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MULTIPLE-FLAME COMBUSTION MODEL
FORTRAN IV COMPUTER PROGRAM

G. D. Sammons, et al

Rockwell International Corporation

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SCIENTIFIC REPORT
MULTIPLE-FLAME COMBUSTION MODEL
FORTRAN IV COMPUTER PROGRAM

FINAL

Submitted to Combustion Energetics Division, AFOSR

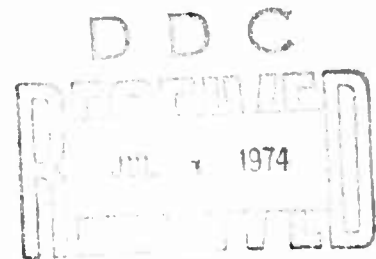
March 8, 1974

Work performed under sponsorship of the Combustion
Energetics Division of the Air Force Office of
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Work of G. D. Sammons

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FOREWORD

This report consists of a User's Guide and Fortran IV source deck for G. D. Sammons' (deceased) Combustion Model Computer Program written under paragraph A.I.3 of Item 0001 in Contract F44620-72-C-0046. This report was assembled for publication by members of the Technical Staff, Rocketdyne, McGregor, Texas. Lloyd R. Lawrence, Jr., Captain USAF, from the Air Force Office of Scientific Research, was monitor for the program.



SCIENTIFIC REPORT
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FORTRAN IV COMPUTER PROGRAM

ABSTRACT

Several investigators have formulated competing-flame models describing composite solid propellant combustion. This report covers Mr. G. D. Sammons' (deceased) competing-flame modeling efforts. His papers describing the model are appended. This report describes and lists the FORTRAN IV computer program which is the practical outcome of any modeling effort. Included is the solution of an example problem--estimation of the burning rate of a low-smoke HTPB propellant. How the necessary input values are obtained and how they are input is discussed in detail. Finally, the computer solution printout is depicted.

The work described here was performed under sponsorship of the Combustion Energetics Division of the Air Force Office of Scientific Research (Contract F44620-72-C-0046).

Combustion modeling studies will be continued during FY 1975. These further studies will be directed primarily toward addition of a mathematical treatment for heterogeneous catalysis of burning rate to the multiple-flame model.



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INTRODUCTION

Considerable efforts over the past seventeen years have been directed toward elucidating the mechanism of combustion of composite solid propellants. The ultimate goal of these efforts has been a truly comprehensive and descriptive mathematical combustion model. The most sophisticated models stemming from these efforts are the competing-flame models of Hermance⁽¹⁾⁽²⁾ and Beckstead, Derr and Price (BDP)⁽³⁾⁽⁴⁾. These combustion models allow one to use some independently determined kinetic and thermal parameters to predict burning rate. This report covers one of the more recent modeling efforts--Mr. G. D. Sammons' (deceased) extension of the BDP competing-flame model.

