8.98449	.01927	.07233	.38753	-.03069	-45.05377	.02819
180.96	777.84	30.03	.05465	48.59813	.99170	8.85165	.01931	.10255	.49008	.03029	-45.02348	.02935
181.84	789.33	32.11	.05476	51.24756	.99992	8.67122	.01936	.09582	.58590	.08461	-44.93887	.03043
182.51	800.05	34.15	.05488	53.87490	1.00810	8.48504	.01941	.07948	.66538	.10669	-44.83217	.03147
183.08	810.12	36.16	.05502	56.47580	1.01623	8.28802	.01946	.07324	.73862	.12378	-44.70839	.03246
183.57	819.61	38.15	.05516	59.05734	1.02431	8.08464	.01951	.06778	.80640	.13560	-44.57279	.03342
184.02	828.60	40.12	.05531	61.61343	1.03234	7.86884	.01956	.06625	.87265	.14955	-44.42324	.03435
184.47	837.06	42.05	.05548	64.11919	1.04033	7.61939	.01961	.07129	.94393	.17816	-44.24508	.03524
184.93	845.04	43.94	.05566	66.56620	1.04828	7.32792	.01966	.08227	1.02621	.20919	-44.03588	.03609
185.40	852.56	45.79	.05587	68.95552	1.05619	6.99509	.01971	.10699	1.13320	.22584	-43.81004	.03690
185.88	859.63	47.58	.05611	71.25861	1.06405	6.59611	.01976	.13497	1.26817	.26402	-43.54602	.03768
186.21	866.66	49.42	.05629	73.63648	1.07188	6.26394	.01981	.10813	1.37630	.22404	-43.32199	.03845
186.76	872.81	51.08	.05660	75.67922	1.07965	5.65715	.01986	.21183	1.58813	.39496	-42.92703	.03915
187.43	878.28	52.60	.05701	77.46046	1.08736	4.83613	.01990	.29193	1.88006	.52909	-42.39794	.03976
188.52	882.06	53.66	.05777	78.38318	1.09496	3.30118	.01995	.53737	2.41744	.99757	-41.40036	.04019
190.17	883.26	54.01	.05911	77.96202	1.10242	.64654	.02000	.88447	3.30190	1.77017	-39.63019	.04029
191.85	883.35	54.03	.06071	76.98236	1.10983	-2.47204	.02004	.98789	4.28979	2.13070	-37.49949	.04024
193.51	882.61	53.82	.06254	75.57424	1.11722	-5.94615	.02009	1.06001	5.34979	2.41410	-35.08539	.04008
195.13	881.26	53.44	.06454	73.82680	1.12458	-9.70149	.02013	1.11630	6.46609	2.63904	-32.44635	.03985
196.44	880.80	53.31	.06632	72.64261	1.13201	-12.98484	.02018	.95198	7.41807	2.33137	-30.11498	.03973
197.88	879.18	52.85	.06845	70.78064	1.13940	-16.83239	.02022	1.08668	8.50475	2.76088	-27.35410	.03949
199.42	876.56	52.12	.07090	68.32371	1.14675	-21.17425	.02026	1.19268	9.69743	3.14918	-24.20492	.03913
201.49	870.44	50.44	.07451	63.64074	1.15393	-27.36808	.02030	1.63308	11.33051	4.56075	-19.64417	.03836
203.19	866.02	49.25	.07771	60.02453	1.16124	-32.66965	.02035	1.36009	12.69060	3.94147	-15.70270	.03777
204.63	862.83	48.41	.08060	57.17817	1.16864	-37.32830	.02039	1.16936	13.85996	3.48929	-12.21340	.03734
206.30	857.98	47.16	.08417	53.23574	1.17598	-42.89579	.02043	1.36493	15.22488	4.20257	-8.01084	.03675
208.12	852.04	45.66	.08828	48.52314	1.18329	-49.09771	.02047	1.48224	16.70712	4.71968	-3.29115	.03604
210.07	845.15	43.97	.09296	43.14433	1.19058	-55.84725	.02051	1.57872	18.28584	5.17081	1.87966	.03522
212.11	837.57	42.17	.09817	37.23652	1.19788	-63.02759	.02055	1.64746	19.93330	5.53287	7.41253	.03435
214.77	826.30	39.61	.10535	28.71628	1.20504	-72.35293	.02059	2.08528	22.01858	7.24007	14.65260	.03310
219.21	804.27	35.12	.11840	13.87493	1.21206	-86.84225	.02063	2.52313	24.54172	11.96619	26.61879	.03083

```
225.00 2354.77  29.03  .13718  -9.21567   1.21028-105.66115   .02061  4.35938 28.90110 14.45951  41.07830   .03067
230.00 2270.55  24.79  .15485 -27.42208   1.20887-120.38681   .02060  3.29765 32.19875 11.42801  52.50631   .02729
235.00 2191.68  21.33  .17366 -44.04207   1.20756-133.76017   .02060  2.95586 35.15461 10.41750  62.92381   .02476
240.00 2118.57  18.51  .19344 -59.18444   1.20634-145.90009   .02060  2.66634 37.82095  9.47359  72.39739   .02257
245.00 2051.32  16.20  .21399 -72.94759   1.20520-156.90549   .02060  2.42177 40.24272  8.58363  80.98102   .02067
250.00 1989.72  14.30  .23513 -85.44770   1.20412-166.88152   .02060  2.21523 42.45795  7.76080  88.74182   .01903
255.00 1933.41  12.73  .25665 -96.80103   1.20309-175.92871   .02060  2.04035 44.49830  7.00684  95.74866   .01761
260.00 1881.96  11.42  .27837-107.12217   1.20211-184.14319   .02059  1.89164 46.38993  6.32284 102.07150   .01638
265.00 1834.95  10.33  .30012-116.51292   1.20117-191.60929   .02059  1.76448 48.15441  5.70162 107.77313   .01531
270.00 1791.97   9.41  .32170-125.06549   1.20026-198.40270   .02059  1.65513 49.80954  5.13829 112.91142   .01437
275.00 1752.67   8.64  .34295-132.86139   1.19939-204.58994   .02059  1.56056 51.37010  4.62668 117.53809   .01356
280.00 1716.71   7.98  .36372-139.97358   1.19855-210.23030   .02059  1.47834 52.84844  4.16202 121.70011   .01284
285.00 1683.80   7.41  .38385-146.46600   1.19772-215.37558   .02059  1.40647 54.25490  3.73882 125.43892   .01221
290.00 1653.67   6.93  .40322-152.39512   1.19693-220.07146   .02059  1.34335 55.59825  3.35253 128.79145   .01166
295.00 1626.08   6.52  .42170-157.81086   1.19614-224.35823   .02059  1.28768 56.88593  2.99909 131.79054   .01117
300.00 1600.71   6.16  .43918-162.78120   1.19538-228.29032   .02059  1.23838 58.12431  2.69371 134.48425   .01074
305.00 1577.51   5.85  .45556-167.31917   1.19462-231.87854   .02059  1.19436 59.31866  2.39386 136.87811   .01036
310.00 1556.30   5.59  .47076-171.45878   1.19388-235.15024   .02059  1.15513 60.47379  2.11658 138.99469   .01003
315.00 1536.95   5.36  .48471-175.22989   1.19314-238.12943   .02059  1.12009 61.59388  1.85910 140.85379   .00973
320.00 1519.33   5.16  .49734-178.65873   1.19242-240.83716   .02059  1.08874 62.68261  1.61899 142.47278   .00947
325.00 1503.33   4.99  .50859-181.76815   1.19172-243.29176   .02059  1.06067 63.74328  1.39394 143.86671   .00924
330.00 1488.61   4.85  .51843-184.57576   1.19104-245.49704   .02059  1.03552 64.77880  1.16976 145.03647   .00905
335.00 1475.48   4.73  .52681-187.09629   1.19036-247.48017   .02059  1.01262 65.79142   .97050 146.00697   .00887
340.00 1463.72   4.63  .53371-189.35049   1.18969-249.25326   .02059   .99237 66.78379   .78073 146.78770   .00872
345.00 1453.28   4.56  .53911-191.35099   1.18902-250.82639   .02059   .97432 67.75811   .59881 147.38651   .00860
350.00 1444.10   4.49  .54298-193.10823   1.18836-252.20789   .02059   .95832 68.71642   .42318 147.80969   .00849
355.00 1436.14   4.45  .54531-194.63063   1.18770-253.40450   .02059   .94422 69.66065   .25240 148.06208   .00841
360.00 1429.37   4.42  .54611-195.92474   1.18705-254.42149   .02059   .93192 70.59257   .08506 148.14715   .00834
360.00 1036.55   1.03 1.70051-268.95662   1.18705-311.37718   .02059   .00000 70.59257   .00000 148.14715   .00000
540.00 1000.00   1.03  .05461  -9.17099    .03930 -10.53334   .00069   .00000 70.59257   .00000 148.14715   .00000
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THETA      T        P       V          H           S          U          N      FLAME SPEED, TEMP., AND EXTENT MASS-FR. BURN.-VOL.
 166.95 2541.13   17.40  .00002      .00381      .00013    -.00663     .00000 677.421912541.13266     .18781    .00010    .00040
 169.07 2541.51   18.30  .00024      .03787      .00125    -.06653     .00002 692.355792538.89896     .39187    .00100    .00394
 171.43 2550.06   19.41  .00111      .19925      .00623    -.32458     .00010 715.489092548.37943     .65387    .00500    .01926
 172.60 2554.17   20.13  .00215      .40749      .01246    -.64186     .00021 727.480672546.29190     .80122    .01000    .03774
 174.20 2565.35   21.29  .00409      .86935      .02489   -1.23883     .00041 751.762422558.72079    1.04280    .02000    .07288
 176.53 2572.67   23.22  .00752     1.79698      .04966   -2.43133     .00083 790.769132578.12265    1.35169    .04000    .13633
 177.99 2585.69   24.87  .01058     2.88413      .07439   -3.49138     .00124 819.177862581.62408    1.56528    .06000    .19315
 179.06 2598.75   26.41  .01336     4.10342      .09908   -4.44179     .00165 845.774252586.87708    1.70606    .08000    .24443
 179.91 2611.26   27.89  .01589     5.44104      .12375   -5.29383     .00207 870.956432592.35233    1.83262    .10000    .29101
 180.96 2628.34   30.03  .01932     7.62968      .16069   -6.42052     .00269 908.714442607.40726    1.97243    .13000    .35349
 181.84 2643.99   32.11  .02238    10.02125      .19758   -7.37835     .00331 941.951772614.08182    2.08508    .16000    .40867
 182.51 2658.76   34.15  .02513    12.61288      .23441   -8.16959     .00393 974.165472620.85892    2.17251    .19000    .45786
 183.08 2672.52   36.16  .02762    15.37513      .27119   -8.81863     .004561005.250952627.35922    2.24560    .22000    .50207
 183.57 2685.38   38.15  .02990    18.29329      .30793   -9.33773     .005181035.373752633.62735    2.28734    .25000    .54207
 184.02 2697.35   40.12  .03200    21.34726      .34462   -9.74371     .005801064.551792639.61224    2.34508    .28000    .57849
 184.47 2708.34   42.05  .03394    24.50578      .38126  -10.06258     .006421092.627792645.21103    2.40259    .31000    .61183
 184.93 2718.37   43.94  .03576    27.74849      .41786  -10.31192     .007051119.665222650.52722    2.46055    .34000    .64250
 185.40 2727.58   45.79  .03748    31.06672      .45443  -10.49855     .007671145.648652655.54974    2.51891    .37000    .67083
 185.88 2735.85   47.58  .03912    34.42420      .49095  -10.65320     .008291170.526892660.26102    2.57856    .40000    .69712
 186.21 2744.30   49.42  .04062    37.93510      .52743  -10.67959     .008911195.864582665.58032    2.62837    .43000    .72158
 186.76 2750.36   51.08  .04213    41.26746      .56385  -10.85782     .009541218.355682669.13165    2.69646    .46000    .74441
 187.43 2754.77   52.60  .04366    44.46488      .60022  -11.15100     .010161238.501462672.33578    2.78304    .49000    .76580
 188.52 2754.27   53.66  .04540    47.00599      .63647  -11.99919     .010781251.898962672.59021    3.05689    .52000    .78587
 190.17 2746.75   54.01  .04757    48.45000      .67259  -13.77300     .011401255.709172669.75861    3.28398    .55000    .80479
 191.85 2737.07   54.03  .04995    49.43100      .70866  -15.93564     .012021255.643162668.16519    3.53648    .58000    .82269
 193.51 2726.06   53.82  .05251    50.04192      .74470  -18.40787     .012641252.554982666.35791    3.78516    .61000    .83966
 195.13 2714.21   53.44  .05523    50.34526      .78072  -21.13637     .013251247.214262664.38669    4.02183    .64000    .85577
 196.44 2706.03   53.31  .05777    51.14469      .81680  -23.44572     .013871245.817322665.37772    4.20755    .67000    .87110
 197.88 2695.19   52.85  .06062    51.32358      .85284  -26.27425     .014491239.269042662.36621    4.38379    .70000    .88568
 199.42 2682.25   52.12  .06378    50.93790      .88885  -29.57320     .015101229.409322659.01791    4.56171    .73000    .89958
 201.49 2659.69   50.44  .06801    48.44779      .92469  -34.62855     .015721205.231982648.91498    4.78342    .76000    .91283
 203.19 2643.06   49.25  .07192    46.89510      .96065  -38.89337     .016331189.783742648.10764    4.97720    .79000    .92549
 204.63 2630.69   48.41  .07557    46.02615      .99671  -42.58297     .016951178.567762647.42303    5.12571    .82000    .93759
 206.30 2614.07   47.16  .07989    44.07098     1.03270  -47.17369     .017571160.505782641.16153    5.27697    .85000    .94916
 208.12 2594.79   45.66  .08477    41.31735     1.06867  -52.42111     .018181138.923392634.84943    5.43334    .88000    .96022
 210.07 2573.36   43.97  .09025    37.84918     1.10462  -58.25411     .018791114.177922627.88657    5.59139    .91000    .97082
 212.11 2550.41   42.17  .09630    33.78652     1.14057  -64.56934     .019411087.728002620.84341    5.74637    .94000    .98097
 214.77 2517.07   39.61  .10437    27.05063     1.17638  -73.07731     .020021048.187502606.30457    5.92646    .97000    .99069
 219.21 2457.35   35.12  .11840    13.87493     1.21206  -86.84225     .02063 973.762122573.25613    6.19125   1.00000   1.00000


**** ALL INPUT DATA HAVE BEEN PROCESSED.
     AT LOC 45270
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                           A MODEL SIMULATING THE INTERNAL-COMBUSTION ENGINE

ENGINE                             FUEL                                          OPERATING CONDITIONS

FOUR STROKE AUTOMOTIVE TYPE        OCTANE C8H18                                  AIR-FUEL RATIO         .92
BORE               3.94 IN.        ACTIVATION ENERGY   39000.00 CAL./MOLE        PISTON TEMP        500.00 K
STROKE             2.46 IN.        ENTHALPY OF                                   WALL TEMP          420.00 K
ROD                7.06 IN.        COMBUSTION        1222770.00 CAL/MOLE         MAN. TEMP          320.00 K
CLEAR. VOL.        3.33 CU.IN.                                                   MAN. PR.              .99 ATM
SWEPT VOL.        30.00 CU.IN.                                                   EXH. PR.             1.03 ATM
COMPRESSION RATIO10.00 TO ONE                                                    SPARK ADV.          16.00
                                                                                 SPEED             2800.00 RPM

COMBUSTION OCCURS IN 39 INCREMENTS.  ERRORS ARE LESS THAN    .00100 PERCENT   FLAME SPEED FACTOR IS   .13500000E 06
HEAT TRANSFER FACTOR IS    .00000   NORMAL RUN

                    SUMMARY OF RESULTS

     PUMPING WORK                    -.47611947E 00 CAL
     NET CYCLE WORK                   .16383728E 03 CAL
     NET HEAT TRANSFERED              .00000000E 00 CAL
     INDICATED THERMAL EFFICIENCY     .40573207E 02 PERCENT
     MEAN EFFECTIVE PRESSURE          .13764381E 02 ATM
     RESIDUAL WEIGHT FRACTION                       0.03329
     VOLUMETRIC EFFICIENCY            .97627462E 00 PERCENT
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 THETA     T       P      V         H          S         U          N        Q        QTOT       W        WTOT       HB
   .00  344.84    .99  .54611 -22.58769    .95518 -35.68175    .01911   .00000   .00000    .00000    .00000   .00000
 10.00  345.51   1.00  .54302 -22.48808    .95518 -35.60766    .01911   .00000   .00000   -.07409   -.07409   .00000
 20.00  347.55   1.02  .53380 -22.18514    .95518 -35.38210    .01911   .00000   .00000   -.22555   -.29965   .00000
 30.00  351.01   1.06  .51855 -21.66938    .95518 -34.99796    .01911   .00000   .00000   -.38415   -.68380   .00000
 40.00  356.02   1.12  .49750 -20.92281    .95518 -34.44157    .01911   .00000   .00000   -.55639  -1.24019   .00000
 50.00  362.73   1.21  .47096 -19.91986    .95518 -33.69353    .01911   .00000   .00000   -.74803  -1.98822   .00000
 60.00  371.37   1.33  .43941 -18.62534    .95518 -32.72705    .01911   .00000   .00000   -.96649  -2.95471   .00000
 70.00  382.23   1.49  .40348 -16.99272    .95518 -31.50656    .01911   .00000   .00000  -1.22048  -4.17519   .00000
 80.00  395.67   1.70  .36400 -14.96164    .95518 -29.98581    .01911   .00000   .00000  -1.52076  -5.69595   .00000
 90.00  412.16   2.01  .32199 -12.45483    .95518 -28.10524    .01911   .00000   .00000  -1.88057  -7.57652   .00000
100.00  432.28   2.43  .27867  -9.37447    .95518 -25.78904    .01911   .00000   .00000  -2.31620  -9.89272   .00000
110.00  456.74   3.04  .23542  -5.59927    .95518 -22.94252    .01911   .00000   .00000  -2.84652 -12.73924   .00000
120.00  486.33   3.94  .19371   -.98560    .95518 -19.45242    .01911   .00000   .00000  -3.49010 -16.22933   .00000
130.00  521.84   5.28  .15510   4.61714    .95518 -15.19795    .01911   .00000   .00000  -4.25447 -20.48381   .00000
140.00  563.67   7.30  .12106  11.31073    .95518 -10.09294    .01911   .00000   .00000  -5.10500 -25.58881   .00000
150.00  610.94  10.30  .09296  18.99131    .95518  -4.20704    .01911   .00000   .00000  -5.88590 -31.47471   .00000
160.00  659.41  14.36  .07199  26.99693    .95518   1.95803    .01911   .00000   .00000  -6.16508 -37.63979   .00000
164.00  677.09  16.13  .06580  29.94867    .95518   4.23851    .01911   .00000   .00000  -2.28048 -39.92026   .00000
166.96  688.78  17.40  .06208  31.91122    .95521   5.74918    .01911   .00000   .00000  -1.51067 -41.43093   .00000
169.09  696.69  18.30  .05985  33.24601    .95547   6.71358    .01911   .00000   .00000   -.96441 -42.39533   .00000
171.46  706.01  19.42  .05784  34.83917    .95664   7.64106    .01912   .00000   .00000   -.92748 -43.32281   .00000
172.63  711.80  20.14  .05702  35.84326    .95808   8.03595    .01912   .00000   .00000   -.39489 -43.71770   .00000
174.23  720.78  21.30  .05609  37.43998    .96096   8.50981    .01914   .00000   .00000   -.47386 -44.19156   .00000
176.57  735.01  23.25  .05514  40.08403    .96668   9.04059    .01917   .00000   .00000   -.53079 -44.72234   .02559
178.03  746.39  24.91  .05479  42.30435    .97234   9.24996    .01920   .00000   .00000   -.20937 -44.93171   .02656
179.10  756.43  26.46  .05465  44.36051    .97797   9.33911    .01923   .00000   .00000   -.08915 -45.02087   .02745
179.95  765.62  27.95  .05461  46.33032    .98356   9.36778    .01927   .00000   .00000   -.02867 -45.04953   .02827
181.00  778.23  30.10  .05465  49.18056    .99188   9.34016    .01932   .00000   .00000    .02762 -45.02191   .02944
181.88  789.76  32.19  .05476  51.94066   1.00015   9.25343    .01936   .00000   .00000    .08674 -44.93518   .03053
182.54  800.51  34.24  .05489  54.65872   1.00835   9.14455    .01941   .00000   .00000    .10888 -44.82630   .03157
183.10  810.59  36.26  .05503  57.34387   1.01650   9.01935    .01946   .00000   .00000    .12520 -44.70110   .03257
183.60  820.10  38.26  .05517  60.00130   1.02461   8.88097    .01951   .00000   .00000    .13838 -44.56272   .03353
184.04  829.09  40.23  .05532  62.63300   1.03267   8.72987    .01956   .00000   .00000    .15110 -44.41162   .03446
184.50  837.57  42.17  .05549  65.21992   1.04068   8.54962    .01961   .00000   .00000    .18025 -44.23137   .03535
184.96  845.57  44.07  .05568  67.77769   1.04866   8.35282    .01966   .00000   .00000    .19680 -44.03457   .03620
185.43  853.12  45.93  .05589  70.29279   1.05661   8.12717    .01971   .00000   .00000    .22565 -43.80892   .03702
185.90  860.26  47.74  .05612  72.76210   1.06452   7.86950    .01976   .00000   .00000    .25766 -43.55125   .03781
186.23  867.33  49.60  .05629  75.29512   1.07240   7.66963    .01981   .00000   .00000    .19988 -43.35138   .03860
186.78  873.54  51.28  .05661  77.57456   1.08024   7.26423    .01986   .00000   .00000    .40539 -42.94598   .03930
187.46  879.10  52.83  .05703  79.68719   1.08805   6.72494    .01991   .00000   .00000    .53930 -42.40669   .03993
188.59  882.94  53.92  .05782  81.17369   1.09584   5.66909    .01996   .00000   .00000   1.05585 -41.35084   .04035
190.23  884.51  54.37  .05916  81.78600   1.10362   3.88925    .02001   .00000   .00000   1.77984 -39.57100   .04050
191.89  885.01  54.51  .06076  81.96679   1.11139   1.75154    .02005   .00000   .00000   2.13771 -37.43329   .04053
193.54  884.69  54.42  .06257  81.79891   1.11916   -.67587    .02010   .00000   .00000   2.42741 -35.00588   .04046
195.07  884.14  54.26  .06446  81.52277   1.12692  -3.19319    .02015   .00000   .00000   2.51732 -32.48856   .04036
196.36  884.09  54.25  .06621  81.46980   1.13470  -5.52423    .02019   .00000   .00000   2.33104 -30.15752   .04032
197.79  882.92  53.91  .06830  80.88959   1.14247  -8.29499    .02024   .00000   .00000   2.77075 -27.38676   .04015
199.32  880.76  53.30  .07073  79.81730   1.15025 -11.47630    .02029   .00000   .00000   3.18131 -24.20545   .03987
201.36  875.33  51.77  .07427  77.08886   1.15803 -16.04000    .02033   .00000   .00000   4.56370 -19.64175   .03919
203.01  871.64  50.76  .07735  75.18480   1.16584 -19.91560    .02037   .00000   .00000   3.87561 -15.76614   .03873
204.41  869.01  50.05  .08015  73.79358   1.17367 -23.36426    .02042   .00000   .00000   3.44865 -12.31749   .03840
206.04  864.82  48.93  .08359  71.53066   1.18151 -27.53979    .02046   .00000   .00000   4.17553  -8.14196   .03789
207.80  859.64  47.58  .08754  68.67415   1.18937 -32.21182    .02050   .00000   .00000   4.67203  -3.46993   .03727
209.68  853.60  46.05  .09201  65.24858   1.19725 -37.35772    .02055   .00000   .00000   5.14590   1.67597   .03656
211.66  846.87  44.39  .09698  61.35702   1.20515 -42.89187    .02059   .00000   .00000   5.53415   7.21012   .03579
214.20  836.81  41.99  .10378  55.42771   1.21308 -50.12120    .02063   .00000   .00000   7.22933  14.43946   .03465
218.37  817.02  37.75  .11584  44.04836   1.22108 -61.87004    .02066   .00000   .00000  11.74883  26.18829   .03258
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220.00 2558.42  35.88  .12084  38.70322   1.22108 -66.29910   .02065  .00000  .00000   4.42907  30.61735  .03258
225.00 2492.68  30.77  .13718  22.77491   1.22109 -79.44677   .02064  .00000  .00000  13.14766  43.76502  .03162
230.00 2428.97  26.54  .15485   7.89184   1.22108 -91.65689   .02062  .00000  .00000  12.21012  55.97514  .02891
235.00 2367.76  23.06  .17366  -5.95078   1.22109-102.94823   .02062  .00000  .00000  11.29135  67.26649  .02651
240.00 2309.85  20.19  .19344 -18.69259   1.22108-113.28922   .02061  .00000  .00000  10.34099  77.60747  .02439
245.00 2255.60  17.82  .21399 -30.37516   1.22107-122.73083   .02060  .00000  .00000   9.44161  87.04908  .02254
250.00 2205.32  15.85  .23513 -41.02566   1.22107-131.30954   .02060  .00000  .00000   8.57870  95.62779  .02093
255.00 2158.81  14.22  .25665 -50.75101   1.22108-139.12247   .02060  .00000  .00000   7.81294 103.44073  .01952
260.00 2116.03  12.85  .27837 -59.61102   1.22109-146.22553   .02060  .00000  .00000   7.10305 110.54378  .01829
265.00 2076.83  11.69  .30012 -67.66924   1.22109-152.67520   .02060  .00000  .00000   6.44967 116.99345  .01721
270.00 2041.02  10.72  .32170 -74.98772   1.22109-158.52501   .02060  .00000  .00000   5.84981 122.84326  .01627
275.00 2008.38   9.90  .34295 -81.62607   1.22109-163.82554   .02060  .00000  .00000   5.30053 128.14379  .01544
280.00 1978.70   9.19  .36372 -87.63829   1.22109-168.62182   .02060  .00000  .00000   4.79628 132.94007  .01472
285.00 1951.78   8.59  .38385 -93.07412   1.22109-172.95498   .02060  .00000  .00000   4.33317 137.27324  .01408
290.00 1927.43   8.08  .40322 -97.97862   1.22110-176.86208   .02060  .00000  .00000   3.90709 141.18033  .01352
295.00 1905.47   7.64  .42170-102.39223   1.22110-180.37617   .02060  .00000  .00000   3.51409 144.69442  .01302
300.00 1885.73   7.26  .43918-106.35117   1.22110-183.52672   .02060  .00000  .00000   3.15055 147.84497  .01259
305.00 1867.92   6.93  .45556-109.91497   1.22110-186.36162   .02059  .00000  .00000   2.83490 150.67987  .01221
310.00 1852.09   6.65  .47076-113.08050   1.22108-188.87877   .02059  .00000  .00000   2.51715 153.19702  .01188
315.00 1838.09   6.41  .48471-115.87372   1.22107-191.09916   .02059  .00000  .00000   2.22038 155.41741  .01158
320.00 1825.84   6.20  .49734-118.31686   1.22107-193.04065   .02059  .00000  .00000   1.94149 157.35890  .01133
325.00 1815.23   6.03  .50859-120.43025   1.22106-194.71977   .02059  .00000  .00000   1.67912 159.03802  .01111
330.00 1806.19   5.89  .51843-122.23008   1.22105-196.14946   .02059  .00000  .00000   1.42969 160.46771  .01092
335.00 1798.65   5.77  .52681-123.73052   1.22105-197.34112   .02059  .00000  .00000   1.19166 161.65937  .01076
340.00 1792.55   5.68  .53371-124.94327   1.22104-198.30416   .02059  .00000  .00000    .96304 162.62241  .01063
345.00 1787.85   5.60  .53911-125.87772   1.22104-199.04612   .02059  .00000  .00000    .74196 163.36437  .01053
350.00 1784.51   5.55  .54298-126.54113   1.22104-199.57282   .02059  .00000  .00000    .52670 163.89107  .01045
355.00 1782.50   5.52  .54531-126.93859   1.22103-199.88836   .02059  .00000  .00000    .31554 164.20661  .01039
360.00 1781.83   5.51  .54611-127.07311   1.22103-199.99516   .02059  .00000  .00000    .10680 164.31341  .01036
360.00 1247.85   1.03 2.04716-230.23209   1.22103-281.30019   .02059  .00000  .00000    .00000 164.31341  .00000
540.00 1000.00   1.03  .05461  -9.17099    .03930 -10.53334   .00069  .00000  .00000    .00000 164.31341  .00000
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THETA      T       P       V           H            S           U           N    FLAME SPEED, TEMP., AND EXTENT  MASS-FR. BURN.-VOL.
166.96 2541.23  17.40  .00002      .00381      .00013     -.00663      .00000  675.034622541.23251      .18781      .00010      .00040
169.09 2541.59  18.30  .00024      .03789      .00125     -.06652      .00002  689.945302538.97421      .39184      .00100      .00394
171.46 2550.13  19.42  .00111      .19934      .00623     -.32450      .00010  713.023392548.45255      .65380      .00500      .01926
172.63 2554.24  20.14  .00215      .40765      .01246     -.64173      .00021  724.966202546.34534      .80120      .01000      .03774
174.23 2565.39  21.30  .00409      .86957      .02489    -1.23865      .00041  749.149672558.76233     1.04276      .02000      .07287
176.57 2585.17  23.25  .00755     1.93536      .04971    -2.31479      .00083  788.408472578.47577     1.35166      .04000      .13691
178.03 2599.95  24.91  .01063     3.12240      .07447    -3.29059      .00124  816.879142581.92993     1.56692      .06000      .19401
179.10 2613.29  26.46  .01341     4.42940      .09920    -4.16678      .00166  843.526982587.18536     1.70808      .08000      .24545
179.95 2625.62  27.95  .01595     5.84612      .12390    -4.95174      .00207  868.519582592.51596     1.83490      .10000      .29213
181.00 2642.48  30.10  .01938     8.15265      .16088    -5.97840      .00269  906.484572607.75507     1.97448      .13000      .35469
181.88 2657.73  32.19  .02245    10.65118      .19780    -6.84548      .00331  939.800292614.47516     2.08684      .16000      .40988
182.54 2671.89  34.24  .02520    13.33242      .23466    -7.56034      .00393  971.989612621.24246     2.17426      .19000      .45904
183.10 2685.10  36.26  .02769    16.17847      .27147    -8.13794      .004561003.055592627.75287     2.24752      .22000      .50319
183.60 2697.44  38.26  .02996    19.17372      .30822    -8.59114      .005181033.125352634.01050     2.28756      .25000      .54313
184.04 2709.00  40.23  .03206    22.30414      .34494    -8.93179      .005801062.273422640.01144     2.34663      .28000      .57948
184.50 2719.71  42.17  .03400    25.54450      .38161    -9.18097      .006431090.331572645.62628     2.40418      .31000      .61276
184.96 2729.80  44.07  .03582    28.89872      .41825    -9.33508      .007051117.354952650.95486     2.46217      .34000      .64340
185.43 2739.19  45.93  .03754    32.34172      .45485    -9.41535      .007671143.404102656.03308     2.52067      .37000      .67171
185.90 2747.92  47.74  .03917    35.86118      .49141    -9.43204      .008291168.479952660.84982     2.58041      .40000      .69797
186.23 2756.70  49.60  .04067    39.52596      .52795    -9.32716      .008921193.909812666.16632     2.63092      .43000      .72241
186.78 2763.63  51.28  .04219    43.09260      .56444    -9.30593      .009541216.262482669.60800     2.69876      .46000      .74524
187.46 2769.44  52.83  .04372    46.61716      .60091    -9.32073      .010161236.996832673.08319     2.78677      .49000      .76666
188.59 2771.72  53.92  .04550    49.72116      .63736    -9.69055      .010791250.695142673.40039     3.06524      .52000      .78686
190.23 2769.52  54.37  .04768    52.17376      .67379   -10.60914      .011411255.917222671.26492     3.29522      .55000      .80597
191.89 2765.46  54.51  .05007    54.29125      .71021   -11.80975      .012031257.458342670.06979     3.54926      .58000      .82404
193.54 2760.09  54.42  .05263    56.12216      .74664   -13.25121      .012651255.980442668.61090     3.79859      .61000      .84114
195.07 2754.65  54.26  .05527    57.85642      .78306   -14.77345      .013271253.813862667.83652     4.03481      .64000      .85733
196.36 2750.69  54.25  .05778    59.77872      .81949   -16.13706      .013891253.801032668.54456     4.21767      .67000      .87265
197.79 2744.62  53.91  .06060    61.23289      .85591   -17.89387      .014511248.975072665.96671     4.39401      .70000      .88722
199.32 2736.71  53.30  .06373    62.22990      .89235   -20.03378      .015131240.767242662.97079     4.57284      .73000      .90109
201.36 2721.91  51.77  .06791    61.68754      .92879   -23.46426      .015741219.425402653.93634     4.79572      .76000      .91434
203.01 2711.40  50.76  .07170    61.84615      .96526   -26.30374      .016361206.239432653.58295     4.98809      .79000      .92691
204.41 2703.59  50.05  .07525    62.44442     1.00174   -28.77381      .016981196.904252653.08716     5.13529      .82000      .93886
206.04 2692.49  48.93  .07944    62.18438     1.03824   -31.96027      .017601181.094622647.49860     5.28569      .85000      .95028
207.80 2679.43  47.58  .08414    61.30721     1.07475   -35.66173      .018211162.031282641.95386     5.44112      .88000      .96117
209.68 2664.56  46.05  .08939    59.81944     1.11128   -39.86973      .018831140.192962635.92868     5.59795      .91000      .97157
211.66 2648.38  44.39  .09518    57.80876     1.14784   -44.51070      .019441116.107512629.48132     5.75190      .94000      .98149
214.20 2624.65  41.99  .10284    53.70671     1.18442   -50.88895      .020051080.192792616.50229     5.93031      .97000      .99097
218.37 2579.93  37.75  .11584    44.04836     1.22108   -61.87003      .020661012.260932587.10577     6.18942     1.00000     1.00000

**** ALL INPUT DATA HAVE BEEN PROCESSED.
     AT LOC 45325
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                                   A MODEL SIMULATING THE INTERNAL-COMBUSTION ENGINE

ENGINE                                 FUEL                                    OPERATING CONDITIONS

FOUR STROKE AUTOMOTIVE TYPE            OCTANE C8H18                            AIR-FUEL RATIO       .92
BORE              3.94 IN.             ACTIVATION ENERGY  39000.00 CAL./MOLE   PISTON TEMP       500.00 K
STROKE            2.46 IN.             ENTHALPY OF                             WALL TEMP         420.00 K
ROD               7.06 IN.             COMBUSTION       1222770.00 CAL/MOLE    MAN. TEMP         320.00 K
CLEAR. VOL.       3.33 CU.IN.                                                  MAN. PR.             .99 ATM
SWEPT VOL.       30.00 CU.IN.                                                  EXH. PR.            1.03 ATM
COMPRESSION RATIO10.00 TO ONE                                                  SPARK ADV.         16.00
                                                                               SPEED            2800.00 RPM

COMBUSTION OCCURS IN 39 INCREMENTS.  ERRORS ARE LESS THAN    .00100 PERCENT.  FLAME SPEED FACTOR IS   .13500000E 06
HEAT TRANSFER FACTOR IS   2.00000   NORMAL RUN




                    SUMMARY OF RESULTS

     PUMPING WORK                    .47611947E 00 CAL
     NET CYCLE WORK                  .13428628E 03 CAL
     NET HEAT TRANSFERED             .11785904E 03 CAL
     INDICATED THERMAL EFFICIENCY    .33255097E 02 PERCENT
     MEAN EFFECTIVE PRESSURE         .11281727E 02 ATM
     RESIDUAL WEIGHT FRACTION        .33289107E-01
     VOLUMETRIC EFFICIENCY           .97627462E 00 PERCENT
```

THETA	T	P	V	H	S	U	N	Q	QTOT	W	WTOT	HB
.00	344.84	.99	.54611	-22.58769	.95518	-35.68175	.01911	.00000	.00000	.00000	.00000	.00000
10.00	345.51	1.00	.54302	-22.48808	.95518	-35.60766	.01911	.00000	.00000	-.07409	-.07409	.00000
20.00	347.55	1.02	.53380	-22.18514	.95518	-35.38210	.01911	.00000	.00000	-.22555	-.29965	.00000
30.00	351.01	1.06	.51855	-21.66938	.95518	-34.99796	.01911	.00000	.00000	-.38415	-.68380	.00000
40.00	356.02	1.12	.49750	-20.92281	.95518	-34.44157	.01911	.00000	.00000	-.55639	1.24019	.00000
50.00	362.73	1.21	.47096	-19.91986	.95518	-33.69353	.01911	.00000	.00000	-.7480[illegible]	1.98822	.00000
60.00	371.37	1.33	.43941	-18.62534	.95518	-32.72705	.01911	.00000	.00000	-.96649	-2.95471	.00000
70.00	382.23	1.49	.40348	-16.99272	.95518	-31.50656	.01911	.00000	.00000	-1.22048	-4.17519	.00000
80.00	395.67	1.70	.36400	-14.96164	.95518	-29.98581	.01911	.00000	.00000	-1.52076	-5.69595	.00000
90.00	412.16	2.01	.32199	-12.45483	.95518	-28.10524	.01911	.00000	.00000	-1.88057	-7.57652	.00000
100.00	432.28	2.43	.27867	-9.37447	.95518	-25.78904	.01911	.00000	.00000	-2.31620	-9.89272	.00000
110.00	456.74	3.04	.23542	-5.59927	.95518	-22.94252	.01911	.00000	.00000	-2.84652	-12.73924	.00000
120.00	486.33	3.94	.19371	-.98560	.95518	-19.45242	.01911	.00000	.00000	-3.49010	-16.22933	.00000
130.00	521.84	5.28	.15510	4.61714	.95518	-15.19795	.01911	.00000	.00000	-4.25447	-20.48381	.00000
140.00	563.67	7.30	.12106	11.31073	.95518	-10.09294	.01911	.00000	.00000	-5.10500	-25.58881	.00000
150.00	610.94	10.30	.09296	18.99131	.95518	-4.20704	.01911	.00000	.00000	-5.88590	-31.47471	.00000
160.00	659.41	14.36	.07199	26.99693	.95518	1.95803	.01911	.00000	.00000	-6.16508	-37.63979	.00000
164.00	677.09	16.13	.06580	29.94867	.95518	4.23851	.01911	.00000	.00000	-2.28048	-39.92026	.00000
166.96	688.78	17.40	.06208	31.91122	.95521	5.74918	.01911	.00000	.00000	-1.51067	-41.43093	.00000
169.09	696.69	18.30	.05985	33.24601	.95547	6.71358	.01911	.00000	.00000	-.96441	-42.39533	.00000
171.46	706.01	19.42	.05784	34.83917	.95664	7.64106	.01912	.00000	.00000	-.92748	-43.32281	.00000
172.63	711.80	20.14	.05702	35.84326	.95808	8.03595	.01912	.00000	.00000	-.39489	-43.71770	.00000
174.23	720.78	21.30	.05609	37.43998	.96096	8.50981	.01914	.00000	.00000	-.47386	-44.19156	.00000
176.58	734.73	23.21	.05514	39.75951	.96657	8.77050	.01917	.27066	.27066	-.53135	-44.72291	.02559
178.04	745.92	24.84	.05479	41.74612	.97216	8.78479	.01920	.19784	.46850	-.21214	-44.93505	.02646
179.13	755.84	26.37	.05465	43.60540	.97772	8.70871	.01923	.16496	.63346	-.08887	-45.02392	.02730
179.98	764.92	27.83	.05461	45.40099	.98326	8.59080	.01927	.14460	.77806	-.02669	-45.05061	.02810
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181.94	788.80	32.01	.05477	50.52974	.99970	8.07009	.01936	.19261	1.17679	.09085	-44.92863	.03032
182.62	799.47	34.03	.05491	53.05557	1.00785	7.79792	.01941	.15988	1.33667	.11229	-44.81634	.03135
183.18	809.49	36.03	.05505	55.56479	1.01595	7.52293	.01946	.14637	1.48304	.12862	-44.68772	.03234
183.68	818.95	38.01	.05520	58.06094	1.02401	7.24686	.01951	.13572	1.61877	.14034	-44.54738	.03329
184.11	827.93	39.97	.05534	60.55308	1.03202	6.97609	.01956	.12536	1.74413	.14541	-44.40197	.03422
184.56	836.36	41.89	.05551	62.97158	1.03999	6.65207	.01961	.14232	1.88645	.18170	-44.22027	.03510
185.02	844.30	43.76	.05571	65.31770	1.04791	6.27479	.01965	.16401	2.05046	.21328	-44.00700	.03595
185.50	851.77	45.59	.05592	67.57427	1.05578	5.82913	.01970	.21345	2.26391	.23221	-43.77479	.03675
185.99	858.76	47.36	.05617	69.70860	1.06360	5.28704	.01975	.27007	2.53399	.27201	-43.50278	.03752
186.32	865.74	49.18	.05635	71.95492	1.07139	4.84284	.01980	.21678	2.75076	.22743	-43.27535	.03828
186.88	871.79	50.80	.05667	73.74064	1.07908	4.01810	.01985	.42283	3.17360	.40190	-42.87344	.03897
187.55	877.10	52.27	.05709	75.15102	1.08669	2.88304	.01990	.58383	3.75742	.55123	-42.32221	.03956
188.65	880.59	53.25	.05786	75.43065	1.09409	.80481	.01995	1.06732	4.82474	1.01091	-41.31130	.03995
190.32	881.28	53.44	.05924	73.89112	1.10122	-2.79194	.01999	1.76556	6.59030	1.83120	-39.48011	.03999
192.02	880.83	53.32	.06089	71.71039	1.10828	-6.91954	.02003	1.96008	8.55038	2.16752	-37.31258	.03984
193.71	879.51	52.94	.06277	69.01791	1.11529	-11.46934	.02008	2.09810	10.64848	2.45170	-34.86089	.03959
195.35	877.57	52.40	.06483	65.94116	1.12226	-16.33493	.02012	2.19816	12.84664	2.66744	-32.19345	.03926
196.69	876.60	52.13	.06668	63.60964	1.12935	-20.57523	.02016	1.87431	14.72095	2.36599	-29.82746	.03903
198.17	874.37	51.51	.06890	60.42368	1.13635	-25.52248	.02020	2.13895	16.85990	2.80830	-27.01917	.03870
199.68	871.51	50.73	.07133	56.83023	1.14332	-30.80437	.02025	2.23279	19.09269	3.04910	-23.97006	.03828
201.79	864.54	48.86	.07505	50.26841	1.14993	-38.54107	.02028	3.16217	22.25486	4.57453	-19.39553	.03743
203.55	859.27	47.49	.07842	44.96883	1.15675	-45.22041	.02033	2.66227	24.91712	4.01707	-15.37845	.03669
205.04	855.40	46.50	.08146	40.70928	1.16374	-51.03528	.02037	2.27369	27.19081	3.54118	-11.83728	.03615
206.77	849.75	45.09	.08522	35.13890	1.17060	-57.92455	.02041	2.63933	29.83014	4.24994	-7.58734	.03547
208.67	842.86	43.42	.08959	28.64188	1.17738	-65.56756	.02045	2.86709	32.69724	4.77591	-2.81143	.03465
210.71	834.97	41.57	.09457	21.38747	1.18413	-73.82078	.02049	3.03480	35.73203	5.21843	2.40700	.03372
212.85	826.37	39.63	.10012	13.57090	1.19085	-82.52167	.02053	3.14209	38.87412	5.55880	7.96580	.03273
215.66	813.63	36.89	.10787	2.57031	1.19726	-93.80233	.02057	3.97646	42.85058	7.30421	15.27001	.03136
220.48	788.83	32.14	.12235	-15.70533	1.20333	-110.94678	.02061	4.82116	47.67173	12.32330	27.59330	.02888