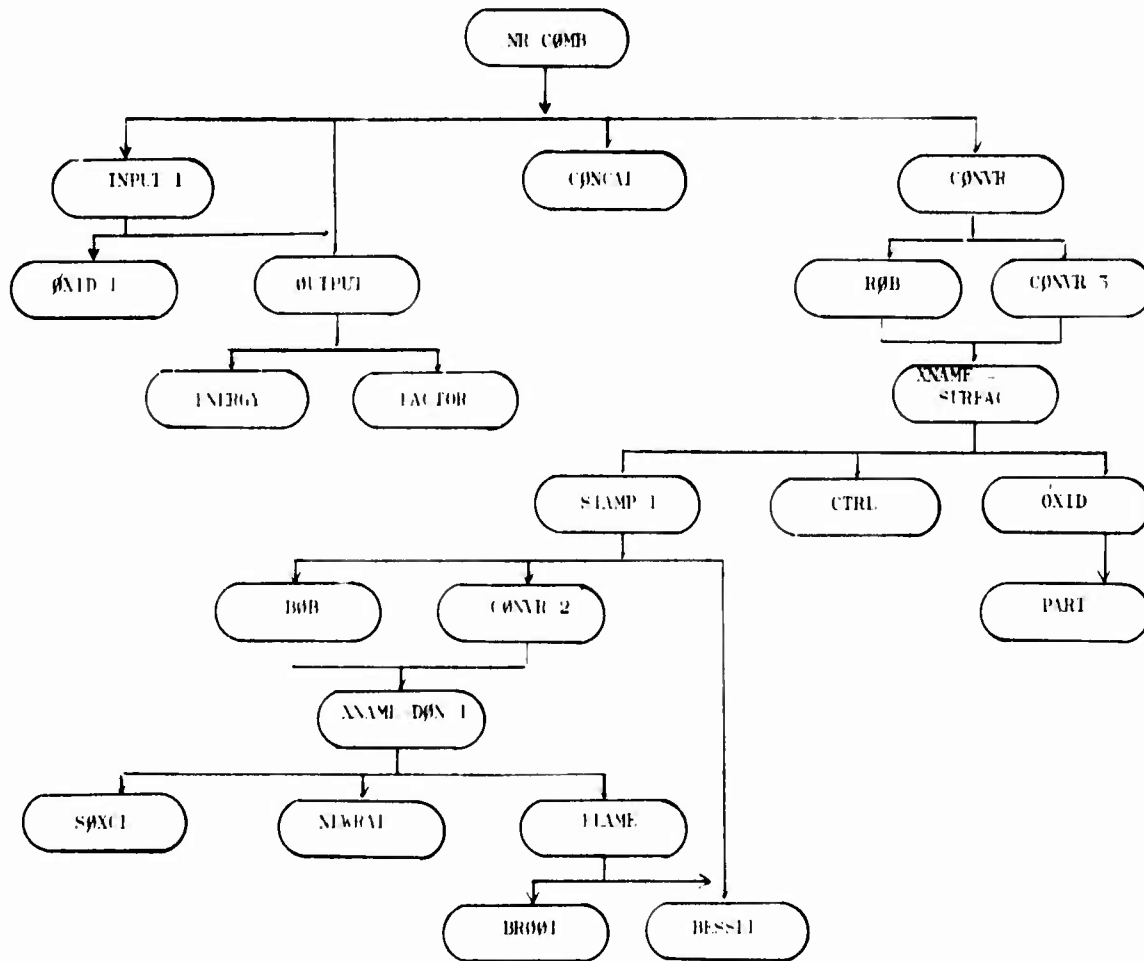
Mr. Sammons' papers presented at the 9th and 10th JANNAF Combustion Meetings, which describe his model, are appended to this report as Appendix I. His computer program originally written in FORTRAN IV for use at a time-share computer terminal has been rewritten for use on an IBM-360. This rewritten program is described here briefly. Also given here is a solved sample problem.

COMPUTER PROGRAM

The NRCOMB Computer Program, listed completely in Appendix B, is written in FORTRAN IV. It has been checked out on an IBM 360 and has been used to estimate the burning rate of composite solid propellants having carboxyl-terminated and hydroxyl-terminated polybutadiene binders.

A flow-chart of NRCOMB is reproduced in Figure 1.

FIGURE 1
SUBROUTINE FLOW CHART OF
COMBUSTION MODEL COMPUTER PROGRAM





NRCOMB is the main program. Its sole function is to control program flow. Calculations are carried out in the subroutines.

Subroutine INPUT does as its name implies--inputs the parameters used to calculate burning rate. These parameters are listed in detail in the section "SAMPLE PROBLEM: PROGRAM INPUTS USED TO COMPUTE BURNING RATE."

Subroutines OUTPUT, ENERGY and FACTOR are output routines that print out parameter names and values and column heads burning rate vs. pressure data, flame parameter vs. pressure data, etc.

Subroutine CONCAL increments the pressure from a start value to a stop value.

Function subroutines BOB and ROB establish the functional relationships $XNAME = DON\ 1$ and $XNAME = SURFAC$.

Function subroutines CONVR 2 and CONVR 3 are convergence routines that force convergence on the desired value when upper and lower extremes are known. CONVR 2 yields surface temperature; CONVR 3 yields critical AP particle size.

The group of subroutines and function subroutines CONVR, ROB, CONVR 3, CRTL, OXID and PART utilize the multi-modal oxidizer particle size input to compute an average particle size, critical AP size, fraction of AP greater and less than critical, and an oxidizer ignition time. The roles of ROB and CONVR 3 have been described. CRTL computes a critical AP size; OXID computes an average diameter and a greater and less than critical size weight fraction. PART computes the AP ignition time utilizing the AP particle size distribution.