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225.00 2229.48  27.47  .13718 -36.21605   1.20074-127.48591    .02060   5.96779  53.63952  10.57133  38.16463    .02854
230.00 2130.20  23.25  .15485 -56.84116   1.19811-144.03248    .02060   5.83074  59.47026  10.71583  48.88047    .02583
235.00 2039.47  19.85  .17366 -75.38710   1.19570-158.85847    .02060   5.11651  64.58678   9.70948  58.58994    .02323
240.00 1957.11  17.10  .19344 -92.04609   1.19346-172.14369    .02060   4.52706  69.11383   8.75816  67.34811    .02100
245.00 1882.51  14.87  .21399-107.02155   1.19139-184.06460    .02059   4.04029  73.15412   7.88062  75.22872    .01909
250.00 1814.93  13.04  .23513-120.50565   1.18944-194.78232    .02059   3.63647  76.79059   7.08126  82.30998    .01746
255.00 1753.64  11.55  .25665-132.67167   1.18761-204.43990    .02059   3.29924  80.08983   6.35833  88.66832    .01606
260.00 1697.99  10.31  .27837-143.66987   1.18589-213.16033    .02059   3.01554  83.10536   5.70489  94.37321    .01485
265.00 1647.36   9.28  .30012-153.63601   1.18424-221.05406    .02059   2.77509  85.88045   5.11864  99.49185    .01381
270.00 1601.20   8.41  .32170-162.68539   1.18268-228.21463    .02059   2.56975  88.45020   4.59083 104.08267    .01290
275.00 1559.07   7.68  .34295-170.91788   1.18118-234.72288    .02059   2.39312  90.84332   4.11513 108.19780    .01211
280.00 1520.56   7.06  .36372-178.42008   1.17973-240.64876    .02059   2.24017  93.08349   3.68571 111.88351    .01142
285.00 1484.70   6.54  .38385-185.32762   1.17834-246.08865    .02059   2.10690  95.19040   3.33299 115.21650    .01082
290.00 1452.01   6.08  .40322-191.59506   1.17700-251.01829    .02059   1.98815  97.17854   2.94149 118.15798    .01028
295.00 1422.03   5.70  .42170-197.32683   1.17570-255.52312    .02059   1.88409  99.06263   2.62074 120.77872    .00981
300.00 1394.50   5.37  .43918-202.57340   1.17443-259.64334    .02059   1.79200 100.85463   2.32823 123.10695    .00940
305.00 1369.22   5.08  .45556-207.37864   1.17320-263.41397    .02059   1.71011 102.56475   2.06051 125.16746    .00903
310.00 1346.00   4.83  .47076-211.78074   1.17201-266.86552    .02059   1.63702 104.20176   1.81454 126.98200    .00870
315.00 1324.66   4.62  .48471-215.81306   1.17083-270.02469    .02059   1.57153 105.77330   1.58763 128.56963    .00842
320.00 1305.08   4.43  .49734-219.50468   1.16969-272.91477    .02059   1.51271 107.28601   1.37736 129.94699    .00816
325.00 1287.12   4.28  .50859-222.88101   1.16857-275.55610    .02059   1.45975 108.74576   1.18158 131.12857    .00794
330.00 1270.67   4.14  .51843-225.96416   1.16747-277.96640    .02059   1.41200 110.15776    .99831 132.12687    .00774
335.00 1255.66   4.03  .52681-228.77333   1.16639-280.16108    .02059   1.36890 111.52666    .82578 132.95265    .00757
340.00 1241.99   3.93  .53371-231.32511   1.16532-282.15345    .02059   1.32998 112.85664    .66238 133.61503    .00742
345.00 1229.60   3.85  .53911-233.63372   1.16428-283.95491    .02059   1.29488 114.15151    .50659 134.12163    .00729
350.00 1218.43   3.79  .54298-235.71124   1.16325-285.57519    .02059   1.26325 115.41477    .35703 134.47865    .00719
355.00 1208.42   3.74  .54531-237.56777   1.16223-287.02241    .02059   1.23485 116.64961    .21237 134.69102    .00710
360.00 1199.55   3.71  .54611-239.21157   1.16122-288.30322    .02059   1.20944 117.85905    .07138 134.76240    .00702
360.00  895.70   1.03 1.46944-293.87319   1.16122-330.52951    .02059    .00000 117.85905    .00000 134.76240    .00000
540.00 1000.00   1.03  .05461  -9.17099    .03930 -10.53334    .00069    .00000 117.85905    .00000 134.76240    .00000
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THETA       T        P      V         H          S          U          N    FLAME SPEED, TEMP., AND EXTENT MASS-FR. BURN.-VOL.
 166.96 2541.23  17.40  .00002     .00381     .00013    -.00663    .00000  675.034622541.23251     .18781    .00010    .00040
 169.09 2541.59  18.30  .00024     .03789     .00125    -.06652    .00002  689.945302538.97421     .39184    .00100    .00394
 171.46 2550.13  19.42  .00111     .19934     .00623    -.32450    .00010  713.023392548.45255     .65380    .00500    .01926
 172.63 2554.24  20.14  .00215     .40765     .01246    -.64173    .00021  724.966202546.34534     .80120    .01000    .03774
 174.23 2565.39  21.30  .00409     .86957     .02489   -1.23865    .00041  749.149672558.76233    1.04276    .02000    .07287
 176.58 2559.88  23.21  .00748    1.65727     .04960   -2.54880    .00083  787.523182577.77811    1.35166    .04000    .13573
 178.04 2570.83  24.84  .01053    2.63968     .07429   -3.69700    .00124  815.544772581.27966    1.56354    .06000    .19225
 179.13 2583.53  26.37  .01330    3.76738     .09896   -4.72468    .00165  841.622882586.37708    1.70391    .08000    .24335
 179.98 2596.26  27.83  .01583    5.02470     .12360   -5.64462    .00207  866.466642591.78738    1.83022    .10000    .28985
 181.05 2613.81  29.95  .01925    7.10050     .16051   -6.86679    .00269  904.052882606.94626    1.97029    .13000    .35227
 181.94 2629.80  32.01  .02232    9.38069     .19735   -7.91914    .00331  936.869772613.55429    2.08282    .16000    .40744
 182.62 2645.11  34.03  .02507   11.87568     .23416   -8.79253    .00393  968.722262620.31250    2.17090    .19000    .45668
 183.18 2659.40  36.03  .02758   14.54972     .27091   -9.51676    .00455  999.529852626.80408    2.24423    .22000    .50095
 183.68 2672.74  38.01  .02986   17.38460     .30762  -10.10685    .005181029.372482633.05392    2.28743    .25000    .54102
 184.11 2685.30  39.97  .03196   20.37083     .34430  -10.57071    .005801058.431352639.11267    2.34400    .28000    .57751
 184.56 2696.54  41.89  .03391   23.44285     .38092  -10.96352    .006421086.225572644.62439    2.40151    .31000    .61091
 185.02 2706.65  43.76  .03574   26.58592     .41749  -11.29765    .007041112.970472649.89545    2.45958    .34000    .64163
 185.50 2715.64  45.59  .03747   29.77385     .45402  -11.59515    .007671138.610402654.85202    2.51805    .37000    .66999
 185.99 2723.43  47.36  .03911   32.96706     .49049  -11.88934    .008291163.093432659.48666    2.57732    .40000    .69629
 186.32 2731.74  49.18  .04061   36.34620     .52694  -12.02789    .008911188.081882664.79422    2.62769    .43000    .72079
 186.88 2736.77  50.80  .04214   39.42682     .56329  -12.41989    .009531210.070592668.19183    2.69589    .46000    .74361
 187.55 2739.49  52.27  .04367   42.26245     .59955  -13.01993    .010151229.504712671.20404    2.78250    .49000    .76496
 188.65 2735.71  53.25  .04542   44.17893     .63561  -14.39687    .010771241.715762671.05820    3.05513    .52000    .78492
 190.32 2722.20  53.44  .04761   44.53704     .67139  -17.08724    .011391243.393162667.44315    3.28167    .55000    .80362
 192.02 2706.47  53.32  .05001   44.34684     .70711  -20.23540    .012011241.317762665.39664    3.53394    .58000    .82134
 193.71 2689.30  52.94  .05261   43.70057     .74277  -23.76197    .012621236.326932663.22443    3.78060    .61000    .83818
 195.35 2671.38  52.40  .05538   42.69584     .77839  -27.58404    .013241228.840532660.79025    4.01750    .64000    .85419
 196.69 2658.57  52.13  .05798   42.35821     .81415  -30.84226    .013861225.275922661.33151    4.20280    .67000    .86951
 198.17 2642.35  51.51  .06091   41.22326     .84980  -34.76254    .014471216.812062657.86435    4.37888    .70000    .88410
 199.68 2625.11  50.73  .06406   39.68678     .88542  -39.01279    .015091206.035962654.71237    4.55647    .73000    .89804
 201.79 2594.29  48.86  .06839   35.32605     .92068  -45.60464    .015701178.906342643.02560    4.77504    .76000    .91128
 203.55 2570.91  47.49  .07246   32.09012     .95616  -51.24720    .016311160.718802641.55038    4.96928    .79000    .92402
 205.04 2553.55  46.50  .07627   29.79376     .99180  -56.10423    .016931147.370862640.59128    5.11856    .82000    .93627
 206.77 2530.84  45.09  .08079   26.19225    1.02732  -62.03124    .017541126.786352633.49783    5.27044    .85000    .94799
 208.67 2504.72  43.42  .08594   21.63027    1.06276  -68.73860    .018161102.106692626.06119    5.42779    .88000    .95923
 210.71 2476.07  41.57  .09174   16.25354    1.09816  -76.10124    .018771074.736502618.31833    5.58667    .91000    .97003
 212.85 2445.81  39.63  .09816   10.23883    1.13354  -83.97101    .019381045.758302610.51782    5.74194    .94000    .98041
 215.66 2401.98  36.89  .10683     .97113    1.16861  -94.47467    .020001002.277992593.97488    5.92327    .97000    .99038
 220.48 2325.81  32.14  .12235  -15.70532    1.20333-110.94678    .02061  920.747312556.23593    6.19413   1.00000   1.00000



**** ALL INPUT DATA HAVE BEEN PROCESSED.
     AT LOC 45267
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DATA SET B

RAPID FLAME PROPAGATION RATES

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                              A MODEL SIMULATING THE INTERNAL-COMBUSTION ENGINE

ENGINE                                FUEL                                  OPERATING CONDITIONS

FOUR STROKE AUTOMOTIVE TYPE           OCTANE C8H18                          AIR-FUEL RATIO        .92
BORE              3.94 IN.            ACTIVATION ENERGY  39000.00 CAL./MOLE PISTON TEMP        500.00 K
STROKE            2.46 IN.            ENTHALPY OF                           WALL TEMP          420.00 K
ROD               7.06 IN.            COMBUSTION       1222770.00 CAL/MOLE  MAN. TEMP          320.00 K
CLEAR. VOL.       3.33 CU.IN.                                               MAN. PR.              .99 ATM
SWEPT VOL.       30.00 CU.IN.                                               EXH. PR.             1.03 ATM
COMPRESSION RATIO10.00 TO ONE                                               SPARK ADV.          16.00
                                                                            SPEED             2800.00 RPM

COMBUSTION OCCURS IN 39 INCREMENTS.  ERRORS ARE LESS THAN    .00100 PERCENT.  FLAME SPEED FACTOR IS   .15525000E 06
HEAT TRANSFER FACTOR IS   1.00000   NORMAL RUN


                    SUMMARY OF RESULTS

    PUMPING WORK                     -.47611947E 00 CAL
    NET CYCLE WORK                    .14891748E 03 CAL
    NET HEAT TRANSFERED               .72684486E 02 CAL
    INDICATED THERMAL EFFICIENCY      .36878417E 02 PERCENT
    MEAN EFFECTIVE PRESSURE           .12510931E 02 ATM
    RESIDUAL WEIGHT FRACTION          .33289108E-01
    VOLUMETRIC EFFICIENCY             .97627462E 00 PERCENT
```

THETA	T	P	V	H	S	U	N	Q	QTOT	W	WTOT	HB
.00	344.84	.99	.54611	-22.58769	.95518	-35.68175	.01911	.00000	.00000	.00000	.00000	.00000
10.00	345.51	1.00	.54302	-22.48808	.95518	-35.60766	.01911	.00000	.00000	-.07409	-.07409	.00000
20.00	347.55	1.02	.53380	-22.18514	.95518	-35.38210	.01911	.00000	.00000	-.22555	-.29965	.00000
30.00	351.01	1.06	.51855	-21.66938	.95518	-34.99796	.01911	.00000	.00000	-.38415	-.68380	.00000
40.00	356.02	1.12	.49750	-20.92281	.95518	-34.44157	.01911	.00000	.00000	-.55639	-1.24019	.00000
50.00	362.73	1.21	.47096	-19.91986	.95518	-33.69353	.01911	.00000	.00000	-.74803	-1.98822	.00000
60.00	371.37	1.33	.43941	-18.62534	.95518	-32.72705	.01911	.00000	.00000	-.96649	-2.95471	.00000
70.00	382.23	1.49	.40348	-16.99272	.95518	-31.50656	.01911	.00000	.00000	-1.22048	-4.17519	.00000
80.00	395.67	1.70	.36400	-14.96164	.95518	-29.98581	.01911	.00000	.00000	-1.52076	-5.69595	.00000
90.00	412.16	2.01	.32199	-12.45483	.95518	-28.10524	.01911	.00000	.00000	-1.88057	-7.57652	.00000
100.00	432.28	2.43	.27867	-9.37447	.95518	-25.78904	.01911	.00000	.00000	-2.31620	-9.89272	.00000
110.00	456.74	3.04	.23542	-5.59927	.95518	-22.94252	.01911	.00000	.00000	-2.84652	-12.73924	.00000
120.00	486.33	3.94	.19371	-.98560	.95518	-19.45242	.01911	.00000	.00000	-3.49010	-16.22933	.00000
130.00	521.84	5.28	.15510	4.61714	.95518	-15.19795	.01911	.00000	.00000	-4.25447	-20.48381	.00000
140.00	563.67	7.30	.12106	11.31073	.95518	-10.09294	.01911	.00000	.00000	-5.10500	-25.58881	.00000
150.00	610.94	10.30	.09296	18.99131	.95518	-4.20704	.01911	.00000	.00000	-5.88590	-31.47471	.00000
160.00	659.41	14.36	.07199	26.99693	.95518	1.95803	.01911	.00000	.00000	-6.16508	-37.63979	.00000
164.00	677.09	16.13	.06580	29.94867	.95518	4.23851	.01911	.00000	.00000	-2.28048	-39.92026	.00000
166.59	687.41	17.25	.06250	31.68026	.95521	5.57040	.01911	.00000	.00000	-1.33189	-41.25215	.00000
168.46	694.60	18.06	.06047	32.89473	.95547	6.44144	.01911	.00000	.00000	-.87104	-42.12320	.00000
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171.57	709.18	19.81	.05775	35.39930	.95809	7.69132	.01912	.00000	.00000	-.38362	-43.37307	.00000
172.97	718.22	20.96	.05680	37.00419	.96097	8.17112	.01914	.00000	.00000	-.47981	-43.85288	.00000
175.02	732.77	22.93	.05571	39.59162	.96665	8.65004	.01917	.11689	.11689	-.59580	-44.44867	.02542
176.30	744.60	24.64	.05522	41.81181	.97229	8.85403	.01920	.08580	.20269	-.28979	-44.73847	.02639
177.23	755.07	26.25	.05496	43.88790	.97789	8.95470	.01923	.07115	.27384	-.17182	-44.91029	.02730
177.98	764.68	27.79	.05480	45.88285	.98346	8.99964	.01927	.06308	.33692	-.10803	-45.01831	.02816
178.89	777.90	30.04	.05467	48.78124	.99176	9.00586	.01931	.08968	.42660	-.09590	-45.11421	.02938
179.70	790.02	32.23	.05462	51.59148	.99999	8.95507	.01936	.08847	.51508	-.03768	-45.15189	.03052
180.22	801.25	34.38	.05461	54.37510	1.00817	8.89659	.01941	.06173	.57681	-.00325	-45.15514	.03161
180.69	811.78	36.51	.05463	57.11790	1.01630	8.81556	.01946	.06228	.63908	.01875	-45.13639	.03266
181.11	821.71	38.61	.05466	59.83092	1.02437	8.72009	.01951	.05871	.69780	.03676	-45.09964	.03366
181.44	831.14	40.69	.05470	62.53645	1.03240	8.62762	.01956	.04871	.74651	.04376	-45.05588	.03464
181.82	840.06	42.75	.05475	65.21341	1.04039	8.51972	.01961	.06011	.80662	.04779	-45.00809	.03558
182.21	848.52	44.79	.05482	67.85229	1.04834	8.38773	.01966	.06861	.87523	.06338	-44.94471	.03649
182.60	856.55	46.79	.05490	70.42085	1.05623	8.20356	.01971	.08706	.96229	.09712	-44.84759	.03737
183.00	864.16	48.76	.05500	72.92402	1.06408	7.97081	.01976	.10982	1.07211	.12292	-44.72467	.03821
183.38	871.45	50.71	.05510	75.39425	1.07189	7.71607	.01981	.11815	1.19026	.13660	-44.58807	.03903
183.81	878.32	52.61	.05524	77.75526	1.07965	7.37494	.01986	.15892	1.34917	.18221	-44.40586	.03981
184.31	884.74	54.43	.05541	79.99041	1.08737	6.93314	.01991	.21936	1.56853	.22244	-44.18342	.04055
184.96	890.53	56.13	.05568	81.95088	1.09502	6.26530	.01996	.30212	1.87065	.36572	-43.81771	.04122
187.72	890.51	56.12	.05720	80.45500	1.10224	2.70643	.02000	1.45136	3.32202	2.10751	-41.71020	.04122
189.18	892.48	56.71	.05828	80.37848	1.10967	.34013	.02005	.85246	4.17448	1.51384	-40.19635	.04134
190.64	893.64	57.05	.05953	79.89698	1.11705	-2.36230	.02009	.92602	5.10049	1.77641	-38.41994	.04142
192.19	893.59	57.04	.06107	78.74187	1.12438	-5.62603	.02014	1.07739	6.17788	2.18634	-36.23360	.04135
193.50	893.93	57.14	.06252	77.90079	1.13175	-8.62485	.02018	.96574	7.14362	2.03308	-34.20052	.04132
194.74	894.00	57.16	.06404	76.94101	1.13912	-11.72129	.02023	.96782	8.11144	2.12862	-32.07189	.04128
195.96	893.74	57.08	.06565	75.81867	1.14649	-14.95234	.02027	.98048	9.09191	2.25058	-29.82131	.04119
197.41	891.87	56.52	.06772	73.68669	1.15377	-19.02499	.02032	1.20037	10.29228	2.87228	-26.94904	.04092
199.28	887.11	55.12	.07067	69.66226	1.16091	-24.67636	.02036	1.59690	11.88918	4.05446	-22.89457	.04030
200.58	885.15	54.55	.07287	67.52435	1.16825	-28.75001	.02040	1.12776	13.01695	2.94589	-19.94868	.03997
202.01	882.09	53.67	.07545	64.62853	1.17553	-33.45416	.02045	1.25849	14.27544	3.44565	-16.50303	.03957
203.52	878.22	52.58	.07837	61.17201	1.18280	-38.62345	.02049	1.34593	15.62137	3.82337	-12.67967	.03906
205.19	873.17	51.18	.08178	56.90371	1.19002	-44.46540	.02053	1.48167	17.10304	4.36028	-8.31938	.03842
207.00	866.99	49.51	.08573	51.81745	1.19722	-50.98375	.02057	1.61104	18.71408	4.90730	-3.41208	.03765
209.24	858.01	47.17	.09094	44.73105	1.20430	-59.15387	.02061	1.95649	20.67057	6.21363	2.80155	.03658
212.67	841.03	43.16	.09964	33.02007	1.21128	-71.12848	.02064	2.34101	23.01158	9.63361	12.43515	.03471
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 220.00 2405.30   33.67  .12084   1.91183   1.20888 -96.62883    .02062   4.02338  29.01330  13.14004  31.93379    .03293
 225.00 2316.82   28.56  .13718 -17.54491   1.20738-112.41795    .02061   3.57032  32.58362  12.21880  44.15259    .02971
 230.00 2233.11   24.38  .15485 -35.38738   1.20600-126.80840    .02060   3.17933  35.76295  11.21111  55.36370    .02685
 235.00 2154.93   20.97  .17366 -51.69755   1.20473-139.90520    .02060   2.84695  38.60990  10.24985  65.61355    .02435
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 250.00 1955.96   14.06  .23513 -92.26486   1.20136-172.31599    .02060   2.13025  45.63579   7.62983  90.99845    .01871
 255.00 1900.65   12.51  .25665-103.38026   1.20036-181.16647    .02059   1.96171  47.59750   6.88877  97.88721    .01731
 260.00 1850.15   11.23  .27837-113.48287   1.19940-189.20127    .02059   1.81850  49.41601   6.21630 104.10351    .01610
 265.00 1804.01   10.16  .30012-122.67315   1.19848-196.50318    .02059   1.69612  51.11212   5.60579 109.70930    .01505
 270.00 1761.86    9.25  .32170-131.04151   1.19759-203.14612    .02059   1.59092  52.70304   5.05203 114.76133    .01413
 275.00 1723.32    8.49  .34295-138.66824   1.19674-209.19545    .02059   1.49997  54.20301   4.54937 119.31069    .01333
 280.00 1688.07    7.84  .36372-145.62468   1.19592-214.70907    .02059   1.42091  55.62392   4.09271 123.40340    .01263
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 290.00 1626.29    6.82  .40322-157.77007   1.19433-224.32598    .02059   1.29117  58.26691   3.29718 130.37731    .01147
 295.00 1599.27    6.41  .42170-163.06317   1.19357-228.51333    .02059   1.23768  59.50460   2.94967 133.32698    .01099
 300.00 1574.55    6.06  .43918-167.89594   1.19282-232.33447    .02059   1.19033  60.69493   2.63081 135.95779    .01057
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 310.00 1531.19    5.50  .47076-176.35016   1.19137-239.01422    .02059   1.11081  62.95402   2.08349 140.37844    .00987
 315.00 1512.26    5.27  .48471-180.03237   1.19066-241.92163    .02059   1.07717  64.03119   1.83024 142.20868    .00958
 320.00 1494.65    5.08  .49734-183.41496   1.18995-244.58355    .02059   1.04709  65.07828   1.61482 143.82350    .00932
 325.00 1478.92    4.91  .50859-186.43637   1.18927-246.96100    .02059   1.01954  66.09782   1.35792 145.18142    .00909
 330.00 1464.69    4.77  .51843-189.16477   1.18860-249.10720    .02059    .99528  67.09310   1.15092 146.33233    .00890
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 THETA    T       P      V          H          S          U          N    FLAME SPEED, TEMP., AND EXTENT MASS-FR. BURN.-VOL.
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 168.46 2538.47  18.06  .00024      .03712    .00125    -.06715    .00002 787.319292536.13147     .39292     .00100     .00394
 170.54 2547.11  19.11  .00113      .19570    .00624    -.32750    .00010 812.654782545.75754     .65649     .00500     .01931
 171.57 2551.59  19.81  .00218      .40142    .01246    -.64684    .00021 826.309202544.25040     .80191     .01000     .03783
 172.97 2563.24  20.96  .00415      .85976    .02490   -1.24666    .00041 854.196742556.95749    1.04391     .02000     .07306
 175.02 2573.47  22.93  .00762     1.80903    .04968   -2.42080    .00083 900.194592577.39182    1.35295     .04000     .13670
 176.30 2587.55  24.64  .01069     2.91892    .07442   -3.46161    .00124 934.162092581.35593    1.56672     .06000     .19360
 177.23 2601.62  26.25  .01346     4.17107    .09913   -4.38433    .00165 966.133782586.98367    1.70732     .08000     .24491
 177.98 2614.82  27.79  .01597     5.54397    .12380   -5.20662    .00207 996.175462592.62112    1.83381     .10000     .29148
 178.89 2633.05  30.04  .01935     7.80324    .16076   -6.27375    .002691041.687822608.50833    1.97336     .13000     .35392
 179.70 2649.42  32.23  .02234    10.26546    .19764   -7.17237    .003311082.215822615.77118    2.09153     .16000     .40898
 180.22 2665.00  34.38  .02502    12.94443    .23448   -7.88988    .003931120.869342622.70496    2.17344     .19000     .45811
 180.69 2679.28  36.51  .02744    15.79047    .27126   -8.46850    .004561158.002912629.33017    2.24359     .22000     .50223
 181.11 2692.54  38.61  .02964    18.79210    .30799   -8.91741    .005181194.472792635.98874    2.28757     .25000     .54215
 181.44 2705.09  40.69  .03164    21.94964    .34468   -9.23616    .005801229.784612642.33673    2.33990     .28000     .57849
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 182.60 2737.52  46.79  .03682    32.08846    .45447   -9.63831    .007671329.328052659.54349    2.50575     .37000     .67066
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 183.38 2755.00  50.71  .03975    39.20807    .52744   -9.60845    .008921390.414662669.67252    2.60628     .43000     .72130
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 184.31 2769.07  54.43  .04242    46.40862    .60023   -9.51507    .010161446.945482678.54718    2.73771     .49000     .76548
 184.96 2773.92  56.13  .04374    49.84914    .63654   -9.60519    .010791472.099472682.07141    2.83260     .52000     .78554
 187.72 2759.65  56.12  .04601    50.36148    .67241  -12.17069    .011401470.013032673.53775    3.14277     .55000     .80429
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 190.64 2747.74  57.05  .04995    53.59828    .74453  -15.42713    .012641484.453222677.75681    3.65930     .61000     .83912
 192.19 2738.35  57.04  .05223    54.46889    .78051  -17.68371    .013261483.824052675.95715    3.90481     .64000     .85521
 193.50 2731.28  57.14  .05443    55.63075    .81654  -19.69332    .013881485.476992676.78320    4.11216     .67000     .87054
 194.74 2724.24  57.16  .05669    56.69188    .85257  -21.78640    .014501485.694562676.44659    4.28580     .70000     .88513
 195.96 2716.99  57.08  .05903    57.60670    .88859  -24.00131    .015111484.447802675.77728    4.45759     .73000     .89905
 197.41 2705.66  56.52  .06179    57.57859    .92453  -27.00529    .015731475.467392671.91589    4.64830     .76000     .91233
 199.28 2686.53  55.12  .06537    55.74592    .96032  -31.51882    .016351453.770032664.15781    4.87979     .79000     .92501
 200.58 2676.61  54.55  .06829    55.65901    .99632  -34.56545    .016961445.747392666.53363    5.05306     .82000     .93716
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 203.52 2649.49  52.58  .07523    53.40975   1.06818  -42.38402    .018191415.255782658.45670    5.37413     .88000     .95990
 205.19 2632.27  51.18  .07937    51.16260   1.10406  -47.22247    .018811393.212662652.79474    5.54231     .91000     .97056
 207.00 2612.34  49.51  .08408    48.05586   1.13991  -52.77007    .019421366.589022646.24710    5.71462     .94000     .98078
 209.24 2584.88  47.17  .09008    42.89794   1.17564  -60.00957    .020031327.926322634.93097    5.90755     .97000     .99059
 212.67 2539.10  43.16  .09964    33.02008   1.21128  -71.12848    .020641258.507512610.84439    6.17306    1.00000    1.00000
8**** ALL INPUT DATA HAVE BEEN PROCESSED.
      AT LOC 45267
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                        A MODEL SIMULATING THE INTERNAL-COMBUSTION ENGINE

ENGINE                            FUEL                                        OPERATING CONDITIONS

FOUR STROKE AUTOMOTIVE TYPE       OCTANE C8H18                                AIR-FUEL RATIO       .92
BORE             3.94 IN.         ACTIVATION ENERGY  39000.00 CAL./MOLE       PISTON TEMP        500.00 K
STROKE           2.46 IN.         ENTHALPY OF                                 WALL TEMP          420.00 K
ROD              7.06 IN.         COMBUSTION        1222770.00 CAL/MOLE       MAN. TEMP          320.00 K
CLEAR. VOL.      3.33 CU.IN.                                                  MAN. PR.              .99 ATM
SWEPT VOL.      30.00 CU.IN.                                                  EXH. PR.             1.03 ATM
COMPRESSION RATIO10.00 TO ONE                                                 SPARK ADV.          16.00
                                                                              SPEED             2800.00 RPM

COMBUSTION OCCURS IN 39 INCREMENTS.  ERRORS ARE LESS THAN    .00100 PERCENT.  FLAME SPEED FACTOR IS   .15525000E 06
HEAT TRANSFER FACTOR IS    .00000  NORMAL RUN




                 SUMMARY OF RESULTS

    PUMPING WORK                   -.47611947E 00 CAL
    NET CYCLE WORK                  .16641193E 03 CAL
    NET HEAT TRANSFERED             .00000000E 00 CAL
    INDICATED THERMAL EFFICIENCY    .41210800E 02 PERCENT
    MEAN EFFECTIVE PRESSURE         .13980684E 02 ATM
    RESIDUAL WEIGHT FRACTION        .33289108E-01
    VOLUMETRIC EFFICIENCY           .97627462E 00 PERCENT
```

THETA	T	P	V	H	S	U	N	Q	QTOT	W	WTOT	HB
.00	344.84	.99	.54611	-22.58769	.95518	-35.68175	.01911	.00000	.00000	.00000	.00000	.00000
10.00	345.51	1.00	.54302	-22.48808	.95518	-35.60766	.01911	.00000	.00000	-.07409	-.07409	.00000
20.00	347.55	1.02	.53380	-22.18514	.95518	-35.38210	.01911	.00000	.00000	-.22555	-.29965	.00000
30.00	351.01	1.06	.51855	-21.66938	.95518	-34.99796	.01911	.00000	.00000	-.38415	-.68380	.00000
40.00	356.02	1.12	.49750	-20.92281	.95518	-34.44157	.01911	.00000	.00000	-.55639	-1.24019	.00000
50.00	362.73	1.21	.47096	-19.91986	.95518	-33.69353	.01911	.00000	.00000	-.74803	-1.98822	.00000
60.00	371.37	1.33	.43941	-18.62534	.95518	-32.72705	.01911	.00000	.00000	-.96649	-2.95471	.00000
70.00	382.23	1.49	.40348	-16.99272	.95518	-31.50656	.01911	.00000	.00000	-1.22048	-4.17519	.00000
80.00	395.67	1.70	.36400	-14.96164	.95518	-29.98581	.01911	.00000	.00000	-1.52076	-5.69595	.00000
90.00	412.16	2.01	.32199	-12.45483	.95518	-28.10524	.01911	.00000	.00000	-1.88057	-7.57652	.00000
100.00	432.28	2.43	.27867	-9.37447	.95518	-25.78904	.01911	.00000	.00000	-2.31620	-9.89272	.00000
110.00	456.74	3.04	.23542	-5.59927	.95518	-22.94252	.01911	.00000	.00000	-2.84652	-12.73924	.00000
120.00	486.33	3.94	.19371	-.98560	.95518	-19.45242	.01911	.00000	.00000	-3.49010	-16.22933	.00000
130.00	521.84	5.28	.15510	4.61714	.95518	-15.19795	.01911	.00000	.00000	-4.25447	-20.48381	.00000
140.00	563.67	7.30	.12106	11.31073	.95518	-10.09294	.01911	.00000	.00000	-5.10500	-25.58881	.00000
150.00	610.94	10.30	.09296	18.99131	.95518	-4.20704	.01911	.00000	.00000	-5.88590	-31.47471	.00000
160.00	659.41	14.36	.07199	26.99693	.95518	1.95803	.01911	.00000	.00000	-6.16508	-37.63979	.00000
164.00	677.09	16.13	.06580	29.94867	.95518	4.23851	.01911	.00000	.00000	-2.28048	-39.92026	.00000
166.59	687.41	17.25	.06250	31.68026	.95521	5.57040	.01911	.00000	.00000	-1.33189	-41.25215	.00000
168.46	694.60	18.06	.06047	32.89473	.95547	6.44144	.01911	.00000	.00000	-.87104	-42.12320	.00000
170.54	703.47	19.11	.05856	34.40938	.95664	7.30770	.01912	.00000	.00000	-.86625	-42.98945	.00000
171.57	709.18	19.81	.05775	35.39930	.95809	7.69132	.01912	.00000	.00000	-.38362	-43.37307	.00000
172.97	718.22	20.96	.05680	37.00419	.96097	8.17112	.01914	.00000	.00000	-.47981	-43.85288	.00000
175.02	732.90	22.95	.05571	39.73161	.96670	8.76667	.01917	.00000	.00000	-.59555	-44.44842	.02542
176.30	744.80	24.67	.05523	42.05386	.97237	9.05598	.01920	.00000	.00000	-.28931	-44.73773	.02644
177.22	755.33	26.28	.05496	44.21416	.97800	9.22747	.01923	.00000	.00000	-.17149	-44.90923	.02736
177.96	764.97	27.84	.05480	46.28465	.98359	9.33611	.01927	.00000	.00000	-.10863	-45.01786	.02823
178.88	778.25	30.10	.05467	49.28985	.99192	9.43246	.01932	.00000	.00000	-.09636	-45.11421	.02946
179.68	790.41	32.31	.05462	52.20514	1.00019	9.47075	.01936	.00000	.00000	-.03829	-45.15250	.03061
180.19	801.67	34.47	.05461	55.06267	1.00839	9.47514	.01941	.00000	.00000	-.00439	-45.15689	.03170
180.66	812.23	36.60	.05463	57.87973	1.01654	9.45748	.01946	.00000	.00000	.01766	-45.13923	.03275
181.08	822.17	38.71	.05466	60.66244	1.02463	9.42153	.01951	.00000	.00000	.03595	-45.10328	.03376
181.42	831.61	40.80	.05470	63.43963	1.03268	9.39029	.01956	.00000	.00000	.03125	-45.07204	.03474
181.80	840.55	42.87	.05475	66.18725	1.04069	9.34293	.01961	.00000	.00000	.04736	-45.02468	.03569
182.19	849.03	44.91	.05482	68.90790	1.04866	9.28083	.01966	.00000	.00000	.06210	-44.96258	.03660
182.58	857.08	46.93	.05490	71.57845	1.05659	9.18371	.01971	.00000	.00000	.09713	-44.86545	.03748
182.99	864.74	48.91	.05500	74.21045	1.06447	9.06078	.01976	.00000	.00000	.12292	-44.74253	.03833
183.34	872.09	50.88	.05509	76.82745	1.07233	8.93097	.01981	.00000	.00000	.12981	-44.61272	.03916
183.77	879.02	52.80	.05523	79.37534	1.08014	8.74899	.01986	.00000	.00000	.18198	-44.43074	.03995
184.27	885.52	54.66	.05540	81.87151	1.08794	8.52938	.01991	.00000	.00000	.21961	-44.21113	.04070
184.92	891.44	56.40	.05566	84.18585	1.09570	8.16242	.01996	.00000	.00000	.36696	-43.84417	.04139
187.69	892.03	56.57	.05718	84.37693	1.10343	6.03286	.02001	.00000	.00000	2.12957	-41.71460	.04142
189.14	894.38	57.27	.05824	85.34582	1.11117	4.55200	.02006	.00000	.00000	1.48086	-40.23375	.04167
190.58	895.94	57.75	.05948	86.00013	1.11890	2.81033	.02011	.00000	.00000	1.74167	-38.49208	.04183
192.11	896.41	57.89	.06099	86.18090	1.12662	.67482	.02015	.00000	.00000	2.13551	-36.35657	.04185
193.39	897.19	58.13	.06240	86.51532	1.13434	-1.33197	.02020	.00000	.00000	2.00679	-34.34977	.04192
194.62	897.66	58.27	.06389	86.70753	1.14205	-3.45693	.02025	.00000	.00000	2.12495	-32.22482	.04195
195.82	897.82	58.32	.06546	86.76054	1.14976	-5.69773	.02030	.00000	.00000	2.24080	-29.98401	.04194
197.25	896.42	57.89	.06749	86.04303	1.15747	-8.58251	.02034	.00000	.00000	2.88477	-27.09924	.04174
199.07	892.46	56.70	.07033	84.01010	1.16519	-12.56714	.02039	.00000	.00000	3.98463	-23.11461	.04122
200.33	891.06	56.28	.07244	83.25893	1.17293	-15.48024	.02043	.00000	.00000	2.91310	-20.20151	.04102
201.72	888.60	55.56	.07492	81.92915	1.18067	-18.87746	.02048	.00000	.00000	3.39722	-16.80429	.04070
203.19	885.39	54.62	.07771	80.16064	1.18842	-22.64198	.02052	.00000	.00000	3.76453	-13.03976	.04028
204.80	881.10	53.39	.08096	77.75078	1.19619	-26.94359	.02056	.00000	.00000	4.30161	-8.73815	.03974
206.56	875.72	51.88	.08474	74.67441	1.20398	-31.80235	.02061	.00000	.00000	4.85876	-3.87940	.03908
208.70	867.85	49.74	.08966	70.08279	1.21179	-37.92711	.02065	.00000	.00000	6.12476	2.24536	.03813
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215.00 2608.10  41.72  .10600  50.95418   1.21963 -56.15980    .02067    .00000    .00000   8.76006  20.47806   .03644
220.00 2540.76  35.62  .12084  34.21611   1.21963 -70.03143    .02065    .00000    .00000  13.87163  34.34968   .03443
225.00 2474.68  30.54  .13718  18.40763   1.21962 -83.05276    .02063    .00000    .00000  13.02133  47.37101   .03140
230.00 2410.54  26.34  .15485   3.60244   1.21963 -95.17372    .02062    .00000    .00000  12.12097  59.49198   .02870
235.00 2349.07  22.88  .17366 -10.14951   1.21963-106.36929    .02061    .00000    .00000  11.19557  70.68755   .02630
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255.00 2140.13  14.09  .25665 -54.64090   1.21963-142.24466    .02060    .00000    .00000   7.74813 106.56291   .01935
260.00 2097.51  12.73  .27837 -63.43280   1.21964-149.28709    .02060    .00000    .00000   7.04243 113.60534   .01813
265.00 2058.50  11.59  .30012 -71.42675   1.21964-155.68066    .02060    .00000    .00000   6.39358 119.99892   .01706
270.00 2022.88  10.63  .32170 -78.68540   1.21964-161.47898    .02060    .00000    .00000   5.79831 125.79723   .01612
275.00 1990.43   9.81  .34295 -85.26850   1.21964-166.73242    .02060    .00000    .00000   5.25344 131.05067   .01530
280.00 1960.94   9.11  .36372 -91.22992   1.21964-171.48573    .02060    .00000    .00000   4.75331 135.80398   .01458
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310.00 1835.21   6.59  .47076-116.45000   1.21963-191.55734    .02059    .00000    .00000   2.49329 155.87560   .01177
315.00 1821.32   6.35  .48471-119.21792   1.21962-193.75680    .02059    .00000    .00000   2.19946 158.07506   .01148
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330.00 1789.66   5.83  .51843-125.51704   1.21960-198.75984    .02059    .00000    .00000   1.41636 163.07809   .01082
335.00 1782.18   5.72  .52681-127.00403   1.21959-199.94041    .02059    .00000    .00000   1.18057 164.25866   .01067
340.00 1776.12   5.62  .53371-128.20592   1.21959-200.89450    .02059    .00000    .00000    .95409 165.21275   .01054
345.00 1771.46   5.55  .53911-129.13202   1.21959-201.62957    .02059    .00000    .00000    .73507 165.94782   .01043
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360.00 1765.48   5.46  .54611-130.31673   1.21958-202.56980    .02059    .00000    .00000    .10581 166.88805   .01026
360.00 1238.17   1.03 2.03129-232.03647   1.21958-282.70864    .02059    .00000    .00000    .00000 166.88805   .00000
540.00 1000.00   1.03  .05461  -9.17099    .03930 -10.53334    .00069    .00000    .00000    .00000 166.88805   .00000
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THETA     T       P      V          H          S          U          N     FLAME SPEED, TEMP., AND EXTENT MASS-FR. BURN.-VOL.
166.59 2537.66  17.25  .00002     .00372     .00013    -.00671     .00000  771.67351 2537.66077   .18781    .00010    .00040
168.46 2538.47  18.06  .00024     .03712     .00125    -.06715     .00002  787.31929 2536.13147   .39292    .00100    .00394
170.54 2547.11  19.11  .00113     .19570     .00624    -.32750     .00010  812.65478 2545.75754   .65649    .00500    .01931
171.57 2551.59  19.81  .00218     .40142     .01246    -.64684     .00021  826.30920 2544.25040   .80191    .01000    .03783
172.97 2563.24  20.96  .00415     .85976     .02490   -1.24666     .00041  854.19674 2556.95749  1.04391    .02000    .07306
175.02 2584.30  22.95  .00764    1.92912     .04973   -2.31963     .00083  900.62765 2577.69019  1.35295    .04000    .13721
176.30 2600.08  24.67  .01073    3.12872     .07450   -3.28475     .00124  934.80958 2581.62927  1.56817    .06000    .19436
177.22 2614.36  26.28  .01351    4.45758     .09924   -4.14251     .00166  966.96433 2587.26184  1.70912    .08000    .24581
177.96 2627.40  27.84  .01603    5.90005     .12393   -4.90579     .00207  997.15874 2592.91687  1.83582    .10000    .29246
178.88 2645.34  30.10  .01941    8.25965     .16092   -5.88789     .00269 1042.89886 2608.86655  1.97516    .13000    .35495
179.68 2661.50  32.31  .02240   10.82178     .19784   -6.70147     .00331 1083.30750 2615.96823  2.09316    .16000    .41005
180.19 2676.42  34.47  .02507   13.57289     .23470   -7.35754     .00394 1122.16884 2622.94498  2.17499    .19000    .45913
180.66 2690.22  36.60  .02749   16.49191     .27150   -7.87382     .00456 1159.69667 2629.74106  2.24493    .22000    .50319
181.08 2703.06  38.71  .02968   19.56288     .30825   -8.26353     .00518 1195.94255 2636.22156  2.28755    .25000    .54305
181.42 2715.31  40.80  .03169   22.79269     .34496   -8.52061     .00580 1231.31805 2642.56088  2.34112    .28000    .57934
181.80 2726.77  42.87  .03354   26.15042     .38162   -8.67103     .00643 1265.90524 2648.71710  2.39650    .31000    .61257
182.19 2737.54  44.91  .03526   29.62587     .41825   -8.72330     .00705 1299.20471 2654.47815  2.45200    .34000    .64315
182.58 2747.47  46.93  .03686   33.18624     .45483   -8.70512     .00767 1331.49641 2659.97931  2.50698    .37000    .67139
182.99 2756.76  48.91  .03836   36.83384     .49137   -8.61440     .00830 1362.80687 2665.23969  2.56246    .40000    .69760
183.34 2765.61  50.88  .03978   40.57693     .52788   -8.44411     .00892 1393.43036 2670.40411  2.60762    .43000    .72200
183.77 2773.74  52.80  .04113   44.36818     .56435   -8.23413     .00954 1422.43733 2674.92868  2.66831    .46000    .74480
184.27 2781.33  54.66  .04245   48.21875     .60080   -7.97468     .01017 1450.39963 2679.28439  2.73937    .49000    .76618
184.92 2787.68  56.40  .04376   52.00648     .63721   -7.76917     .01079 1476.11848 2682.93909  2.83541    .52000    .78628
187.69 2782.77  56.57  .04606   54.16165     .67360   -8.94010     .01141 1477.03209 2675.64716  3.14814    .55000    .80544
189.14 2782.37  57.27  .04796   56.96879     .71000   -9.56140     .01203 1488.43785 2680.20718  3.42962    .58000    .82346
190.58 2780.64  57.75  .04999   59.54084     .74638  -10.38094     .01265 1494.92026 2680.15588  3.66925    .61000    .84051
192.11 2776.91  57.89  .05225   61.72704     .78275  -11.52528     .01327 1496.62033 2678.90005  3.91476    .64000    .85669
193.39 2774.25  58.13  .05441   64.05293     .81913  -12.55191     .01390 1500.28465 2679.99045  4.11751    .67000    .87202
194.62 2771.21  58.27  .05664   66.26236     .85550  -13.67640     .01452 1502.26396 2679.88040  4.29478    .70000    .88659
195.82 2767.82  58.32  .05894   68.35210     .89186  -14.90139     .01514 1502.89113 2679.56683  4.46671    .73000    .90044
197.25 2761.33  57.89  .06166   69.74002     .92823  -16.71625     .01576 1496.01099 2676.17554  4.65845    .76000    .91367
199.07 2749.59  56.70  .06515   69.89343     .96461  -19.56728     .01637 1477.76097 2669.51492  4.88957    .79000    .92631
200.33 2743.81  56.28  .06797   71.20387    1.00100  -21.44498     .01699 1472.07028 2671.99750  5.06122    .82000    .93832
201.72 2735.96  55.56  .07116   71.94901    1.03739  -23.79633     .01761 1460.76537 2668.50565  5.21959    .85000    .94979
203.19 2726.71  54.62  .07466   72.24518    1.07380  -26.52307     .01823 1446.70029 2665.04987  5.38031    .88000    .96075
204.80 2715.32  53.39  .07864   71.88298    1.11022  -29.80028     .01884 1427.57799 2660.10248  5.54752    .91000    .97124
206.56 2701.78  51.88  .08315   70.81988    1.14667  -33.66172     .01946 1403.97902 2654.30023  5.71934    .94000    .98126
208.70 2682.89  49.74  .08884   68.19744    1.18313  -38.82385     .02007 1369.24832 2644.27747  5.91089    .97000    .99085
211.95 2649.17  46.00  .09773   61.47587    1.21963  -47.39974     .02068 1306.69623 2623.09903  6.17132   1.00000   1.00000
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**** ALL INPUT DATA HAVE BEEN PROCESSED.
     AT LOC 45270
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                            A MODEL SIMULATING THE INTERNAL-COMBUSTION ENGINE

ENGINE                              FUEL                                        OPERATING CONDITIONS

FOUR STROKE AUTOMOTIVE TYPE         OCTANE C8H18                                AIR-FUEL RATIO       .92
BORE              3.94 IN.          ACTIVATION ENERGY  39000.00 CAL./MOLE       PISTON TEMP       500.00 K
STROKE            2.46 IN.          ENTHALPY OF                                 WALL TEMP         420.00 K
ROD               7.06 IN.          COMBUSTION        1222770.00 CAL/MOLE       MAN. TEMP         320.00 K
CLEAR. VOL.       3.33 CU.IN.                                                   MAN. PR.             .99 ATM
SWEPT VOL.       30.00 CU.IN.                                                   EXH. PR.            1.03 ATM
COMPRESSION RATIO10.00 TO ONE                                                   SPARK ADV.         16.00
                                                                                SPEED            2800.00 RPM

COMBUSTION OCCURS IN 39 INCREMENTS.  ERRORS ARE LESS THAN    .00100 PERCENT.  FLAME SPEED FACTOR IS   .15525000E 06
HEAT TRANSFER FACTOR IS   2.00000   NORMAL RUN