Subroutine STAMP 1, utilizing several subroutines for the competing flame, computes surface temperature and as a final

step calculates burning rate using the expression: Total Mass Flow/Propellant Density. STAMP 1 calls on BOB and CONVR 2, both of whose roles have been described. It also calls on DON 1 which in turn calls on SOXCAL, NEWRAF, FLAME, BESSEL and BR00T.

Function subroutine DON 1 computes propellant surface temperature. It uses SOXCAL to compute the fraction of total propellant surface involved in AP only decomposition. It utilizes FLAME, BESSEL, BR00T and NEWRAF to compute the parameters needed in primary diffusion flame and final flame calculations.

SAMPLE PROBLEM: PROGRAM INPUTS USED TO COMPUTE BURNING RATE

Given here are descriptions of the program inputs used to estimate propellant burning rate. For this example, a typical low-smoke HTPB propellant having the composition listed below has been selected.

<u>Ingredient</u>	<u>Weight Percent</u>
HTPB Binder	12.0
Ammonium Perchlorate	
400 μ (nominal diameter)	55.5
200 μ (nominal diameter)	13.0
80 μ (nominal diameter)	12.2
7-11 μ (finely ground)	5.0
Aluminum, 5 μ	<u>0.3</u>
	100.0



Oxidizer Particle Size and Weight Fractions -
INPUTS DMAX, DMIN, AND SIG

The oxidizer particle size distribution given in the formulation is broken down into several particle size weight fraction ranges for inputting by using the typical AP particle size analytical data given in Table 1. Such an input for the example propellant is shown here.

<u>DMAX(μ)</u>	<u>DMIN(μ)</u>	<u>SIG</u>	<u>Subscript</u>
600	420 ^(a)	0.205	1
420	230 ^(b)	0.357	2
230	140 ^(b)	0.265	3
140	72 ^(c)	0.096	4
72	60 ^(d)	0.027	5
60	9.8 ^(e)	0.039	6
9.8	3 ^(e)	0.011	7

- (a) From nominal 400 μ fraction
- (b) From nominal 400 μ and 200 μ fractions
- (c) From nominal 200 μ and 80 μ fractions
- (d) From nominal 200 μ , 80 μ and 7-11 μ fractions
- (e) From nominal 80 μ and 7-11 μ fractions

The 600-420 fraction is obtained by multiplying 0.555 by 0.37; the 420-230 fraction by multiplying 0.555 by 0.59 and 0.13 by 0.23 and using the sum, etc.; to produce a 7-modal AP distribution (NN = 7) input.



TABLE I

TYPICAL AP PARTICLE SIZE DISTRIBUTIONS

A. Nominal 400 μ AP (as received)

<u>Particle Diameter Range</u> <u>(Microns)</u>	<u>Weight Percent</u>
600-420	37.0
420-350	29.0
350-250	30.0
250-210	1.0
210-177	1.0
177-74	2.0

B. Nominal 200 μ AP (as received)

<u>Particle Diameter Range</u> <u>(Microns)</u>	<u>Weight Percent</u>
500-230	23.0
230-140	59.0
140-78	13.0
78-25	5.0

C. Nominal 80 μ AP (as received)

<u>Particle Diameter Range</u> <u>(Microns)</u>	<u>Weight Percent</u>
110-72	60
72-54	20
54-35	10
35-11	8
11-4.3	2

D. Fine Grind - Rocketdyne's Nominal 7-11 μ AP

<u>Particle Diameter Range</u> <u>(Microns)</u>	<u>Weight Percent</u>
80-60	5
60-9.8	75
9.8-5	15
5-3	5



Modality of AP - Input NN

In the previous section, the oxidizer was divided into a 7-modal distribution. So this input is: NN = 7