                  SUMMARY OF RESULTS

    PUMPING WORK                   -.47611947E 00 CAL
    NET CYCLE WORK                  .13452925E 03 CAL
    NET HEAT TRANSFERED             .12129069E 03 CAL
    INDICATED THERMAL EFFICIENCY    .33315267E 02 PERCENT
    MEAN EFFECTIVE PRESSURE         .11302140E 02 ATM
    RESIDUAL WEIGHT FRACTION        .33289107E-01
    VOLUMETRIC EFFICIENCY           .97627462E 00 PERCENT
```

THETA	T	P	V	H	S	U	N	Q	QTOT	W	WTOT	HB
.00	344.84	.99	.54611	-22.58769	.95518	-35.68175	.01911	.00000	.00000	.00000	.00000	.00000
10.00	345.51	1.00	.54302	-22.48808	.95518	-35.60766	.01911	.00000	.00000	-.07409	-.07409	.00000
20.00	347.55	1.02	.53380	-22.18514	.95518	-35.38210	.01911	.00000	.00000	-.22555	-.29965	.00000
30.00	351.01	1.06	.51855	-21.66938	.95518	-34.99796	.01911	.00000	.00000	-.38415	-.68380	.00000
40.00	356.02	1.12	.49750	-20.92281	.95518	-34.44157	.01911	.00000	.00000	-.55639	-1.24019	.00000
50.00	362.73	1.21	.47096	-19.91986	.95518	-33.69353	.01911	.00000	.00000	-.74803	-1.98822	.00000
60.00	371.37	1.33	.43941	-18.62534	.95518	-32.72705	.01911	.00000	.00000	-.96649	-2.95471	.00000
70.00	382.23	1.49	.40348	-16.99272	.95518	-31.50656	.01911	.00000	.00000	-1.22048	-4.17519	.00000
80.00	395.67	1.70	.36400	-14.96164	.95518	-29.98581	.01911	.00000	.00000	-1.52076	-5.69595	.00000
90.00	412.16	2.01	.32199	-12.45483	.95518	-28.10524	.01911	.00000	.00000	-1.88057	-7.57652	.00000
100.00	432.28	2.43	.27867	-9.37447	.95518	-25.78904	.01911	.00000	.00000	-2.31620	-9.89272	.00000
110.00	456.74	3.04	.23542	-5.59927	.95518	-22.94252	.01911	.00000	.00000	-2.84652	-12.73924	.00000
120.00	486.33	3.94	.19371	-.98560	.95518	-19.45242	.01911	.00000	.00000	-3.49010	-16.22933	.00000
130.00	521.84	5.28	.15510	4.61714	.95518	-15.19795	.01911	.00000	.00000	-4.25447	-20.48381	.00000
140.00	563.67	7.30	.12106	11.31073	.95518	-10.09294	.01911	.00000	.00000	-5.10500	-25.58881	.00000
150.00	610.94	10.30	.09296	18.99131	.95518	-4.20704	.01911	.00000	.00000	-5.88590	-31.47471	.00000
160.00	659.41	14.36	.07199	26.99693	.95518	1.95803	.01911	.00000	.00000	-6.16508	-37.63979	.00000
164.00	677.09	16.13	.06580	29.94867	.95518	4.23851	.01911	.00000	.00000	-2.28048	-39.92026	.00000
166.59	687.41	17.25	.06250	31.68026	.95521	5.57040	.01911	.00000	.00000	-1.33189	-41.25215	.00000
168.46	694.60	18.06	.06047	32.89473	.95547	6.44144	.01911	.00000	.00000	-.87104	-42.12320	.00000
170.54	703.47	19.11	.05856	34.40938	.95664	7.30770	.01912	.00000	.00000	-.86625	-42.98945	.00000
171.57	709.18	19.81	.05775	35.39930	.95809	7.69132	.01912	.00000	.00000	-.38362	-43.37307	.00000
172.97	718.22	20.96	.05680	37.00419	.96097	8.17112	.01914	.00000	.00000	-.47981	-43.85288	.00000
175.02	732.65	22.91	.05571	39.45129	.96661	8.53329	.01917	.23389	.23389	-.59606	-44.44894	.02542
176.30	744.39	24.61	.05522	41.56945	.97221	8.65213	.01920	.17150	.40539	-.29033	-44.73927	.02635
177.24	754.82	26.21	.05495	43.56069	.97779	8.68166	.01923	.14260	.54799	-.17213	-44.91140	.02723
177.99	764.39	27.74	.05480	45.48048	.98333	8.66325	.01927	.12604	.67404	-.10763	-45.01904	.02808
178.91	777.55	29.98	.05467	48.27117	.99160	8.57852	.01931	.17955	.85358	-.09482	-45.11385	.02930
179.72	789.61	32.16	.05462	50.97629	.99980	8.43896	.01936	.17644	1.03002	-.03687	-45.15073	.03043
180.24	800.82	34.30	.05461	53.68590	1.00796	8.31738	.01941	.12374	1.15376	-.00217	-45.15289	.03151
180.72	811.33	36.41	.05463	56.35429	1.01606	8.17298	.01946	.12441	1.27817	.02000	-45.13290	.03256
181.14	821.24	38.51	.05467	58.99815	1.02411	8.01854	.01951	.11680	1.39497	.03764	-45.09526	.03356
181.44	830.68	40.59	.05470	61.65984	1.03213	7.88811	.01956	.08978	1.48474	.04066	-45.05460	.03454
181.82	839.58	42.64	.05475	64.26532	1.04010	7.71909	.01961	.12043	1.60517	.04858	-45.00602	.03548
182.21	848.03	44.67	.05482	66.82491	1.04802	7.51935	.01966	.13571	1.74089	.06402	-44.94199	.03639
182.61	856.02	46.66	.05490	69.28779	1.05588	7.24517	.01971	.17431	1.91520	.09987	-44.84212	.03726
183.01	863.61	48.62	.05500	71.66936	1.06369	6.90882	.01976	.21527	2.13046	.12108	-44.72103	.03810
183.40	870.84	50.54	.05511	73.98711	1.07146	6.52444	.01981	.24364	2.37411	.14074	-44.58030	.03891
183.83	877.65	52.42	.05524	76.16504	1.07917	6.02762	.01986	.31484	2.68894	.18199	-44.39831	.03968
184.33	883.99	54.22	.05542	78.14676	1.08681	5.37058	.01990	.43322	3.12216	.22383	-44.17448	.04040
184.97	889.70	55.88	.05568	79.80318	1.09437	4.44446	.01995	.59142	3.71358	.33470	-43.83978	.04106
187.72	889.09	55.70	.05720	76.67012	1.10108	-.49692	.01999	2.85138	6.56495	2.09000	-41.74978	.04104
189.19	890.71	56.18	.05829	75.62439	1.10820	-3.67987	.02004	1.68575	8.25070	1.49720	-40.25258	.04102
190.66	891.50	56.41	.05955	74.11623	1.11527	-7.24564	.02008	1.81908	10.06978	1.74670	-38.50588	.04103
192.23	890.99	56.26	.06111	71.74547	1.12223	-11.52874	.02013	2.12079	12.19057	2.16231	-36.34358	.04089
193.56	890.86	56.22	.06260	69.75398	1.12926	-15.49055	.02017	1.91048	14.10105	2.05133	-34.29225	.04076
194.83	890.51	56.12	.06415	67.67433	1.13629	-19.52270	.02021	1.89716	15.99821	2.13499	-32.15725	.04064
196.07	889.83	55.92	.06580	65.41665	1.14331	-23.70063	.02026	1.91872	17.91693	2.25921	-29.89804	.04048
197.53	887.47	55.23	.06791	61.94257	1.15018	-28.88820	.02030	2.32534	20.24227	2.86223	-27.03582	.04013
199.45	881.87	53.61	.07095	56.01897	1.15674	-36.10619	.02034	3.12371	23.36599	4.09427	-22.94154	.03941
200.87	878.83	52.75	.07338	52.11953	1.16362	-41.63524	.02038	2.32741	25.69340	3.20164	-19.73991	.03890
202.34	875.14	51.72	.07608	47.74868	1.17047	-47.54948	.02042	2.43637	28.12977	3.47787	-16.26203	.03839
203.91	870.54	50.46	.07914	42.70534	1.17727	-54.01541	.02046	2.60319	30.73296	3.86274	-12.39929	.03779
205.63	864.69	48.90	.08272	36.70350	1.18398	-61.26536	.02050	2.85349	33.58645	4.39646	-8.00283	.03705
207.51	857.62	47.06	.08689	29.75418	1.19061	-69.28467	.02054	3.08621	36.67266	4.93309	-3.06974	.03618
209.85	847.44	44.53	.09242	20.38366	1.19701	-79.27808	.02058	3.74362	40.41628	6.24980	3.18006	.03498
213.50	828.38	40.24	.10187	5.62875	1.20311	-93.64177	.02062	4.48885	44.90513	9.87484	13.05490	.03292
215.00	2388.98	38.12	.10600	-1.97214	1.20217	-99.82658	.02061	2.27649	47.18162	3.90831	16.96321	.03259

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 220.00 2276.53  31.85  .12084 -26.32447   1.19909-119.52989   .02060  7.28943  54.47105 12.41388  29.37709  .03150
 225.00 2171.15  26.75  .13718 -48.40530   1.19629-137.27710   .02060  6.30939  60.78044 11.43782  40.81491  .02811
 230.00 2074.28  22.64  .15485 -68.30939   1.19375-153.20713   .02060  5.49101  66.27145 10.43902  51.25393  .02516
 235.00 1986.15  19.33  .17366 -86.19291   1.19141-167.47982   .02060  4.81568  71.08712  9.45701  60.71094  .02262
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 250.00 1768.68  12.71  .23513-129.69328   1.18537-202.07681   .02059  3.42296  82.57291  6.90108  83.82215  .01701
 255.00 1709.39  11.25  .25665-141.42221   1.18361-211.37902   .02059  3.10611  85.67901  6.19610  90.01825  .01565
 260.00 1655.54  10.05  .27837-152.02805   1.18194-219.78105   .02059  2.83962  88.51863  5.56241  95.58067  .01448
 265.00 1606.55   9.05  .30012-161.63865   1.18035-227.38673   .02059  2.61372  91.13235  4.99196 100.57263  .01346
 270.00 1561.91   8.20  .32170-170.36466   1.17884-234.28572   .02059  2.42081  93.55315  4.47818 105.05081  .01258
 275.00 1521.16   7.49  .34295-178.30217   1.17739-240.55567   .02059  2.25488  95.80803  4.01507 109.06588  .01182
 280.00 1483.30   6.89  .36372-185.59553   1.17600-246.29945   .02059  2.11121  97.91924  3.63258 112.69845  .01115
 285.00 1448.82   6.38  .38385-192.20501   1.17465-251.49784   .02059  1.98402  99.90326  3.21436 115.91282  .01055
 290.00 1417.23   5.94  .40322-198.24159   1.17336-256.24172   .02059  1.87314 101.77640  2.87075 118.78356  .01003
 295.00 1388.26   5.56  .42170-203.76101   1.17210-260.57552   .02059  1.77549 103.55188  2.55831 121.34187  .00958
 300.00 1361.67   5.24  .43918-208.81164   1.17088-264.53783   .02059  1.68905 105.24093  2.27327 123.61514  .00917
 305.00 1337.25   4.96  .45556-213.43558   1.16969-268.16232   .02059  1.61219 106.85311  2.01230 125.62744  .00882
 310.00 1314.82   4.72  .47076-217.66955   1.16854-271.47836   .02059  1.54358 108.39669  1.77246 127.39990  .00850
 315.00 1294.22   4.51  .48471-221.54559   1.16741-274.51161   .02059  1.48214 109.87883  1.55111 128.95101  .00822
 320.00 1275.33   4.33  .49734-225.09172   1.16630-277.28452   .02059  1.42697 111.30580  1.34595 130.29696  .00798
 325.00 1258.02   4.18  .50859-228.33237   1.16522-279.81667   .02059  1.37732 112.68311  1.15483 131.45179  .00776
 330.00 1242.18   4.05  .51843-231.28885   1.16416-282.12514   .02059  1.33257 114.01568   .97590 132.42769  .00757
 335.00 1227.74   3.94  .52681-233.97968   1.16311-284.22478   .02059  1.29222 115.30790   .80742 133.23512  .00740
 340.00 1214.60   3.85  .53371-236.42078   1.16209-286.12837   .02059  1.25582 116.56372   .64777 133.88288  .00726
 345.00 1202.72   3.77  .53911-238.62585   1.16108-287.84691   .02059  1.22302 117.78673   .49552 134.37840  .00713
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 540.00 1000.00   1.03  .05461  -9.17099   .03930 -10.53334   .00069   .00000 121.29070   .00000 135.00537  .00000
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 THETA     T       P      V          H          S          U           N     FLAME SPEED, TEMP., AND EXTENT MASS-FR. BURN.-VOL.
 166.59 2537.66  17.25  .00002     .00372     .00013    -.00671      .00000  771.67351 2537.66077     .18781     .00010     .00040
 168.46 2538.47  18.06  .00024     .03712     .00125    -.06715      .00002  787.31929 2536.13147     .39292     .00100     .00394
 170.54 2547.11  19.11  .00113     .19570     .00624    -.32750      .00010  812.65478 2545.75754     .65649     .00500     .01931
 171.57 2551.59  19.81  .00218     .40142     .01246    -.64684      .00021  826.30920 2544.25040     .80191     .01000     .03783
 172.97 2563.24  20.96  .00415     .85976     .02490   -1.24666      .00041  854.19674 2556.95749    1.04391     .02000     .07306
 175.02 2562.50  22.91  .00759    1.68882     .04963   -2.52191      .00083  899.75685 2577.09015    1.35295     .04000     .13619
 176.30 2574.86  24.61  .01065    2.70918     .07434   -3.63814      .00124  933.50958 2581.08075    1.56525     .06000     .19283
 177.24 2588.68  26.21  .01341    3.88398     .09902   -4.62612      .00165  965.27422 2586.68924    1.70550     .08000     .24399
 177.99 2602.04  27.74  .01592    5.18697     .12367   -5.50765      .00207  995.17088 2592.31448    1.83175     .10000     .29048
 178.91 2620.56  29.98  .01929    7.34562     .16059   -6.66017      .00269 1040.24724 2608.00507    1.97152     .13000     .35286
 179.72 2637.17  32.16  .02228    9.70875     .19745   -7.64281      .00331 1080.70000 2615.32202    2.08987     .16000     .40791
 180.24 2653.45  34.30  .02496   12.31622     .23426   -8.42142      .00393 1119.12622 2622.21634    2.17188     .19000     .45709
 180.72 2668.20  36.41  .02739   15.08787     .27102   -9.06334      .00455 1156.57430 2629.08603    2.24223     .22000     .50126
 181.14 2681.90  38.51  .02959   18.02057     .30773   -9.57101      .00518 1192.74619 2635.61893    2.28760     .25000     .54123
 181.44 2695.07  40.59  .03160   21.13108     .34440   -9.93018      .00580 1228.04591 2642.00534    2.33843     .28000     .57765
 181.82 2707.01  42.64  .03345   24.34585     .38102  -10.20284      .00642 1262.15971 2647.95618    2.39403     .31000     .61098
 182.21 2718.00  44.67  .03518   27.65979     .41760  -10.39305      .00705 1295.23021 2653.67886    2.44918     .34000     .64164
 182.61 2727.70  46.66  .03678   31.01391     .45412  -10.55075      .00767 1327.20905 2659.10870    2.50452     .37000     .66994
 183.01 2736.45  48.62  .03829   34.41290     .49059  -10.67197      .00829 1357.79106 2664.11917    2.55995     .40000     .69618
 183.40 2744.48  50.54  .03971   37.86331     .52701  -10.75104      .00891 1387.77905 2669.10239    2.60491     .43000     .72061
 183.83 2751.37  52.42  .04107   41.28928     .56337  -10.85215      .00954 1416.49739 2673.69110    2.66540     .46000     .74342
 184.33 2756.92  54.22  .04239   44.63353     .59967  -11.02371      .01016 1443.61513 2677.83835    2.73549     .49000     .76477
 184.97 2760.53  55.88  .04370   47.77283     .63588  -11.36984      .01078 1468.68739 2681.45169    2.82965     .52000     .78481
 187.72 2736.88  55.70  .04594   46.69024     .67125  -15.28460      .01140 1463.89445 2671.74725    3.13650     .55000     .80313
 189.19 2727.00  56.18  .04785   47.52176     .70703  -17.57725      .01201 1471.58069 2676.14819    3.41047     .58000     .82087
 190.66 2715.67  56.41  .04989   47.96632     .74275  -20.19335      .01263 1474.83195 2675.56134    3.64818     .61000     .83773
 192.23 2700.86  56.26  .05217   47.63982     .77836  -23.45470      .01325 1472.04071 2673.23132    3.89288     .64000     .85373
 193.56 2689.12  56.22  .05440   47.66465     .81405  -26.41676      .01386 1471.63460 2673.70422    4.10159     .67000     .86904
 194.83 2677.83  56.12  .05669   47.61189     .84973  -29.44085      .01448 1470.00739 2673.10687    4.27556     .70000     .88366
 196.07 2666.49  55.92  .05907   47.39325     .88541  -32.60115      .01510 1466.86111 2672.08551    4.44765     .73000     .89763
 197.53 2650.12  55.23  .06186   46.02265     .92094  -36.72038      .01571 1456.14140 2667.92209    4.63694     .76000     .91095
 199.45 2623.16  53.61  .06554   42.29852     .95616  -42.79453      .01632 1430.59120 2658.84976    4.86879     .79000     .92367
 200.87 2606.77  52.75  .06868   40.45646     .99169  -47.29157      .01694 1418.21089 2660.16757    5.04402     .82000     .93593
 202.34 2589.03  51.72  .07210   38.12787    1.02720  -52.18570      .01755 1402.09901 2656.31854    5.20544     .85000     .94769
 203.91 2569.06  50.46  .07589   35.10663    1.06265  -57.64741      .01817 1382.18069 2651.38156    5.36800     .88000     .95898
 205.63 2545.65  48.90  .08022   31.09778    1.09801  -63.91603      .01878 1357.08076 2644.93701    5.53710     .91000     .96983
 207.51 2518.91  47.06  .08517   26.09212    1.13330  -70.99281      .01940 1326.97392 2637.40720    5.71012     .94000     .98027
 209.85 2482.42  44.53  .09152   18.60653    1.16835  -80.08986      .02001 1284.39009 2624.76984    5.90439     .97000     .99031
 213.50 2423.04  40.24  .10187    5.62875    1.20311  -93.64177      .02062 1207.79457 2597.43137    6.17494    1.00000    1.00000




 **** ALL INPUT DATA HAVE BEEN PROCESSED.
      AT LOC 45267
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DATA SET C

REDUCED FLAME PROPAGATION RATES

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                        A MODEL SIMULATING THE INTERNAL-COMBUSTION ENGINE
 ENGINE                                FUEL                                OPERATING CONDITIONS

 FOUR STROKE AUTOMOTIVE TYPE           OCTANE C8H18                        AIR-FUEL RATIO       .92
 BORE              3.94 IN.            ACTIVATION ENERGY  39000.00 CAL./MOLE   PISTON TEMP      500.00 K
 STROKE            2.46 IN.            ENTHALPY OF                         WALL TEMP         420.00 K
 ROD               7.06 IN.            COMBUSTION       1222770.00 CAL/MOLE    MAN. TEMP     320.00 K
 CLEAR. VOL.       3.33 CU.IN.                                             MAN. PR.             .99 ATM
 SWEPT VOL.       30.00 CU.IN.                                             EXH. PR.            1.03 ATM
 COMPRESSION RATIO10.00 TO ONE                                             SPARK ADV.         16.00
                                                                           SPEED            2800.00 RPM

 COMBUSTION OCCURS IN 39 INCREMENTS.  ERRORS ARE LESS THAN    .00100 PERCENT.  FLAME SPEED FACTOR IS   .11475000E 06
 HEAT TRANSFER FACTOR IS   1.00000   NORMAL RUN

                    SUMMARY OF RESULTS

     PUMPING WORK                     -.47611947E 00 CAL
     NET CYCLE WORK                    .14192007E 03 CAL
     NET HEAT TRANSFERED               .66320603E 02 CAL
     INDICATED THERMAL EFFICIENCY      .35145557E 02 PERCENT
     MEAN EFFECTIVE PRESSURE           .11923061E 02 ATM
     RESIDUAL WEIGHT FRACTION          .33289107E-01
     VOLUMETRIC EFFICIENCY             .97627462E 00 PERCENT
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THETA	T	P	V	H	S	U	N	Q	QTOT	W	WTOT	HB
.00	344.84	.99	.54611	-22.58769	.95518	-35.68175	.01911	.00000	.00000	.00000	.00000	.00000
10.00	345.51	1.00	.54302	-22.48808	.95518	-35.60766	.01911	.00000	.00000	-.07409	-.07409	.00000
20.00	347.55	1.02	.53380	-22.18514	.95518	-35.38210	.01911	.00000	.00000	-.22555	-.29965	.00000
30.00	351.01	1.06	.51855	-21.66938	.95518	-34.99796	.01911	.00000	.00000	-.38415	-.68380	.00000
40.00	356.02	1.12	.49750	-20.92281	.95518	-34.44157	.01911	.00000	.00000	-.55639	-1.24019	.00000
50.00	362.73	1.21	.47096	-19.91986	.95518	-33.69353	.01911	.00000	.00000	-.74803	-1.98822	.00000
60.00	371.37	1.33	.43941	-18.62534	.95518	-32.72705	.01911	.00000	.00000	-.96649	-2.95471	.00000
70.00	382.23	1.49	.40348	-16.99272	.95518	-31.50656	.01911	.00000	.00000	-1.22048	-4.17519	.00000
80.00	395.67	1.70	.36400	-14.96164	.95518	-29.98581	.01911	.00000	.00000	-1.52076	-5.69595	.00000
90.00	412.16	2.01	.32199	-12.45483	.95518	-28.10524	.01911	.00000	.00000	-1.88057	-7.57652	.00000
100.00	432.28	2.43	.27867	-9.37447	.95518	-25.78904	.01911	.00000	.00000	-2.31620	-9.89272	.00000
110.00	456.74	3.04	.23542	-5.59927	.95518	-22.94252	.01911	.00000	.00000	-2.84652	-12.73924	.00000
120.00	486.33	3.94	.19371	-.98560	.95518	-19.45242	.01911	.00000	.00000	-3.49010	-16.22933	.00000
130.00	521.84	5.28	.15510	4.61714	.95518	-15.19795	.01911	.00000	.00000	-4.25447	-20.48381	.00000
140.00	563.67	7.30	.12106	11.31073	.95518	-10.09294	.01911	.00000	.00000	-5.10500	-25.58881	.00000
150.00	610.94	10.30	.09296	18.99131	.95518	-4.20704	.01911	.00000	.00000	-5.88590	-31.47471	.00000
160.00	659.41	14.36	.07199	26.99693	.95518	1.95803	.01911	.00000	.00000	-6.16508	-37.63979	.00000
164.00	677.09	16.13	.06580	29.94867	.95518	4.23851	.01911	.00000	.00000	-2.28048	-39.92026	.00000
167.45	690.58	17.60	.06153	32.21366	.95521	5.98332	.01911	.00000	.00000	-1.74481	-41.66507	.00000
169.93	699.32	18.61	.05908	33.69022	.95547	7.05779	.01911	.00000	.00000	-1.07447	-42.73954	.00000
172.68	709.03	19.79	.05698	35.35205	.95663	8.03895	.01912	.00000	.00000	-.98117	-43.72071	.00000
174.04	714.79	20.52	.05619	36.35057	.95808	8.42980	.01912	.00000	.00000	-.39085	-44.11155	.00000
175.91	723.46	21.65	.05536	37.89117	.96095	8.86026	.01914	.00000	.00000	-.43045	-44.54201	.00000
178.66	736.46	23.45	.05470	40.14294	.96659	9.07455	.01917	.15987	.15987	-.37417	-44.91617	.02571
180.38	746.70	24.96	.05462	42.01612	.97221	9.00379	.01920	.11666	.27653	-.04590	-44.96207	.02653
181.61	755.73	26.35	.05472	43.76666	.97779	8.84557	.01923	.09395	.37048	.06427	-44.89780	.02731
182.60	764.02	27.68	.05490	45.44841	.98335	8.63999	.01927	.08325	.45373	.12233	-44.77547	.02804
183.82	775.43	29.61	.05524	47.89305	.99164	8.28125	.01931	.11683	.57057	.24191	-44.53356	.02909
184.89	785.77	31.45	.05565	50.24318	.99988	7.85851	.01936	.11471	.68527	.30803	-44.22553	.03006
185.69	795.57	33.28	.05602	52.62136	1.00807	7.46968	.01941	.09382	.77909	.29501	-43.93052	.03100
186.38	804.80	35.09	.05638	54.98821	1.01621	7.08130	.01946	.08664	.86573	.30174	-43.62878	.03190
186.94	813.61	36.88	.05671	57.37174	1.02432	6.71540	.01951	.07652	.94225	.28938	-43.33940	.03278
187.51	821.83	38.63	.05706	59.69606	1.03238	6.30862	.01956	.08112	1.02337	.32565	-43.01374	.03362
188.08	829.49	40.32	.05745	61.95167	1.04041	5.85252	.01961	.08716	1.11053	.36895	-42.64480	.03441
188.66	836.59	41.94	.05787	64.08827	1.04838	5.30383	.01965	.11171	1.22224	.43697	-42.20782	.03515
189.25	843.17	43.49	.05833	66.10613	1.05631	4.66207	.01970	.14466	1.36690	.49711	-41.71072	.03585
189.79	849.50	45.03	.05878	68.10725	1.06420	4.01102	.01975	.15619	1.52309	.49486	-41.21585	.03653
190.48	854.85	46.36	.05939	69.75437	1.07203	3.07043	.01980	.24588	1.76897	.69470	-40.52115	.03710
191.36	859.08	47.44	.06022	70.94065	1.07980	1.75024	.01985	.35644	2.12541	.96375	-39.55740	.03755
194.87	851.33	45.48	.06420	66.36100	1.08711	-4.35642	.01989	1.54249	3.66790	4.56417	-34.99323	.03667
196.90	848.52	44.79	.06698	64.19504	1.09465	-8.45549	.01993	1.00888	4.67678	3.09019	-31.90303	.03622
198.85	845.23	43.99	.06997	61.77002	1.10219	-12.76670	.01998	1.05009	5.72687	3.26111	-28.64192	.03579
200.92	840.55	42.87	.07347	58.55350	1.10968	-17.73275	.02002	1.19345	6.92032	3.77261	-24.86931	.03522
202.52	837.94	42.26	.07643	56.40046	1.11727	-21.81617	.02006	.97249	7.89280	3.11093	-21.75838	.03486
204.23	834.36	41.43	.07978	53.69459	1.12484	-26.35529	.02011	1.06687	8.95967	3.47226	-18.28612	.03443
205.96	830.29	40.50	.08342	50.67718	1.13241	-31.15113	.02015	1.11028	10.06995	3.68556	-14.60057	.03394
207.92	824.57	39.23	.08781	46.68102	1.13992	-36.75425	.02019	1.27601	11.34597	4.32710	-10.27347	.03329
210.29	816.16	37.42	.09351	41.04173	1.14735	-43.70840	.02023	1.55226	12.89823	5.40189	-4.87157	.03237
212.25	810.14	36.17	.09851	36.75588	1.15493	-49.54172	.02028	1.28675	14.18497	4.54657	-.32500	.03168
214.10	804.71	35.07	.10348	32.76098	1.16256	-55.13235	.02032	1.21964	15.40461	4.37099	4.04599	.03109
216.14	798.10	33.77	.10925	27.97823	1.17017	-61.36817	.02036	1.34356	16.74818	4.89226	8.93825	.03040
218.43	790.14	32.26	.11601	22.26584	1.17775	-68.36222	.02040	1.48906	18.23724	5.50498	14.44323	.02958
220.75	782.14	30.79	.12320	16.43606	1.18536	-75.44677	.02044	1.49673	19.73397	5.58782	20.03105	.02876
222.95	774.99	29.53	.13033	11.06298	1.19305	-82.15270	.02049	1.41165	21.14562	5.29428	25.32534	.02805
225.72	765.00	27.84	.13965	3.69811	1.20064	-90.47902	.02053	1.74152	22.88713	6.58481	31.91014	.02709
229.34	751.08	25.62	.15243	-6.48157	1.20808	-101.08393	.02057	2.19960	25.08673	8.40531	40.31545	.02580
236.88	719.46	21.21	.18101	-27.29611	1.21531	-120.26429	.02060	2.75711	27.84384	16.42325	56.73871	.02307
240.00	2224.61	19.44	.19344	-37.05705	1.21452	-128.13207	.02060	1.78605	29.62989	6.08172	62.82043	.02291

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 245.00 2154.89  17.02  .21399 -51.63729  1.21331-139.84531  .02060  2.70522  32.33511  9.00803  71.82845  .02171
 250.00 2090.54  15.03  .23513 -64.90686  1.21216-150.47359  .02060  2.47796  34.81307  8.15032  79.97877  .01999
 255.00 2031.42  13.38  .25665 -76.97657  1.21106-160.11945  .02060  2.28430  37.09737  7.36156  87.34033  .01850
 260.00 1977.24  12.00  .27837 -87.95834  1.21002-168.88120  .02060  2.11891  39.21629  6.64283  93.98316  .01721
 265.00 1927.63  10.85  .30012 -97.95552  1.20902-176.84669  .02060  1.97711  41.19340  5.98837  99.97153  .01608
 270.00 1882.22   9.89  .32170-107.06621  1.20805-184.09779  .02059  1.85497  43.04837  5.39613 105.36767  .01510
 275.00 1840.63   9.07  .34295-115.37619  1.20712-190.70532  .02059  1.74919  44.79756  4.85834 110.22601  .01424
 280.00 1802.55   8.37  .36372-122.96221  1.20622-196.73218  .02059  1.65711  46.45467  4.36974 114.59575  .01349
 285.00 1767.65   7.78  .38385-129.89193  1.20534-202.23350  .02059  1.57655  48.03122  3.92478 118.52053  .01282
 290.00 1735.54   7.27  .40322-136.25044  1.20449-207.27794  .02059  1.50573  49.53695  3.53871 122.05924  .01224
 295.00 1706.13   6.84  .42170-142.06296  1.20364-211.88637  .02059  1.44297  50.97991  3.16546 125.22470  .01173
 300.00 1679.17   6.46  .43918-147.37658  1.20282-216.09684  .02059  1.38734  52.36725  2.82314 128.04783  .01127
 305.00 1654.49   6.14  .45556-152.23259  1.20201-219.94270  .02059  1.33786  53.70511  2.50800 130.55583  .01087
 310.00 1631.91   5.86  .47076-156.66730  1.20121-223.45321  .02059  1.29372  54.99884  2.21678 132.77261  .01052
 315.00 1611.28   5.62  .48471-160.71251  1.20043-226.65396  .02059  1.25426  56.25309  1.94649 134.71911  .01021
 320.00 1592.46   5.41  .49734-164.39613  1.19967-229.56742  .02059  1.21890  57.47200  1.69455 136.41366  .00993
 325.00 1575.34   5.23  .50859-167.74256  1.19891-232.21319  .02059  1.18719  58.65919  1.45859 137.87224  .00969
 330.00 1559.81   5.08  .51843-170.77274  1.19817-234.60806  .02059  1.15874  59.81792  1.23613 139.10838  .00948
 335.00 1545.80   4.96  .52681-173.50529  1.19743-236.76710  .02059  1.13322  60.95114  1.02582 140.13419  .00930
 340.00 1533.22   4.85  .53371-175.95594  1.19671-238.70285  .02059  1.11036  62.06150   .82538 140.95958  .00914
 345.00 1522.01   4.77  .53911-178.13795  1.19599-240.42595  .02059  1.08995  63.15145   .63316 141.59273  .00901
 350.00 1512.11   4.71  .54298-180.06231  1.19528-241.94525  .02059  1.07178  64.22323   .44751 142.04025  .00889
 355.00 1503.48   4.66  .54531-181.73795  1.19458-243.26791  .02059  1.05572  65.27896   .26694 142.30718  .00881
 360.00 1495.88   4.63  .54611-183.17993  1.19391-244.39857  .02059  1.04165  66.32060   .08902 142.39620  .00874
 360.00 1076.70   1.03 1.76639-261.71504  1.19391-305.77901  .02059   .00000  66.32060   .00000 142.39620  .00000
 540.00 1000.00   1.03  .05461  -9.17099   .03930 -10.53334  .00069   .00000  66.32060   .00000 142.39620  .00000
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THETA	T	P	V	H	S	U	N	FLAME SPEED,	TEMP.,	AND EXTENT	MASS-FR.	BURN.-VOL.
167.45	2545.72	17.60	.00002	.00393	.00013	-.00653	.00000	578.08720	2545.72406	.18781	.00010	.00040
169.93	2545.38	18.61	.00023	.03883	.00125	-.06574	.00002	592.18315	2542.46326	.39044	.00100	.00393
172.68	2553.45	19.79	.00109	.20330	.00623	-.32124	.00010	612.50503	2551.40607	.65041	.00500	.01920
174.04	2556.93	20.52	.00211	.41386	.01245	-.63665	.00021	622.45848	2548.51422	.80034	.01000	.03762
175.91	2566.85	21.65	.00402	.87543	.02488	-1.23398	.00041	642.34013	2560.18518	1.04140	.02000	.07266
178.66	2569.26	23.45	.00743	1.75694	.04962	-2.46533	.00083	672.76707	2577.38882	1.35023	.04000	.13590
180.38	2579.81	24.96	.01052	2.78550	.07434	-3.57463	.00124	694.50113	2580.17596	1.56373	.06000	.19266
181.61	2591.61	26.35	.01335	3.94602	.09903	-4.57429	.00165	714.81129	2584.87314	1.71380	.08000	.24399
182.60	2602.86	27.68	.01596	5.21152	.12369	-5.48679	.00207	733.99926	2589.78619	1.83215	.10000	.29065
183.82	2618.63	29.61	.01952	7.28701	.16064	-6.70820	.00269	763.10695	2603.66779	1.97342	.13000	.35331
184.89	2632.75	31.45	.02274	9.53519	.19753	-7.78633	.00331	788.37389	2609.65405	2.08953	.16000	.40867
185.69	2646.63	33.28	.02566	11.99049	.23437	-8.69171	.00393	813.13393	2616.11981	2.17998	.19000	.45806
186.38	2659.62	35.09	.02833	14.61007	.27118	-9.46025	.00455	837.00906	2622.14270	2.25598	.22000	.50244
186.94	2672.03	36.88	.03077	17.39487	.30794	-10.09086	.00518	860.36851	2628.10770	2.29947	.25000	.54259
187.51	2683.23	38.63	.03305	20.28375	.34466	-10.63516	.00580	882.58956	2633.40228	2.36213	.28000	.57914
188.08	2693.33	40.32	.03519	23.25568	.38134	-11.11046	.00642	903.72313	2638.34152	2.42543	.31000	.61260
188.66	2702.00	41.94	.03723	26.25148	.41796	-11.56680	.00704	923.69524	2642.89377	2.48909	.34000	.64334
189.25	2709.48	43.49	.03918	29.25993	.45455	-12.01355	.00767	942.51939	2647.11191	2.55440	.37000	.67172
189.79	2716.61	45.03	.04103	32.34709	.49109	-12.39500	.00829	960.97351	2651.54623	2.61194	.40000	.69804
190.48	2721.22	46.36	.04291	35.24367	.52758	-12.93797	.00891	976.40470	2654.03885	2.68796	.43000	.72254
191.36	2722.97	47.44	.04489	37.84277	.56400	-13.73244	.00953	988.79188	2655.58490	2.78704	.46000	.74541
194.87	2690.09	45.48	.04923	35.79969	.59997	-18.43115	.01014	961.73959	2631.52084	3.08247	.49000	.76686
196.90	2674.00	44.79	.05272	35.66959	.63617	-21.51543	.01076	955.05754	2636.84543	3.45078	.52000	.78712
198.85	2657.74	43.99	.05641	35.28828	.67236	-24.80573	.01138	945.18372	2633.55383	3.71376	.55000	.80623
200.92	2638.22	42.87	.06056	34.18302	.70850	-28.69796	.01199	930.85149	2627.65616	3.95535	.58000	.82427
202.52	2625.86	42.26	.06430	33.95009	.74475	-31.85751	.01261	924.13770	2628.88889	4.14893	.61000	.84134
204.23	2611.38	41.43	.06841	33.19733	.78098	-35.44694	.01323	913.52208	2624.62906	4.31976	.64000	.85751
205.96	2596.16	40.50	.07282	32.12410	.81720	-39.30014	.01384	901.72520	2620.67700	4.48777	.67000	.87285
207.92	2576.76	39.23	.07793	30.11509	.85337	-43.92703	.01446	884.83929	2613.53311	4.66277	.70000	.88742
210.29	2549.96	37.42	.08428	26.52967	.88946	-49.85287	.01507	860.56046	2602.76517	4.85467	.73000	.90127
212.25	2531.13	36.17	.09009	24.10846	.92569	-54.80613	.01569	845.04574	2601.76526	5.01345	.76000	.91445
214.10	2514.59	35.07	.09593	21.89341	.96197	-59.58313	.01631	830.69186	2598.43643	5.14118	.79000	.92699
216.14	2494.95	33.77	.10258	18.87000	.99824	-65.02144	.01692	812.72359	2591.37323	5.27472	.82000	.93894
218.43	2471.64	32.26	.11025	14.88286	1.03447	-71.24472	.01754	791.58764	2583.03009	5.41356	.85000	.95034
220.75	2448.63	30.79	.11842	10.69592	1.07074	-77.62298	.01815	771.21184	2576.68668	5.54733	.88000	.96121
222.95	2428.59	29.53	.12663	6.86913	1.10708	-83.69805	.01877	753.62069	2572.37665	5.66695	.91000	.97159
225.72	2400.05	27.84	.13707	1.00551	1.14333	-91.42872	.01938	728.05232	2559.94394	5.80086	.94000	.98149
229.34	2359.44	25.62	.15105	-7.75615	1.17942	-101.50292	.01999	692.95245	2542.15146	5.96103	.97000	.99096
236.88	2270.56	21.21	.18101	-27.29611	1.21531	-120.26429	.02060	614.26028	2487.33002	6.24214	1.00000	1.00000

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                        A MODEL SIMULATING THE INTERNAL-COMBUSTION ENGINE

ENGINE                               FUEL                                      OPERATING CONDITIONS

FOUR STROKE AUTOMOTIVE TYPE          OCTANE C8H18                              AIR-FUEL RATIO        .92
BORE             3.94 IN.            ACTIVATION ENERGY  39000.00 CAL./MOLE     PISTON TEMP        500.00 K
STROKE           2.46 IN.            ENTHALPY OF                               WALL TEMP          420.00 K
ROD              7.06 IN.            COMBUSTION        1222770.00 CAL/MOLE     MAN. TEMP          320.00 K
CLEAR. VOL.      3.33 CU.IN.                                                   MAN. PR.              .99 ATM
SWEPT VOL.      30.00 CU.IN.                                                   EXH. PR.             1.03 ATM
COMPRESSION RATIO10.00 TO ONE                                                  SPARK ADV.          16.00
                                                                               SPEEC             2800.00 RPM

COMBUSTION OCCURS IN 39 INCREMENTS.  ERRORS ARE LESS THAN    .00100 PERCENT.  FLAME SPEED FACTOR IS   .11475000E 06
HEAT TRANSFER FACTOR IS    .00000   NORMAL RUN









                  SUMMARY OF RESULTS

     PUMPING WORK                   -.47611947E 00 CAL
     NET CYCLE WORK                  .15566373E 03 CAL
     NET HEAT TRANSFERED             .00000000E 00 CAL
     INDICATED THERMAL EFFICIENCY    .38549080E 02 PERCENT
     MEAN EFFECTIVE PRESSURE         .13077700E 02 ATM
     RESIDUAL WEIGHT FRACTION        .33289108E-01
     VOLUMETRIC EFFICIENCY           .97627462E 00 PERCENT
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THETA	T	P	V	H	S	U	N	Q	QTOT	W	WTOT	HB
.00	344.84	.99	.54611	-22.58769	.95518	-35.68175	.01911	.00000	.00000	.00000	.00000	.00000
10.00	345.51	1.00	.54302	-22.48808	.95518	-35.60766	.01911	.00000	.00000	-.07409	-.07409	.00000
20.00	347.55	1.02	.53380	-22.18514	.95518	-35.38210	.01911	.00000	.00000	-.22555	-.29965	.00000
30.00	351.01	1.06	.51855	-21.66938	.95518	-34.99796	.01911	.00000	.00000	-.38415	-.68380	.00000
40.00	356.02	1.12	.49750	-20.92281	.95518	-34.44157	.01911	.00000	.00000	-.55639	-1.24019	.00000
50.00	362.73	1.21	.47096	-19.91986	.95518	-33.69353	.01911	.00000	.00000	-.74803	-1.98822	.00000
60.00	371.37	1.33	.43941	-18.62534	.95518	-32.72705	.01911	.00000	.00000	-.96649	-2.95471	.00000
70.00	382.23	1.49	.40348	-16.99272	.95518	-31.50656	.01911	.00000	.00000	-1.22048	-4.17519	.00000
80.00	395.67	1.70	.36400	-14.96164	.95518	-29.98581	.01911	.00000	.00000	-1.52076	-5.69595	.00000
90.00	412.16	2.01	.32199	-12.45483	.95518	-28.10524	.01911	.00000	.00000	-1.88057	-7.57652	.00000
100.00	432.28	2.43	.27867	-9.37447	.95518	-25.78904	.01911	.00000	.00000	-2.31620	-9.89272	.00000
110.00	456.74	3.04	.23542	-5.59927	.95518	-22.94252	.01911	.00000	.00000	-2.84652	-12.73924	.00000
120.00	486.33	3.94	.19371	-.98560	.95518	-19.45242	.01911	.00000	.00000	-3.49010	-16.22933	.00000
130.00	521.84	5.28	.15510	4.61714	.95518	-15.19795	.01911	.00000	.00000	-4.25447	-20.48381	.00000
140.00	563.67	7.30	.12106	11.31073	.95518	-10.09294	.01911	.00000	.00000	-5.10500	-25.58881	.00000
150.00	610.94	10.30	.09296	18.99131	.95518	-4.20704	.01911	.00000	.00000	-5.88590	-31.47471	.00000
160.00	659.41	14.36	.07199	26.99693	.95518	1.95803	.01911	.00000	.00000	-6.16508	-37.63979	.00000
164.00	677.09	16.13	.06580	29.94867	.95518	4.23851	.01911	.00000	.00000	-2.28048	-39.92026	.00000
167.45	690.58	17.60	.06153	32.21366	.95521	5.98332	.01911	.00000	.00000	-1.74481	-41.66507	.00000
169.93	699.32	18.61	.05908	33.69022	.95547	7.05779	.01911	.00000	.00000	-1.07447	-42.73954	.00000
172.68	709.03	19.79	.05698	35.35205	.95663	8.03895	.01912	.00000	.00000	-.98117	-43.72071	.00000
174.04	714.79	20.52	.05619	36.35057	.95808	8.42980	.01912	.00000	.00000	-.39085	-44.11155	.00000
175.91	723.46	21.65	.05536	37.89117	.96095	8.86026	.01914	.00000	.00000	-.43045	-44.54201	.00000
178.66	736.63	23.48	.05470	40.33485	.96666	9.23429	.01917	.00000	.00000	-.37404	-44.91604	.02571
180.37	746.97	25.00	.05462	42.34777	.97231	9.28034	.01920	.00000	.00000	-.04605	-44.96209	.02660
181.61	756.09	26.40	.05472	44.21102	.97794	9.21660	.01923	.00000	.00000	.06374	-44.89836	.02740
182.59	764.44	27.75	.05490	45.99293	.98353	9.09521	.01927	.00000	.00000	.12140	-44.77696	.02815
183.79	775.94	29.70	.05523	48.58010	.99186	8.85646	.01931	.00000	.00000	.23875	-44.53821	.02920
184.86	786.34	31.55	.05564	51.06843	1.00014	8.55070	.01936	.00000	.00000	.30576	-44.23245	.03018
185.66	796.20	33.40	.05600	53.56069	1.00836	8.25848	.01941	.00000	.00000	.29222	-43.94023	.03113
186.34	805.47	35.22	.05636	56.03376	1.01654	7.96030	.01946	.00000	.00000	.29819	-43.64205	.03204
186.85	814.43	37.06	.05665	58.54546	1.02467	7.70218	.01951	.00000	.00000	.25811	-43.38393	.03294
187.41	822.70	38.82	.05700	60.97175	1.03276	7.38241	.01956	.00000	.00000	.31978	-43.06416	.03378
187.98	830.39	40.52	.05738	63.31671	1.04081	7.00252	.01961	.00000	.00000	.37988	-42.68427	.03457
188.56	837.55	42.17	.05779	65.59001	1.04882	6.57000	.01966	.00000	.00000	.43252	-42.25175	.03532
189.15	844.22	43.74	.05825	67.79362	1.05680	6.08588	.01971	.00000	.00000	.48411	-41.76763	.03603
189.67	850.66	45.31	.05867	70.00824	1.06475	5.61579	.01976	.00000	.00000	.47009	-41.29754	.03673
190.36	856.13	46.69	.05928	71.95383	1.07267	4.92825	.01981	.00000	.00000	.68754	-40.61000	.03732
191.22	860.59	47.83	.06008	73.58503	1.08056	3.98436	.01986	.00000	.00000	.94389	-39.66611	.03780
194.71	853.72	46.08	.06400	70.87076	1.08844	-.55354	.01990	.00000	.00000	4.53790	-35.12821	.03696
196.71	851.51	45.53	.06671	69.94768	1.09634	-3.60945	.01994	.00000	.00000	3.05591	-32.07230	.03667
198.65	848.78	44.85	.06964	68.78059	1.10426	-6.86784	.01999	.00000	.00000	3.25839	-28.81391	.03633
200.69	844.73	43.87	.07308	67.02077	1.11219	-10.61803	.02003	.00000	.00000	3.75019	-25.06372	.03585
202.23	842.84	43.41	.07588	66.15816	1.12014	-13.62461	.02008	.00000	.00000	3.00658	-22.05714	.03562
203.90	839.85	42.71	.07913	64.77960	1.12810	-17.05995	.02013	.00000	.00000	3.43534	-18.62180	.03527
205.59	836.38	41.89	.08264	63.12082	1.13607	-20.72871	.02017	.00000	.00000	3.66876	-14.95304	.03487
207.51	831.34	40.74	.08688	60.67106	1.14405	-25.05440	.02021	.00000	.00000	4.32569	-10.62735	.03430
209.81	823.89	39.08	.09233	56.97514	1.15206	-30.41421	.02026	.00000	.00000	5.35982	-5.26754	.03347
211.69	818.71	37.96	.09706	54.32340	1.16010	-34.90705	.02030	.00000	.00000	4.49284	-.77470	.03291
213.53	813.61	36.88	.10195	51.64920	1.16817	-39.41942	.02034	.00000	.00000	4.51237	3.73767	.03236
215.50	807.79	35.69	.10740	48.53179	1.17627	-44.29915	.02039	.00000	.00000	4.87973	8.61740	.03175
217.68	800.78	34.29	.11375	44.69444	1.18439	-49.77492	.02043	.00000	.00000	5.47577	14.09317	.03102
219.88	793.74	32.93	.12047	40.75315	1.19255	-55.33587	.02047	.00000	.00000	5.56095	19.65412	.03031
221.97	787.44	31.75	.12712	37.13013	1.20074	-60.63279	.02051	.00000	.00000	5.29691	24.95104	.02968
224.59	778.53	30.15	.13579	31.91554	1.20897	-67.24328	.02055	.00000	.00000	6.61049	31.56153	.02880
227.98	766.12	28.03	.14756	24.50374	1.21724	-75.66112	.02059	.00000	.00000	8.41784	39.97937	.02761
234.78	738.03	23.77	.17281	7.86010	1.22559	-91.64307	.02063	.00000	.00000	15.98195	55.96132	.02508
240.00	2367.83	20.71	.19344	-5.74319	1.22559	-102.75016	.02062	.00000	.00000	11.10710	67.06842	.02508

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 245.00 2313.92  18.29  .21399 -17.67298   1.22558-112.44208   .02061   .00000   .00000  9.69191  76.76033   .02311
 250.00 2263.51  16.28  .23513 -28.58864   1.22558-121.27368   .02061   .00000   .00000  8.83160  85.59193   .02147
 255.00 2216.88  14.60  .25665 -38.51925   1.22557-129.28151   .02060   .00000   .00000  8.00783  93.59976   .02004
 260.00 2173.78  13.20  .27837 -47.58189   1.22559-136.57005   .02060   .00000   .00000  7.28854 100.88830   .01878
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 275.00 2064.64  10.17  .34295 -70.14353   1.22560-154.64998   .02060   .00000   .00000  5.44704 118.96823   .01587
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 335.00 1850.74   5.94  .52681-113.34516   1.22557-189.08854   .02059   .00000   .00000  1.22728 153.40679   .01108
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 350.00 1836.26   5.71  .54298-116.23626   1.22556-191.38674   .02059   .00000   .00000   .54238 155.70499   .01075
 355.00 1834.21   5.68  .54531-116.64505   1.22555-191.71163   .02059   .00000   .00000   .32489 156.02988   .01069
 360.00 1833.52   5.67  .54611-116.78341   1.22555-191.82160   .02059   .00000   .00000   .10997 156.13985   .01066
 360.00 1278.38   1.03 2.09724-224.52061   1.22555-276.83809   .02059   .00000   .00000   .00000 156.13985   .00000
 540.00 1000.00   1.03  .05461  -9.17099    .03930 -10.53334   .00069   .00000   .00000   .00000 156.13985   .00000
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 THETA     T        P       V          H          S          U          N      FLAME SPEED, TEMP., AND EXTENT MASS-FR. BURN.-VOL.
 167.45 2545.72  17.60  .00002      .00393     .00013    -.00653      .00000 578.087202545.72406      .18781      .00010      .00040
 169.93 2545.38  18.61  .00023      .03883     .00125    -.06574      .00002 592.183152542.46326      .39044      .00100      .00393
 172.68 2553.45  19.79  .00109      .20330     .00623    -.32124      .00010 612.505032551.40607      .65041      .00500      .01920
 174.04 2556.93  20.52  .00211      .41386     .01245    -.63665      .00021 622.458482548.51422      .80034      .01000      .03762
 175.91 2566.85  21.65  .00402      .87543     .02488   -1.23398      .00041 642.340132560.18518     1.04140      .02000      .07266
 178.66 2584.12  23.48  .00747     1.92084     .04969   -2.32737      .00083 673.224562577.81104     1.35023      .04000      .13660
 180.37 2597.08  25.00  .01058     3.07264     .07445   -3.33271      .00124 695.130302580.51791     1.56572      .06000      .19371
 181.61 2609.02  26.40  .01342     4.33404     .09917   -4.24713      .00166 715.827382585.40479     1.71625      .08000      .24522
 182.59 2619.97  27.75  .01603     5.69070     .12387   -5.08249      .00207 735.036922590.21384     1.83472      .10000      .29197
 183.79 2635.28  29.70  .01959     7.89766     .16085   -6.19258      .00269 764.378622604.18008     1.97567      .13000      .35470
 184.86 2649.09  31.55  .02282    10.27751     .19779   -7.15889      .00331 789.851822610.19501     2.09127      .16000      .41010
 185.66 2662.29  33.40  .02573    12.84132     .23467   -7.97206      .00393 814.753062616.66458     2.18191      .19000      .45943
 186.34 2674.70  35.22  .02839    15.56443     .27150   -8.65256      .00456 838.792642622.71014     2.25769      .22000      .50375
 186.85 2686.79  37.06  .03081    18.46067     .30829   -9.18853      .00518 862.459162628.82419     2.30110      .25000      .54381
 187.41 2697.59  38.82  .03308    21.45009     .34503   -9.64700      .00580 884.990432634.12054     2.36330      .28000      .58028
 187.98 2707.25  40.52  .03521    24.51151     .38174  -10.04602      .00642 906.265392639.07407     2.42648      .31000      .61365
 188.56 2716.00  42.17  .03724    27.64155     .41840  -10.38817      .00705 926.459882643.70993     2.48996      .34000      .64435
 189.15 2723.98  43.74  .03918    30.83146     .45504  -10.68068      .00767 945.574392648.02441     2.55512      .37000      .67272
 189.67 2731.76  45.31  .04101    34.12457     .49164  -10.88715      .00829 964.448662652.61188     2.61282      .40000      .69902
 190.36 2737.62  46.69  .04289    37.31379     .52822  -11.18168      .00891 980.546722655.37570     2.68823      .43000      .72354
 191.22 2741.49  47.83  .04485    40.34232     .56476  -11.61206      .00954 993.453902657.09464     2.78745      .46000      .74646
 194.71 2720.57  46.08  .04919    40.09467     .60130  -14.79685      .01015 969.182172634.70956     3.08272      .49000      .76853
 196.71 2711.18  45.53  .05264    41.16885     .63786  -16.86822      .01077 964.149872640.09195     3.45513      .52000      .78900
 198.65 2701.23  44.85  .05629    42.01737     .67443  -19.12770      .01139 955.845162637.16284     3.71901      .55000      .80828
 200.69 2688.86  43.87  .06040    42.34135     .71102  -21.82553      .01201 943.506002632.03912     3.96184      .58000      .82648
 202.23 2681.94  43.41  .06401    43.37145     .74763  -23.92970      .01263 938.621032633.80780     4.15615      .61000      .84355
 203.90 2672.89  42.71  .06803    43.93496     .78424  -26.42392      .01325 929.552122629.80783     4.32679      .64000      .85971
 205.59 2662.99  41.89  .07231    44.21465     .82086  -29.15444      .01386 919.349182626.35846     4.49550      .67000      .87500
 207.51 2649.82  40.74  .07728    43.74904     .85750  -32.50614      .01448 904.423872620.04617     4.67164      .70000      .88953
 209.81 2631.37  39.08  .08340    42.09789     .89416  -36.84459      .01510 882.366422610.35510     4.86408      .73000      .90334
 211.69 2618.62  37.96  .08894    41.31693     .93086  -40.45244      .01571 868.957442609.93253     5.02241      .76000      .91638
 213.53 2606.34  36.88  .09468    40.45574     .96759  -44.12512      .01633 854.956692606.04041     5.14973      .79000      .92875
 215.50 2592.59  35.69  .10101    39.12011    1.00434  -48.18968      .01695 838.773572600.23218     5.28362      .82000      .94052
 217.68 2576.18  34.29  .10826    37.03450    1.04111  -52.87383      .01756 819.597912592.82236     5.42165      .85000      .95172
 219.88 2559.93  32.93  .11594    34.77195    1.07793  -57.70032      .01818 801.172142587.26434     5.55447      .88000      .96236
 221.97 2545.63  31.75  .12362    32.74257    1.11478  -62.32931      .01879 785.294382583.53806     5.67318      .91000      .97247
 224.59 2525.03  30.15  .13336    29.08295    1.15166  -68.30213      .01941 761.744092572.36276     5.80623      .94000      .98211
 227.98 2495.74  28.03  .14627    23.15170    1.18859  -76.14045      .02002 729.623022556.78836     5.96489      .97000      .99129
 234.78 2427.65  23.77  .17281     7.86011    1.22559  -91.64306      .02063 657.469082508.96545     6.23693     1.00000     1.00000



**** ALL INPUT DATA HAVE BEEN PROCESSED.
     AT LOC 45267
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                         A MODEL SIMULATING THE INTERNAL-COMBUSTION ENGINE

ENGINE                                 FUEL                                   OPERATING CONDITIONS

FOUR STROKE AUTOMOTIVE TYPE            OCTANE C8H18                           AIR-FUEL RATIO        .92
BORE               3.94 IN.            ACTIVATION ENERGY  39000.00 CAL./MOLE  PISTON TEMP       500.00 K
STROKE             2.46 IN.            ENTHALPY OF                            WALL TEMP         420.00 K
ROD                7.06 IN.            COMBUSTION        1222770.00 CAL/MOLE  MAN. TEMP         320.00 K
CLEAR. VOL.        3.33 CU.IN.                                                MAN. PR.             .99 ATM
SWEPT VOL.        30.00 CU.IN.                                                EXH. PR.            1.03 ATM
COMPRESSION RATIO10.00 TO ONE                                                 SPARK ADV.         16.00
                                                                              SPEED            2800.00 RPM

COMBUSTION OCCURS IN 39 INCREMENTS.  ERRORS ARE LESS THAN    .00100 PERCENT.  FLAME SPEED FACTOR IS   .11475000E 06
HEAT TRANSFER FACTOR IS    2.00000   NORMAL RUN










                       SUMMARY OF RESULTS

     PUMPING WORK                      -.47611947E 00 CAL
     NET CYCLE WORK                     .13045873E 03 CAL
     NET HEAT TRANSFERED                .11131061E 03 CAL
     INDICATED THERMAL EFFICIENCY       .32307231E 02 PERCENT
     MEAN EFFECTIVE PRESSURE            .10960165E 02 ATM
     RESIDUAL WEIGHT FRACTION           .33289108E-01
     VOLUMETRIC EFFICIENCY              .97627462E 00 PERCENT
```