Weight Fraction Oxidizer and Aluminum - Inputs ALFA and EPS

From the formulation, it is evident that the values are:

$$ALFA = .857$$

$$EPS = .003$$

Density of Oxidizer, Binder and Aluminum - Inputs RHØX, RHØF and RHAL

Values for these quantities are (standard values):

$$RHØX = 1.95 \text{ gm/cm}^3$$

$$RHØF = 0.91 \text{ gm/cm}^3$$

$$RHAL = 2.70 \text{ gm/cm}^3$$

Initial Propellant Temperature and Flame Temperature - Inputs TZERO and TF

Flame temperature value is obtained from thermodynamic calculations. Values for these inputs for the example propellant are:

$$TZERO = 300 \text{ K}$$

$$TF = 2908 \text{ K}$$

Binder and Oxidizer Kinetic Parameters - Inputs AF, EF, AØX and EØX

Pyrolysis rates for the separate fuel and oxidizer components are expressed by Arrhenius expressions of the form:

$$\dot{m} = A \exp (E/RT_s)$$

where A and E are input parameters. For the fuel component, the frequency factor $AF = 299 \text{ gm/cm}^2 \text{ sec}$ and activation energy $EF = 16,900 \text{ cal/mole}$ which were obtained by pyrolyzing an HTPB binder⁽⁷⁾ are used as inputs. For the oxidizer component, ammonium perchlorate, $A\phi X$ values ranging from 10^4 to 10^{20} and $E\phi X$ values ranging from 17,000 to 73,400 for pure AP have been reported. For use here, we have selected frequently used values in modeling studies--namely, $A\phi X = 4 \times 10^7 \text{ gm/cm}^2 \text{ sec}$ and $E\phi X = 30,000 \text{ cal/mole}$.

Gaseous Diffusivity - D_o Input as GAMMA

In this program, gaseous diffusivity is calculated using Beckstead, et al's expression⁽³⁾⁽⁴⁾.

$$D = D_o \left[\frac{T^{1.75}}{P} \right]$$

D_o is an input parameter. It is estimated using the Chapman-Enskog relation⁽⁵⁾.

$$D_{AB} = 0.0018583 \left[\frac{T^3 \left(\frac{1}{M_A} + \frac{1}{M_B} \right)}{P \sigma_{AB}^2 \Omega_{D_{AB}}} \right]$$

and

$$D_o = D_{AB} \left(\frac{P_o}{T_o^{1.75}} \right) = D_{AB} \left[\frac{1}{(273.2)^{1.75}} \right]$$

For this sample calculation, we have assumed that the gaseous fuel species is C_3H_8 which is consistent with the PMW value given in a later section. For oxidizer we have used O_2 . Using appropriate values for these gases in the Chapman-Enskog equation, a value for $C_3H_8-O_2$ diffusion of $0.0928 \text{ cm}^2/\text{sec}$ is obtained which yields the value of D_o below.

$$D_o = 5.07 \times 10^{-6} \text{ (input as GAMMA) cm}^2/\text{sec}$$

D_{AB} might also be estimated using the empirical relationship developed by Gilliland which can be found in many chemical engineering textbooks⁽⁶⁾.

Ammonium Perchlorate Oxidizer
Flame Temperature - Input TAP

This is the temperature of one of the three competing flames-- the temperature of the oxidizer monopropellant flame. The standard value used by Beckstead⁽³⁾⁽⁴⁾ is used here.

$$TAP = 1400 \text{ K}$$

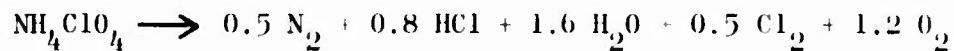
Stoichiometric Ratios of the Primary Flame
and of the Final Flame - Inputs XNUP and XNU1

To estimate these stoichiometric ratios, the general formula below is used:

$$(\text{Stoichiometric Ratio}) = \frac{\text{Moles Fuel Species/Gram}}{\text{Moles Oxygen/117.5}}$$

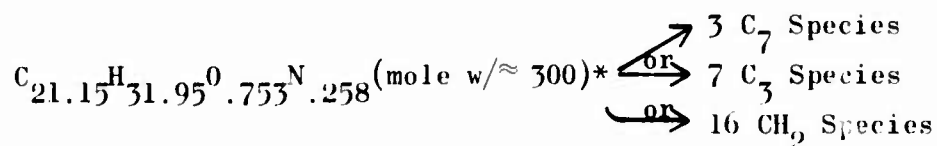


AP decomposition can be represented by the stoichiometric equation:



which gives a molar oxygen flow rate of $\frac{1.2}{117.5} = 0.0102$ moles oxygen/gm