THETA	T	P	V	H	S	U	N	Q	QTOT	W	WTOT	HB
.00	344.84	.99	.54611	-22.58769	.95518	-35.68175	.01911	.00000	.00000	.00000	.00000	.00000
10.00	345.51	1.00	.54302	-22.48808	.95518	-35.60766	.01911	.00000	.00000	-.07409	-.07409	.00000
20.00	347.55	1.02	.53380	-22.18514	.95518	-35.38210	.01911	.00000	.00000	-.22555	-.29965	.00000
30.00	351.01	1.06	.51855	-21.66938	.95518	-34.99796	.01911	.00000	.00000	-.38415	-.68380	.00000
40.00	356.02	1.12	.49750	-20.92281	.95518	-34.44157	.01911	.00000	.00000	-.55639	-1.24019	.00000
50.00	362.73	1.21	.47096	-19.91986	.95518	-33.69353	.01911	.00000	.00000	-.74803	-1.98822	.00000
60.00	371.37	1.33	.43941	-18.62534	.95518	-32.72705	.01911	.00000	.00000	-.96649	-2.95471	.00000
70.00	382.23	1.49	.40348	-16.99272	.95518	-31.50656	.01911	.00000	.00000	-1.22048	-4.17519	.00000
80.00	395.67	1.70	.36400	-14.96164	.95518	-29.98581	.01911	.00000	.00000	-1.52076	-5.69595	.00000
90.00	412.16	2.01	.32199	-12.45483	.95518	-28.10524	.01911	.00000	.00000	-1.88057	-7.57652	.00000
100.00	432.28	2.43	.27867	-9.37447	.95518	-25.78904	.01911	.00000	.00000	-2.31620	-9.89272	.00000
110.00	456.74	3.04	.23542	-5.59927	.95518	-22.94252	.01911	.00000	.00000	-2.84652	-12.73924	.00000
120.00	486.33	3.94	.19371	-.98560	.95518	-19.45242	.01911	.00000	.00000	-3.49010	-16.22933	.00000
130.00	521.84	5.28	.15510	4.61714	.95518	-15.19795	.01911	.00000	.00000	-4.25447	-20.48381	.00000
140.00	563.67	7.30	.12106	11.31073	.95518	-10.09294	.01911	.00000	.00000	-5.10500	-25.58881	.00000
150.00	610.94	10.30	.09296	18.99131	.95518	-4.20704	.01911	.00000	.00000	-5.88590	-31.47471	.00000
160.00	659.41	14.36	.07199	26.99693	.95518	1.95803	.01911	.00000	.00000	-6.16508	-37.63979	.00000
164.00	677.09	16.13	.06580	29.94867	.95518	4.23851	.01911	.00000	.00000	-2.28048	-39.92026	.00000
167.45	690.58	17.60	.06153	32.21329	.95521	5.98303	.01911	.00000	.00000	-1.74452	-41.66478	.00000
169.93	699.32	18.61	.05908	33.68949	.95547	7.05720	.01911	.00000	.00000	-1.07417	-42.73895	.00000
172.68	709.03	19.79	.05699	35.35097	.95663	8.03807	.01912	.00000	.00000	-.98087	-43.71982	.00000
174.03	714.78	20.52	.05619	36.34925	.95808	8.42871	.01912	.00000	.00000	-.39064	-44.11046	.00000
175.91	723.46	21.65	.05536	37.89147	.96095	8.86050	.01914	.00000	.00000	-.43180	-44.54225	.00000
178.66	736.29	23.43	.05470	39.95083	.96653	8.91492	.01917	.31974	.31974	-.37416	-44.91642	.02571
180.39	746.41	24.91	.05462	41.68386	.97210	8.72756	.01920	.23296	.55270	-.04560	-44.96202	.02647
181.62	755.37	26.29	.05472	43.32085	.97765	8.47435	.01923	.18766	.74036	.06555	-44.89646	.02722
182.62	763.59	27.61	.05491	44.90122	.98318	8.18374	.01926	.16663	.90700	.12398	-44.77248	.02794
183.83	774.92	29.52	.05525	47.20319	.99142	7.70474	.01931	.23122	1.13821	.24778	-44.52470	.02898
184.91	785.19	31.34	.05566	49.41230	.99961	7.16335	.01936	.22960	1.36781	.31179	-44.21291	.02994
185.72	794.93	33.16	.05603	51.67616	1.00777	6.67753	.01941	.18730	1.55511	.29852	-43.91439	.03086
186.41	804.12	34.95	.05640	53.93731	1.01589	6.19936	.01946	.17296	1.72806	.30522	-43.60917	.03176
187.01	812.82	36.72	.05675	56.19663	1.02396	5.72863	.01951	.16106	1.88912	.30967	-43.29950	.03263
187.58	821.01	38.45	.05711	58.42386	1.03200	5.23914	.01955	.16086	2.04998	.32863	-42.97087	.03346
188.15	828.63	40.13	.05750	60.57227	1.03999	4.69160	.01960	.17360	2.22358	.37394	-42.59693	.03425
188.74	835.64	41.72	.05794	62.55630	1.04793	4.01387	.01965	.22684	2.45041	.45090	-42.14603	.03498
189.34	842.14	43.25	.05841	64.40021	1.05580	3.22467	.01970	.28776	2.73817	.50144	-41.64459	.03567
189.90	848.33	44.74	.05887	66.17990	1.06364	2.38658	.01975	.32148	3.05965	.51662	-41.12797	.03632
190.60	853.54	46.03	.05950	67.53168	1.07139	1.19611	.01980	.48876	3.54841	.70171	-40.42627	.03689
191.48	857.61	47.06	.06034	68.30288	1.07903	-.47441	.01984	.70415	4.25256	.96637	-39.45990	.03732
195.00	849.01	44.91	.06437	61.90255	1.08578	-8.10384	.01988	3.04535	7.29792	4.58408	-34.87582	.03639
197.05	845.61	44.08	.06720	58.52039	1.09295	-13.21535	.01992	1.98638	9.28430	3.12512	-31.75070	.03578
199.04	841.61	43.12	.07028	54.77580	1.10010	-18.62106	.01997	2.07373	11.35803	3.33197	-28.41872	.03524
201.15	836.20	41.85	.07389	50.13541	1.10715	-24.76101	.02001	2.33530	13.69333	3.80465	-24.61407	.03456
202.89	832.42	40.98	.07713	46.46241	1.11436	-30.09580	.02005	2.00478	15.69811	3.33001	-21.28405	.03404
204.63	828.21	40.04	.08061	42.50438	1.12155	-35.66126	.02009	2.06749	17.76561	3.49796	-17.78610	.03351
206.42	823.42	38.98	.08443	38.15291	1.12872	-41.54577	.02013	2.15610	19.92170	3.72842	-14.05768	.03294
208.42	816.97	37.59	.08900	32.69817	1.13580	-48.33051	.02018	2.44917	22.37087	4.33557	-9.72211	.03220
210.88	807.55	35.64	.09499	25.25604	1.14268	-56.73137	.02022	2.97900	25.34988	5.42186	-4.30025	.03118
212.92	800.63	34.26	.10030	19.43157	1.14981	-63.80002	.02026	2.47643	27.82630	4.59222	.29197	.03037
214.73	795.17	33.20	.10525	14.52778	1.15708	-70.11257	.02030	2.19103	30.01733	4.12151	4.41349	.02976
216.87	787.71	31.81	.11136	8.20674	1.16423	-77.57412	.02034	2.55807	32.57541	4.90347	9.31696	.02900
219.27	778.74	30.19	.11859	.76372	1.17128	-85.93923	.02039	2.83359	35.40900	5.53153	14.84849	.02809
221.73	769.71	28.63	.12633	-6.80417	1.17838	-94.39674	.02043	2.84040	38.24939	5.61711	20.46560	.02718
224.07	761.63	27.29	.13402	-13.78698	1.18559	-102.37410	.02047	2.66597	40.91536	5.31140	25.77700	.02638
227.00	750.51	25.54	.14411	-23.08885	1.19256	-112.21681	.02051	3.26651	44.18187	6.57619	32.35318	.02536
230.88	735.04	23.25	.15807	-35.71984	1.19921	-124.72738	.02056	4.11999	48.30187	8.39058	40.74376	.02398
239.34	699.58	18.72	.19077	-60.33552	1.20534	-146.82207	.02060	5.18818	53.49005	16.90651	57.65027	.02107
245.00	2020.42	15.96	.21399	-79.23451	1.20273	-161.92594	.02060	5.46610	58.95615	9.63777	67.28804	.02076

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 250.00 1946.72  13.99  .23513 -94.12656   1.20060-173.79926    .02060   4.27935  63.23549   7.59397  74.88201    .01874
 255.00 1879.77  12.38  .25665-107.56360   1.19860-184.49478    .02059   3.88090  67.11640   6.81462  81.69663    .01723
 260.00 1818.90  11.04  .27837-119.71199   1.19670-194.15137    .02059   3.54525  70.66164   6.11134  87.80797    .01592
 265.00 1763.48   9.93  .30012-130.72164   1.19490-202.89242    .02059   3.26056  73.92220   5.48050  93.28847    .01479
 270.00 1712.94   9.00  .32170-140.72046   1.19318-210.82252    .02059   3.01733  76.93953   4.91277  98.20124    .01381
 275.00 1666.77   8.21  .34295-149.81958   1.19153-218.03208    .02059   2.80806  79.74758   4.40150 102.60275    .01296
 280.00 1624.53   7.55  .36372-158.11469   1.18994-224.59872    .02059   2.62679  82.37437   3.93985 106.54259    .01221
 285.00 1585.85   6.98  .38385-165.68957   1.18842-230.59023    .02059   2.46879  84.84316   3.52272 110.06531    .01156
 290.00 1550.36   6.50  .40322-172.61667   1.18694-236.06513    .02059   2.33026  87.17342   3.14464 113.20995    .01098
 295.00 1517.78   6.08  .42170-178.95901   1.18551-241.07426    .02059   2.20815  89.38157   2.80098 116.01093    .01048
 300.00 1487.28   5.72  .43918-184.83060   1.18412-245.69757    .02059   2.09998  91.48155   2.52334 118.53426    .01003
 305.00 1459.46   5.41  .45556-190.16793   1.18276-249.89612    .02059   2.00186  93.48341   2.19668 120.73094    .00963
 310.00 1433.88   5.15  .47076-195.06300   1.18145-253.74431    .02059   1.91493  95.39834   1.93326 122.66420    .00928
 315.00 1410.36   4.92  .48471-199.55308   1.18016-257.27183    .02059   1.83704  97.23538   1.69048 124.35469    .00897
 320.00 1388.74   4.72  .49734-203.67062   1.17891-260.50458    .02059   1.76702  99.00240   1.46573 125.82042    .00869
 325.00 1368.88   4.55  .50859-207.44390   1.17767-263.46515    .02059   1.70393 100.70633   1.25664 127.07706    .00845
 330.00 1350.66   4.40  .51843-210.89750   1.17647-266.17321    .02059   1.64696 102.35328   1.06110 128.13816    .00824
 335.00 1333.98   4.28  .52681-214.05278   1.17528-268.64588    .02059   1.59545 103.94873    .87721 129.01538    .00805
 340.00 1318.75   4.18  .53371-216.92820   1.17412-270.89793    .02059   1.54886 105.49759    .70320 129.71857    .00789
 345.00 1304.89   4.09  .53911-219.53961   1.17297-272.94210    .02059   1.50671 107.00430    .53746 130.25603    .00775
 350.00 1292.34   4.02  .54298-221.90051   1.17184-274.78923    .02059   1.46862 108.47292    .37851 130.63454    .00763
 355.00 1281.03   3.97  .54531-224.02221   1.17073-276.44844    .02059   1.43428 109.90720    .22493 130.85947    .00753
 360.00 1270.94   3.93  .54611-225.91406   1.16963-277.92725    .02059   1.40342 111.31061    .07539 130.93485    .00744
 360.00  939.75   1.03 1.54171-286.16306   1.16963-324.62229    .02059    .00000 111.31061    .00000 130.93485    .00000
 540.00 1000.00   1.03  .05461  -9.17099    .03930 -10.53334    .00069    .00000 111.31061    .00000 130.93485    .00000
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THETA     T       P    V          H         S          U        N      FLAME SPEED, TEMP., AND EXTENT MASS-FR. BURN.-VOL.
167.45 2545.72  17.60  .00002    .00393     .00013   -.00653    .00000 578.081892545.71854      .18781     .00010     .00040
169.93 2544.12  18.61  .00023    .03848     .00125   -.06603    .00002 592.180322542.46326      .39037     .00100     .00392
172.68 2552.94  19.79  .00109    .20259     .00623   -.32184    .00010 612.502012551.40607      .65036     .00500     .01920
174.03 2556.54  20.52  .00211    .41280     .01245   -.63754    .00021 622.455562548.51422      .80029     .01000     .03762
175.91 2566.87  21.65  .00402    .87556     .02488  -1.23387    .00041 642.337972560.18518     1.04140     .02000     .07266
178.66 2554.11  23.43  .00739   1.59251     .04956  -2.60344    .00083 672.420582577.06775     1.35023     .04000     .13520
180.39 2562.29  24.91  .01046   2.49957     .07423  -3.81481    .00124 693.912102579.86728     1.56170     .06000     .19160
181.62 2573.85  26.29  .01328   3.55750     .09889  -4.90090    .00165 714.021162584.55426     1.71128     .08000     .24273
182.62 2585.38  27.61  .01588   4.73065     .12352  -5.89135    .00207 733.082432589.46973     1.82952     .10000     .28929
183.83 2601.61  29.52  .01944   6.67308     .16042  -7.22547    .00269 761.828742603.15701     1.97115     .13000     .35187
184.91 2616.06  31.34  .02266   8.78908     .19727  -8.41531    .00331 786.907392609.11688     2.08740     .16000     .40721
185.72 2630.62  33.16  .02559  11.13482     .23408  -9.41390    .00393 811.510152615.58597     2.17800     .19000     .45665
186.41 2644.23  34.95  .02826  13.65132     .27085 -10.27013    .00455 835.240362621.59430     2.25422     .22000     .50110
187.01 2656.97  36.72  .03072  16.32314     .30758 -10.99673    .00517 858.000272627.18500     2.29765     .25000     .54133
187.58 2668.65  38.45  .03300  19.11482     .34427 -11.62378    .00580 880.355802632.76038     2.36054     .28000     .57796
188.15 2679.03  40.13  .03516  21.98035     .38092 -12.18984    .00642 901.351392637.66772     2.42412     .31000     .61148
188.74 2687.51  41.72  .03721  24.83024     .41751 -12.76996    .00704 920.732002641.87405     2.48789     .34000     .64227
189.34 2694.59  43.25  .03917  27.66814     .45404 -13.36143    .00766 939.318452646.07965     2.55345     .37000     .67068
189.90 2701.03  44.74  .04104  30.54363     .49053 -13.92223    .00828 957.290892650.30685     2.61108     .40000     .69703
190.60 2704.42  46.03  .04293  33.15259     .52694 -14.70898    .00891 972.524992652.87997     2.68748     .43000     .72150
191.48 2704.17  47.06  .04491  35.34476     .56323 -15.84735    .00953 984.300932654.21085     2.78669     .46000     .74431
195.00 2659.09  44.91  .04925  31.55030     .59864 -22.01452    .01014 954.477262628.36087     3.08049     .49000     .76514
197.05 2636.03  44.08  .05276  30.24136     .63446 -26.08195    .01075 946.077362633.55182     3.44493     .52000     .78514
199.04 2612.60  43.12  .05651  28.58063     .67027 -30.43532    .01137 934.297232629.61795     3.70677     .55000     .80407
201.15 2585.51  41.85  .06073  26.08630     .70598 -35.47425    .01198 918.119712623.21246     3.94782     .58000     .82194
202.89 2565.82  40.98  .06471  24.39021     .74184 -39.84072    .01260 907.804842622.72958     4.14098     .61000     .83898
204.63 2545.78  40.04  .06894  22.39555     .77768 -44.44852    .01321 895.787532618.84201     4.31388     .64000     .85515
206.42 2524.77  38.98  .07349  19.99686     .81351 -49.38377    .01383 882.144032614.20193     4.48116     .67000     .87053
208.42 2498.87  37.59  .07878  16.53131     .84924 -55.19084    .01444 863.654042606.56165     4.65512     .70000     .88514
210.88 2463.43  35.64  .08539  11.14979     .88478 -62.55834    .01506 836.625642594.28659     4.84603     .73000     .89901
212.92 2438.21  34.26  .09151   7.18161     .92056 -68.75363    .01567 819.372472592.95264     5.00496     .76000     .91233
214.73 2419.00  33.20  .09737   4.00852     .95649 -74.29110    .01629 805.553342590.92242     5.13293     .79000     .92509
216.87 2393.34  31.81  .10437   -.57695     .99229 -80.97386    .01690 785.569912581.93442     5.26567     .82000     .93723
219.27 2363.00  30.19  .11252  -6.32311    1.02801 -88.59055    .01752 762.244492572.42535     5.40526     .85000     .94884
221.73 2333.21  28.63  .12127 -12.28664    1.06376 -96.37194    .01814 739.914882565.23666     5.54000     .88000     .95996
224.07 2307.49  27.29  .13009 -17.77362    1.09962-103.75791    .01875 720.822832560.47116     5.66047     .91000     .97062
227.00 2271.38  25.54  .14134 -25.63213    1.13525-113.05019    .01937 693.176622546.62494     5.79524     .94000     .98081
230.88 2220.36  23.25  .15658 -36.91211    1.17055-125.08233    .01998 655.461772526.66293     5.95695     .97000     .99059
239.34 2112.99  18.72  .19077 -60.33551    1.20534-146.82207    .02060 570.112342463.79385     6.24834    1.00000    1.00000



**** ALL INPUT DATA HAVE BEEN PROCESSED.
     AT LOC 45267
```

DATA SET D

FUEL-AIR CYCLE ENGINE CALCULATIONS

```
                   IDEALIZED THERMODYNAMIC CYCLE FOR THE INTERNAL COMBUSTION ENGINE

THIS IS A NORMAL RUN EMPLOYING OCTANE,C8H18 AS A FUEL.  ADDITIONAL COMMENTS ARE.