The approximate formula for an HMDI cured Poly BD R-45M HTPB binder (the formula used for material balance in thermodynamic calculations) provides a basis for estimating the moles of fuel per gram of fuel flow. Using this formula and setting the heaviest species at C_7 gives the following:



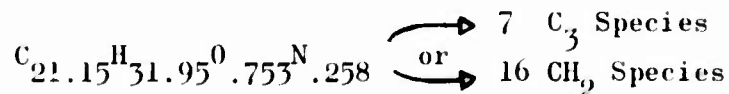
--about 8.7 moles of fuel species per 300 grams of binder on the average so that

$$\text{XNUP} = \frac{8.7/300}{0.01} = 2.9$$

* Polybutadiene is $(\text{CH}_{1.5})_x$



In the final diffusion flame further breakdown of the binder decomposition products is assumed so that



This is, on the average, 11.5 moles of fuel species. This gives

$$\text{XNU1} = \frac{11.5/300}{0.01} = 3.83$$

The diffusion flame solution employed in this model requires XNUP and XNU1 values greater than 2.8.

Molecular Weights for the Primary and Final Flames - Inputs PMW and GMW

To be consistent with stoichiometric ratios these values are calculated as follows:

$$\text{Mole Wt.} = \frac{(300 + 117)}{(\text{Moles Fuel} + \text{Moles O}_2)}$$

giving

$$\text{PMW} = \frac{417}{9.9} \approx 42$$

$$\text{GMW} = \frac{417}{12.7} \approx 33 \quad (\text{Average mole wt. of combustion products of this propellant is approx. 30})$$

Burning Surface Temperature--Input TS

The program calculates the temperature of the burning surface. This calculation requires an initial estimate. For use in this example:

$$\text{TS} = 750 \text{ K}$$



Flame Height Factor and Oxidizer Ignition Delay
Time Parameters--Inputs AFH, CIGN, POWIGN, and POWD

$$\begin{aligned} \text{AFH} &= 0.5 \\ \text{CIGN} &= 190 \text{ sec atm}^m/\text{cm}^n \\ \text{POWIGN} &= 0.75 \text{ (an exponent: } m) \\ \text{POWD} &= 0.8 \text{ (an exponent: } n) \end{aligned}$$

The flame height factor and ignition delay time parameters are those used by both Hermance and Beckstead⁽¹⁾⁽²⁾⁽³⁾⁽⁴⁾.

Rate Constant Parameters for the Diffusion
and AP Flames--Inputs KPF, KAP1 and KAP2

These are the rate constants for gas phase reactions of arbitrary reaction order and expressed in the following general form

$$W = k P^{\sigma}$$

Values used here for these k's are

$$\begin{aligned} \text{KPF} &= 30 \text{ gm/cm}^3 \text{ sec Atm} \\ \text{KAP1} &= 1.12 \text{ gm/cm}^3 \text{ sec Atm} \\ \text{KAP2} &= 2.13 \text{ gm/cm}^3 \text{ sec Atm} \end{aligned}$$

These are "standard" values for the gas phase rate constants.

Reaction Order Constants for Diffusion
Flame and AP Flame--Inputs XN1, XN2, and XN3

$$\begin{aligned} \text{XN1} &= 1.5 \\ \text{XN2} &= 1.8 \\ \text{XN3} &= 1.8 \end{aligned}$$

These values should be considered "standard" values for the parameters in AP composite propellants. σ



Average C_p Value for Flames and Solids and
Gas Conductivity - Inputs CSUBP and XLAMB

C_p is used in this model in several calculations. For example:

- (1) The energy balance term accounting for propellant heat up

$$m_t C_p (T_s - T_o)$$

- (2) As an enthalpy term in the AP flame relationship

$$C_p (T_{AP} - T_o)$$

- (3) In non-dimensional standoff distance calculations in the multipliers

$$\frac{C_p M_t}{\lambda} \text{ and } \frac{C_p M_{ox}}{\lambda}$$

Each requires a C_p value. This model, like the BDP model uses only one C_p value for both gases and solids. This value is an overall average value. Why this approximate approach has been used becomes evident on calculating this overall average value.

The specific heat of AP below and above the phase transition temperature yields an average value

$$C_p = \frac{.309 + .365}{2} = 0.337 \text{ cal./gm-K}$$

The specific heat of the example propellant is

$$C_p = 0.352 \text{ cal/gm-K}$$

Each gaseous product contributes its proportional share to C_p . To obtain the C_p value for the AP flame, the products shown in the stoichiometry section provided the basis for the material balance and the AP flame temperature and propellant surface temperature provided the average temperature from which the C_p contributions in the table were obtained.

$$T(\text{ave}) = \frac{750 + 1400}{2} = 1075 \text{ K}$$

<u>Gas</u>	<u>Wt. Fraction</u>	<u>C_p Contribution</u> *
N_2	0.096	0.0259
HCl	0.201	0.0386
H_2O	0.198	0.1026
Cl_2	0.241	0.0300
O_2	0.264	0.066

* Estimated from charts in Hougen and Watson, "Chemical Process Principles: Part One - Material and Energy Balances," John Wiley

These contributions sum up to the C_p value for the AP flame.

$$C_p = 0.263 \text{ cal/gm} - \text{K}$$

To obtain the C_p value for the propellant flame, the final combustion product distribution was used to provide an estimated average value at an average temperature as shown below:

$$T(\text{ave.}) = \frac{\text{Surface Temp} + \text{Flame Temp.}}{2} = \frac{750 + 2910}{2} = 1830 \text{ K}$$

<u>Gas</u>	<u>Wt. Fraction*</u>	<u>C_p Contribution**</u>
N ₂	0.102	0.0287
H ₂ O	0.286	0.1604
CO ₂	0.173	0.0500
CO	0.174	0.0491
HCl	0.265	0.0560

* From flame temperature calculations

** Estimated from charts in Hougen and Watson, "Chemical Process Principles: Part One - Material and Energy Balances," John Wiley.

These tabulated contributions sum up to

$$C_p = 0.344 \text{ cal/gm} - \text{K}$$

In arriving at these C_p values for the flames, ideal gas behavior has been assumed.

The overall average of these values is used as input.

$$CSUBP = \frac{0.337 + 0.352 + 0.263 + 0.344}{4} = 0.324 \text{ cal/gm} - K$$

Beckstead's "Standard" value⁽³⁾⁽⁴⁾ for gas conductivity (ideal behavior assumed) is used here as gas conductivity input.

$$XLAMB = 0.0003 \text{ cal/cm sec} - K$$

Aluminum Heat Absorption - Input QAL

The latent heat of fusion - the heat absorbed when molten drops of aluminum are formed on the propellant surface--is input.

$$QAL = \left[(\text{Heat of Fusion}) + \langle C_p (\text{mean}) \times 660 \rangle \right] = 257 \text{ cal/gm}$$

Heat to Vaporize the Fuel Binder - Input QFUEL

For this input the measured value for an HTPB binder⁽⁷⁾ is used.

$$QFUEL = 433 \text{ cal/gm}$$

Heat Stemming from AP Decomposition, Reaction of Less Than Critical Size AP with Fuel, and from Liquid Layer--Inputs QL, QSOLID and QLIQ

The BDP model employed a QL input only to account for decomposition of the oxidizer, AP, at the surface⁽³⁾⁽⁴⁾. This parameter, QL, was varied to account for more or less reaction in the solid phase. Mr. Sammons introduced two additional adjustable parameters,

QSOLID and QLIQ, to account for reaction in the solid phase. Here the following values for these parameters (values used by Sammons) are input.

$$QL = 0.0 \text{ cal/gm}$$

$$QSOLID = 1085.0 \text{ cal/gm}$$

$$QLIQ = 1000.0 \text{ cal/gm}$$

Pressure Programming Inputs PSTART and PSTOP

Two pressure programming inputs to start and stop the incremental pressure increases employed in calculating a burning rate vs. pressure curve are required. Inputs used here are:

$$PSTART = 1.0$$

$$PSTOP = 220.0$$

Pressures used in the burning rate calculations are in atmospheres. These pressures are converted to psia before outputting.