CONVERGENCE ERRORS ARE LESS THAN .001 PERCENT

MANIFOLD PRESSURE =  14.54900 PSI         EXHAUST PRESSURE =  15.13700 PSI          AIR-FUEL RATIO =    .92000

MANIFOLD TEMPERATURE = 574.99999 °R       COMPRESSION RATIO =  10.00000             H OF COMBUSTION =1222770.00 CAL/MOLE

CLEARANCE VOLUME =   1.00000 CU.IN.       SWEPT VOLUME =   9.00000 CU.IN.

              SUMMARY OF RESULTS IN ENGLISH SYSTEM

STATION      T - *R      P - PSI.     H - BTU.       S - BTU./*R       U -  BTU.
   0         575.000     14.549     -.01598258       .00000000       .00000000
   1         625.262     14.549     -.02365288       .00062745      -.03923317
   2        1294.103    301.120      .04632732       .00062745       .01408081
   3        5234.630   1326.517      .15613554       .00079917       .01408089
   4        3125.905     78.430     -.16076147       .00079917      -.24475101
  45        2201.272     15.137     -.27756449       .00079917      -.33670970
   5        2201.272     15.137     -.00760723       .00002190      -.00922822


         RESULTS

UNDER THE FOLLOWING ASSUMPTIONS
1) ISENTROPIC COMPRESSION AND EXPANSION
2) CONSTANT VOLUME COMBUSTION
3) NO HEAT TRANSFER



    COMPRESSION WORK             =   .53313985E-01 BTU
    EXPANSION WORK               =   .25883190E 00 BTU
    PUMPING WORK                 =  -.56667733E-03 BTU
    NET CYCLE WORK               =   .20495123E 00 BTU
    INDICATED THERMAL EFFICIENCY=    .42688828E 02 PERCENT
    MEAN EFFECTIVE PRESSURE      =   .21266302E 03 PSI
    RESIDUAL WEIGHT FRACTION     =   .27406932E-01 = F
    VOLUMETRIC EFFICIENCY        =   .89984529E 00 BASED ON 1 ATM. AND 25*C


**** ALL INPUT DATA HAVE BEEN PROCESSED.
    AT LOC 22062
```

DATA SET E

NORMAL RATES OF FLAME PROPAGATION AND HEAT TRANSFER - 1200 °K EXHAUST TEMPERATURE

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                                  A MODEL SIMULATING THE INTERNAL-COMBUSTION ENGINE
ENGINE                                FUEL                                 OPERATING CONDITIONS

FOUR STROKE AUTOMOTIVE TYPE           OCTANE C8H18                         AIR-FUEL RATIO          .92
BORE                3.94 IN.          ACTIVATION ENERGY  39000.00 CAL./MOLE PISTON TEMP          500.00 K
STROKE              2.46 IN.          ENTHALPY OF                          WALL TEMP            420.00 K
ROD                 7.06 IN.          COMBUSTION        1222770.00 CAL/MOLE MAN. TEMP            320.00 K
CLEAR. VOL.         3.33 CU.IN.                                            MAN. PR.                .99 ATM
SWEPT VOL.         30.00 CU.IN.                                            EXH. PR.               1.03 ATM
COMPRESSION RATIO10.00 TO ONE                                              SPARK ADV.            16.00
                                                                           SPEED               2800.00 RPM

COMBUSTION OCCURS IN 39 INCREMENTS.  ERRORS ARE LESS THAN    .00100 PERCENT.  FLAME SPEED FACTOR IS   .13500000E 06
HEAT TRANSFER FACTOR IS   1.00000   NORMAL RUN




                    SUMMARY OF RESULTS

    PUMPING WORK                         -.47611947E 00 CAL
    NET CYCLE WORK                        .14762896E 03 CAL
    NET HEAT TRANSFERED                   .71429917E 02 CAL
    INDICATED THERMAL EFFICIENCY          .36641216E 02 PERCENT
    MEAN EFFECTIVE PRESSURE               .12402679E 02 ATM
    RESIDUAL WEIGHT FRACTION              .27956433E-01
    VOLUMETRIC EFFICIENCY                 .97409263E 00 PERCENT
```

THETA	T	P	V	H	S	U	N	Q	QTOT	W	WTOT	HB
.00	347.66	.99	.54611	-20.02049	.94852	-33.11455	.01895	.00000	.00000	.00000	.00000	.00000
10.00	348.34	1.00	.54302	-19.92079	.94852	-33.04032	.01895	.00000	.00000	-.07424	-.07424	.00000
20.00	350.39	1.02	.53380	-19.61799	.94852	-32.81476	.01895	.00000	.00000	-.22555	-.29979	.00000
30.00	353.88	1.06	.51855	-19.10252	.94852	-32.43063	.01895	.00000	.00000	-.38413	-.68392	.00000
40.00	358.92	1.12	.49750	-18.35633	.94852	-31.87427	.01895	.00000	.00000	-.55637	-1.24029	.00000
50.00	365.67	1.21	.47096	-17.35397	.94852	-31.12629	.01895	.00000	.00000	-.74797	-1.98826	.00000
60.00	374.36	1.32	.43941	-16.06025	.94852	-30.15992	.01895	.00000	.00000	-.96637	-2.95463	.00000
70.00	385.28	1.48	.40348	-14.42873	.94852	-28.93965	.01895	.00000	.00000	-1.22027	-4.17491	.00000
80.00	398.80	1.70	.36400	-12.39918	.94852	-27.41926	.01895	.00000	.00000	-1.52039	-5.69530	.00000
90.00	415.39	2.01	.32199	-9.89447	.94852	-25.53928	.01895	.00000	.00000	-1.87998	-7.57528	.00000
100.00	435.63	2.43	.27867	-6.81701	.94852	-23.22403	.01895	.00000	.00000	-2.31525	-9.89053	.00000
110.00	460.22	3.04	.23542	-3.04581	.94852	-20.37899	.01895	.00000	.00000	-2.84504	-12.73557	.00000
120.00	489.96	3.93	.19371	1.56231	.94852	-16.89117	.01895	.00000	.00000	-3.48782	-16.22339	.00000
130.00	525.65	5.27	.15510	7.15741	.94852	-12.64012	.01895	.00000	.00000	-4.25105	-20.47444	.00000
140.00	567.69	7.29	.12106	13.84065	.94852	-7.54011	.01895	.00000	.00000	-5.10001	-25.57444	.00000
150.00	615.17	10.29	.09296	21.50783	.94852	-1.66111	.01895	.00000	.00000	-5.87900	-31.45345	.00000
160.00	663.85	14.34	.07199	29.49792	.94852	4.49556	.01895	.00000	.00000	-6.15667	-37.61012	.00000
164.00	681.60	16.11	.06580	32.44356	.94852	6.77263	.01895	.00000	.00000	-2.27707	-39.88718	.00000
166.88	693.05	17.34	.06217	34.35307	.94855	8.24312	.01895	.00000	.00000	-1.47049	-41.35767	.00000
168.96	700.84	18.22	.05998	35.66051	.94881	9.18718	.01895	.00000	.00000	-.94406	-42.30173	.00000
171.26	710.11	19.32	.05798	37.23493	.94997	10.10203	.01896	.00000	.00000	-.91485	-43.21658	.00000
172.40	715.91	20.04	.05717	38.23393	.95141	10.49496	.01897	.00000	.00000	-.39293	-43.60951	.00000
173.97	724.93	21.19	.05623	39.82725	.95427	10.96998	.01898	.00000	.00000	-.47502	-44.08453	.00000
176.25	739.18	23.13	.05524	42.32347	.95990	11.38438	.01902	.13336	.13336	-.54776	-44.63229	.02558
177.67	750.62	24.78	.05486	44.44241	.96550	11.51563	.01905	.09756	.23092	-.22881	-44.86110	.02651
178.72	760.74	26.33	.05469	46.41781	.97106	11.54354	.01908	.08099	.31192	-.10891	-44.97001	.02738
179.55	770.00	27.81	.05462	48.31103	.97659	11.51428	.01911	.07145	.38336	-.04218	-45.01219	.02821
180.58	782.72	29.97	.05463	51.05936	.98483	11.41071	.01916	.10149	.48486	.00208	-45.01012	.02938
181.44	794.37	32.06	.05470	53.73497	.99301	11.26275	.01921	.09457	.57943	.05339	-44.95673	.03047
182.09	805.21	34.12	.05480	56.37642	1.00113	11.09917	.01926	.07886	.65829	.08472	-44.87200	.03152
182.64	815.39	36.14	.05491	58.99147	1.00921	10.92484	.01931	.07207	.73035	.10226	-44.76974	.03252
183.12	825.00	38.15	.05503	61.58592	1.01724	10.74321	.01935	.06678	.79713	.11485	-44.65489	.03349
183.53	834.12	40.14	.05515	64.17048	1.02523	10.56216	.01940	.06106	.85819	.11999	-44.53489	.03443
183.97	842.69	42.08	.05529	66.69493	1.03317	10.33903	.01945	.06980	.92799	.15332	-44.38157	.03532
184.42	850.78	43.99	.05546	69.16143	1.04107	10.07492	.01950	.08041	1.00841	.18370	-44.19787	.03618
184.87	858.44	45.86	.05564	71.58037	1.04893	9.77774	.01955	.10268	1.11108	.19450	-44.00337	.03701
185.33	865.64	47.69	.05585	73.91726	1.05674	9.41789	.01960	.12992	1.24100	.22993	-43.77344	.03780
185.66	872.76	49.55	.05600	76.31433	1.06453	9.11292	.01965	.10530	1.34630	.19968	-43.57376	.03859
186.19	879.08	51.25	.05627	78.41421	1.07225	8.56463	.01970	.20139	1.54768	.34690	-43.22687	.03930
186.81	884.81	52.84	.05662	80.29588	1.07991	7.83806	.01975	.27325	1.82093	.45332	-42.77354	.03994
187.75	889.23	54.09	.05722	81.53481	1.08749	6.57722	.01980	.46609	2.28702	.79476	-41.97878	.04044
189.40	890.79	54.53	.05846	81.25218	1.09489	4.04640	.01985	.88784	3.17486	1.64298	-40.33580	.04060
191.05	891.33	54.69	.05992	80.47388	1.10226	1.10371	.01989	.97258	4.14744	1.97010	-38.36570	.04060
192.69	890.98	54.59	.06161	79.24133	1.10959	-2.21652	.01994	1.05166	5.19910	2.26857	-36.09712	.04049
194.31	889.91	54.28	.06350	77.61463	1.11689	-5.86423	.01998	1.12220	6.32130	2.52551	-33.57161	.04029
195.61	889.71	54.22	.06517	76.51930	1.12426	-9.06630	.02002	.94923	7.27053	2.25284	-31.31877	.04020
197.02	888.42	53.86	.06715	74.78601	1.13157	-12.79984	.02007	1.07679	8.34731	2.65675	-28.66203	.03999
198.43	886.67	53.36	.06929	72.82623	1.13889	-16.72119	.02011	1.11108	9.45840	2.81027	-25.85176	.03973
200.14	882.74	52.26	.07212	69.47995	1.14610	-21.79775	.02015	1.39065	10.84904	3.68592	-22.16584	.03922
201.85	878.43	51.07	.07516	65.88405	1.15332	-27.07970	.02020	1.40494	12.25399	3.87700	-18.28884	.03865
203.26	875.48	50.28	.07785	63.16618	1.16064	-31.62745	.02024	1.18076	13.43475	3.36700	-14.92184	.03824
204.88	871.01	49.08	.08113	59.43508	1.16790	-37.01667	.02028	1.36477	14.79952	4.02444	-10.89740	.03769
206.63	865.50	47.65	.08491	54.99569	1.17514	-42.99195	.02032	1.47536	16.27488	4.49992	-6.39747	.03701
208.53	858.93	45.99	.08924	49.80880	1.18236	-49.58424	.02036	1.58871	17.86360	5.00357	-1.39390	.03622
210.54	851.50	44.17	.09413	43.98737	1.18956	-56.69641	.02040	1.67424	19.53783	5.43793	4.04403	.03535
213.10	840.62	41.60	.10078	35.72497	1.19663	-65.81870	.02044	2.08972	21.62755	7.03257	11.07660	.03412
217.28	820.17	37.17	.11258	21.61096	1.20358	-79.73681	.02047	2.51922	24.14677	11.39890	22.47550	.03193
220.00	2442.20	33.93	.12084	10.32239	1.20272	-88.98951	.02046	2.13167	26.27844	7.12103	29.59653	.03176

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225.00 2353.89  28.79  .13718  -9.32860   1.20120-104.99456   .02045   3.68010  29.95854  12.32495  41.92147   .03005
230.00 2269.63  24.59  .15485 -27.40170   1.19979-119.61203   .02044   3.28215  33.24069  11.33532  53.25679   .02718
235.00 2190.72  21.16  .17366 -43.89931   1.19849-132.88659   .02044   2.94174  36.18243  10.33281  63.58961   .02466
240.00 2117.57  18.36  .19344 -58.92938   1.19728-144.93618   .02044   2.65341  38.83583   9.39619  72.98579   .02247
245.00 2050.30  16.07  .21399 -72.58986   1.19614-155.85922   .02044   2.40984  41.24568   8.51320  81.49899   .02058
250.00 1988.68  14.18  .23513 -84.99645   1.19507-165.76040   .02044   2.20418  43.44985   7.69700  89.19599   .01895
255.00 1932.36  12.62  .25665 -96.26459   1.19404-174.73951   .02044   2.03004  45.47990   6.94907  96.14506   .01753
260.00 1880.90  11.33  .27837-106.50804   1.19307-182.89198   .02044   1.88197  47.36186   6.27050 102.41556   .01630
265.00 1833.87  10.25  .30012-115.82815   1.19213-190.30177   .02044   1.75536  49.11722   5.65443 108.07000   .01524
270.00 1790.89   9.33  .32170-124.31605   1.19123-197.04367   .02044   1.64648  50.76370   5.09542 113.16541   .01431
275.00 1751.57   8.56  .34295-132.05322   1.19036-203.18417   .02044   1.55233  52.31604   4.58816 117.75357   .01350
280.00 1715.60   7.91  .36372-139.11178   1.18952-208.78187   .02044   1.47047  53.78650   4.12724 121.88081   .01278
285.00 1682.68   7.35  .38385-145.55536   1.18870-213.88834   .02044   1.39891  55.18541   3.70756 125.58837   .01216
290.00 1652.54   6.87  .40322-151.43996   1.18791-218.54886   .02044   1.33607  56.52148   3.32445 128.91282   .01161
295.00 1624.95   6.46  .42170-156.81517   1.18713-222.80345   .02044   1.28064  57.80211   2.97395 131.88677   .01112
300.00 1599.57   6.11  .43918-161.74839   1.18637-226.70608   .02044   1.23155  59.03366   2.67108 134.55785   .01070
305.00 1576.35   5.80  .45556-166.25261   1.18562-230.26752   .02044   1.18772  60.22138   2.37373 136.93158   .01032
310.00 1555.14   5.54  .47076-170.36157   1.18487-233.51493   .02044   1.14866  61.37004   2.09875 139.03032   .00998
315.00 1535.78   5.31  .48471-174.10493   1.18415-236.47212   .02044   1.11377  62.48381   1.84343 140.87375   .00969
320.00 1518.15   5.12  .49734-177.50870   1.18343-239.15999   .02044   1.08255  63.56636   1.60531 142.47906   .00943
325.00 1502.14   4.95  .50859-180.59560   1.18272-241.59674   .02044   1.05460  64.62095   1.38216 143.86122   .00920
330.00 1487.40   4.81  .51843-183.38361   1.18205-243.78609   .02044   1.02956  65.65051   1.15979 145.02101   .00900
335.00 1474.26   4.69  .52681-185.88618   1.18137-245.75503   .02044   1.00673  66.65723    .96222 145.98323   .00883
340.00 1462.49   4.59  .53371-188.12457   1.18070-247.51564   .02044    .98655  67.64378    .77406 146.75728   .00868
345.00 1452.04   4.52  .53911-190.11131   1.18004-249.07790   .02044    .96858  68.61236    .59368 147.35097   .00856
350.00 1442.85   4.46  .54298-191.85675   1.17938-250.45008   .02044    .95263  69.56499    .41955 147.77052   .00845
355.00 1434.88   4.41  .54531-193.36929   1.17873-251.63891   .02044    .93859  70.50358    .25024 148.02075   .00837
360.00 1428.10   4.38  .54611-194.65540   1.17808-252.64957   .02044    .92633  71.42992    .08432 148.10508   .00831
360.00 1037.60   1.03 1.68912-266.69466   1.17808-308.83118   .02044    .00000  71.42992    .00000 148.10508   .00000
540.00 1200.00   1.03  .05461  -6.63366    .03367  -7.99601   .00057    .00000  71.42992    .00000 148.10508   .00000
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THETA       T      P        V           H         S          U         N FLAME SPEED, TEMP., AND EXTENT  MASS-FR.  BURN.-VOL.
166.88 2550.22  17.34   .00002      .00403    .00012    -.00637    .00000 693.568172550.22064      .18768     .00010     .00040
168.96 2550.99  18.22   .00024      .04020    .00124    -.06382    .00002 709.041682548.47394      .39182     .00100     .00393
171.26 2559.60  19.32   .00112      .21093    .00619    -.31093    .00010 732.479902557.99228      .65396     .00500     .01923
172.40 2563.78  20.04   .00215      .43096    .01237    -.61446    .00021 744.816542556.04697      .80083     .01000     .03769
173.97 2574.94  21.19   .00409      .91613    .02472   -1.18414    .00041 769.489082568.44778     1.04218     .02000     .07278
176.25 2582.65  23.13   .00752     1.89394    .04932   -2.31913    .00082 809.479002588.05792     1.35103     .04000     .13617
177.67 2595.70  24.78   .01058     3.02941    .07389   -3.32307    .00123 838.833632591.69345     1.56457     .06000     .19293
178.72 2608.96  26.33   .01335     4.30094    .09842   -4.21394    .00164 866.328712597.07632     1.70534     .08000     .24416
179.55 2621.42  27.81   .01588     5.68592    .12292   -5.01054    .00205 892.046102602.44113     1.83185     .10000     .29069
180.58 2638.80  29.97   .01929     7.95764    .15961   -6.04375    .00267 930.853232617.62723     1.97164     .13000     .35314
181.44 2654.74  32.06   .02233    10.43696    .19625   -6.90396    .00329 965.657972624.73230     2.08377     .16000     .40829
182.09 2669.59  34.12   .02507    13.10873    .23283   -7.60389    .00390 998.632842631.40555     2.17138     .19000     .45746
182.64 2683.42  36.14   .02755    15.95217    .26936   -8.16064    .004521030.682372637.98550     2.24425     .22000     .50165
183.12 2696.34  38.15   .02981    18.95150    .30585   -8.58738    .005141061.729062644.32162     2.28758     .25000     .54165
183.53 2708.52  40.14   .03188    22.09815    .34229   -8.89111    .005761091.958162650.46838     2.34305     .28000     .57807
183.97 2719.59  42.08   .03381    25.34316    .37869   -9.11328    .006381120.958542656.11258     2.39998     .31000     .61141
184.42 2729.72  43.99   .03561    28.67371    .41504   -9.26440    .006991148.911542661.50839     2.45737     .34000     .64208
184.87 2739.10  45.86   .03730    32.08812    .45136   -9.34585    .007611175.885482666.66266     2.51507     .37000     .67042
185.33 2747.55  47.69   .03891    35.54608    .48763   -9.39170    .008231201.750432671.48312     2.57337     .40000     .69672
185.66 2756.09  49.55   .04039    39.14792    .52387   -9.31723    .008851227.911612676.80453     2.62238     .43000     .72119
186.19 2762.46  51.25   .04187    42.60189    .56005   -9.36893    .009471251.541082680.60849     2.68828     .46000     .74404
186.81 2767.41  52.84   .04334    45.95755    .59617   -9.50482    .010091273.103962684.13425     2.77031     .49000     .76544
187.75 2768.66  54.09   .04495    48.84111    .63220  -10.04084    .010701289.488682685.50375     3.02652     .52000     .78553
189.40 2761.78  54.53   .04703    50.47759    .66806  -11.63083    .011321294.783892682.56412     3.24648     .55000     .80445
191.05 2753.06  54.69   .04928    51.71059    .70388  -13.56013    .011931296.586872681.49118     3.49778     .58000     .82235
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201.85 2669.28  51.07   .06954    51.98136    .95413  -34.03473    .016221245.893012664.48178     4.94686     .79000     .92526
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208.53 2602.39  45.99   .08663    44.15932   1.09699  -52.32226    .018661172.750982645.73459     5.57636     .91000     .97071
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213.10 2547.47  41.60   .09984    33.93795   1.16818  -66.65591    .019871106.353962624.86008     5.92082     .97000     .99065
217.28 2491.14  37.17   .11258    21.61097   1.20358  -79.73681    .020471033.459382594.17960     6.18577    1.00000    1.00000

**** ALL INPUT DATA HAVE BEEN PROCESSED.
     AT LOC 42742
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