SAMPLE PROGRAM RUN

Following are the computer inputs and computer printout obtained with the example data described in the previous section.

CARD 1: TITLE CARD
NO. REQUIRED: One card per run
FUNCTION: Identify run output
FORMAT: (20A4)

Column	Format	Variable	Description
2--80	20A4	TIT1	79 columns of alphanumeric data may be input to identify run

CARD 2: CONTROL CARD
 NO. REQUIRED: One card per run
 FUNCTION: Specify run options to be executed
 FORMAT: (12I6)

Column	Format	Variable	Description
1--6	I6	NJØB	Specifies run option 1 - Input complete set of data (NJØB must always be 1 for first run) 2 - Stacked run; input new values for AF and AØX 3 - Stacked run; input new value for QL 4 - Stacked run; input new value for XNU1 5 - Stacked run; input new value for AFH 6 - Stacked run; input new values for PSTART and PSTOP 7 - Stacked run; input new values for IX and TZEK0 8 - Stacked run; input new value for QF 9 - Stacked run; input new modality of oxidizer and aluminum weight fraction 10 - Rerun same problem - not used 11 - Rerun using weight fraction and modality of oxidizer data stored in INPUT1 100 - Repeat printout of last run 105 - Repeat last run - printout only HDN1, HDPI and SØX1
7--12	I6	IPLØT	If IPLØT > 0, do not print propellant data input
13--18	I6	IPLT	0--Do not write tape for plotting 2--Write log(P) and log (rate) on logical unit 10 for plotting. Do not print output. #0 } --Write log (P) and log (rate) on #2 } logical unit 10 for plotting and print output
19--80	--	--	Not read - may be used to identify card

CARD 3: DATA CARD
 NO. REQUIRED: One card per run for NJOB=1
 FUNCTION: Specify propellant parameters
 FORMAT: (6E12.5)

Column	Format	Variable	Description
1--12	E12.5	TZERO	Initial propellant temperature, deg K
13--24	E12.5	ALFA	Oxidizer weight fraction
25--36	E12.5	TF	Flame temperature, deg K
37--48	E12.5	GMW	Molecular weight of final flame
49--60	E12.5	XNU1	Stoichiometric ratio of the final flame > 2.8
61--72	E12.5	DZERO	Mean AP particle size, μ input as 0.0 for multimodal AP
73--80	--	--	Not read - may be used to identify card



CARD 3A: DATA CARD

NO. REQUIRED: One card per run for NJOB=2 through 8
(Do not include for NJOB=1 or NJOB > 8)

FUNCTION: Specify input data changes to previous run

FORMAT: As noted

Column	Format	Variable	Description	
1--12	E12.5	AF	Frequency factor--See Card 4	NJOB=2
13--24	E12.5	A/X	Frequency factor--See Card 5	
1--12	E12.5	QL	Heat from AP decomposition, cal/gm	NJOB=3
1--12	E12.5	XNU1	Stoichiometric ratio of final flame > 2.8	NJOB=4
1--12	E12.5	AFH	Flame height factor	NJOB=5
1--12	E12.5	PSTART	Pressure to start incremental calculations, atm	NJOB=6
13--24	E12.5	PSTOP	Pressure to stop incremental calculations, atm	
1--6	I6	IX	Output control(1)	NJOB=7
7--12	6X	--	Blank	
13--24	E12.5	TZERO	Initial propellant temperature, deg K	
1--12	E12.5	QFUEL	Heat to vaporize the fuel binder, cal/gm	NJOB=8

(1)

- IX = {
- 1 Normal output
 - 2 Print energy terms vs pressure in subroutine energy
 - 3 Print weight factors with respect to critical particle size and critical particle size vs pressure in subroutine factor
 - 4 Print burning rate and XTAR's vs pressure only

CARD 4: DATA CARD
 NO. REQUIRED: One card per run for NJOB=1
 FUNCTION: Specify propellant parameters
 FORMAT: (6E12.5)

Column	Format	Variable	Description
1--12	E12.5	QFUEL	Heat to vaporize the fuel binder, cal/gm
13--24	E12.5	RHOF	Density of binder, gm/cm ³
25--36	E12.5	AF	Frequency factor, ⁽¹⁾ gm/cm ² -sec
37--48	E12.5	EF	Activation energy, ⁽¹⁾ cal/mole
49--60	E12.5	XNUP	Stoichiometric ratio of the final flame > 2.8
61--72	E12.5	PMW	Molecular weight of primary flame
73--80	--	--	Not read - may be used to identify card

⁽¹⁾ Kinetic parameters used to calculate binder pyrolysis rates were:

$$\dot{m} = AF \exp(EF/RT_s)$$



CARD 5: DATA CARD
NO. REQUIRED: One card per run for NJOB=1
FUNCTION: Specify propellant parameters
FORMAT: (6E12.5)

Column	Format	Variable	Description
1--12	E12.5	QL	Heat from AP decomposition, cal/gm
13--24	E12.5	RHOX	Density of oxidizer, gm/cm ³
25--36	E12.5	A0X	Frequency factor ⁽¹⁾ , gm/cm ² -sec
37--48	E12.5	E0X	Activation energy ⁽¹⁾ , cal/mole
49--60	E12.5	TAP	Ammonium perchlorate flame temperature, deg K
61--72	E12.5	--	Not used
73--80	--	--	Not read - may be used to identify card

⁽¹⁾ Kinetic parameters used to calculate oxidizer pyrolysis rates were:

$$\dot{m} = A0X \exp(E0X/RT_s)$$



CARD 6: DATA CARD
NO. REQUIRED: One card per run for NJOB=1
FUNCTION: Specify oxidizer ignition parameters and pressure range for calculations
FORMAT: (6E12.5)

Column	Format	Variable	Description
1--12	E12.5	CIGN	Oxidizer ignition delay time coefficient ⁽¹⁾ , sec-atm ^{POWIGN} /cm ^{POWD}
13--24	E12.5	POWIGN	Oxidizer ignition delay time pressure exponent ⁽¹⁾
25--36	E12.5	POWD	Oxidizer ignition delay time diameter exponent ⁽¹⁾
37--48	E12.5	PSTART	Pressure to start incremental calculations, atm
49--60	E12.5	PSTOP	Pressure to stop incremental calculations, atm
61--72	E12.5	--	Not used
73--80	--	--	Not read - may be used to identify card

⁽¹⁾ Oxidizer ignition delay time parameters use in the following expression:

$$\frac{n}{D_o} = \frac{1}{2} \left(1 \pm \frac{1}{\sqrt{3}} \right) \left(1 - \frac{r_{ox}}{r_f} \right) + r_{ox} \frac{CIGN * D_o^{POWD}}{p^{POWIGN}}$$

CARD 7: DATA CARD

NO. REQUIRED: One card per run for NJOB=1

FUNCTION: Specify rate and reaction order constants
for diffusion flame and AP flame

FORMAT: (6E12.5)

Column	Format	Variable	Description
1--12	E12.5	KPF	Rate coefficient for diffusion flame, $\text{gm}/\text{cm}^3\text{-sec-atm}$
13--24	E12.5	KAP1	Rate coefficient #1 for AP flame, $\text{gm}/\text{cm}^3\text{-sec-atm}$
25--36	E12.5	KAP2	Rate coefficient #2 for AP flame, $\text{gm}/\text{cm}^3\text{-sec-atm}$
37--48	E12.5	XN1	Reaction order constant for diffusion flame
49--60	E12.5	XN2	Reaction order constant #1 for AP flame
61--72	E12.5	XN3	Reaction order constant #2 for AP flame
73--80	--	--	Not read - may be used to identify card



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CARD 8: DATA CARD

NO. REQUIRED: One card per run for NJOB=1

FUNCTION: Specify thermal properties and flame height

FORMAT: (6E12.5)

Column	Format	Variable	Description
1--12	E12.5	CSUBP	Specific heat of flame, cal/gm-deg K
13--24	E12.5	XLAMB	Gas conductivity, cal/cm-sec-deg K
25--36	E12.5	GAMMA	Gaseous diffusivity, cm ² /sec
37--48	E12.5	AFH	Flame height factor
49--60	E12.5	--	Not used
61--72	E12.5	--	Not used
73--80	--	--	Not read - may be used to identify card

CARD 9: DATA CARD
 NO. REQUIRED: One card per run NJOB=1
 FUNCTION: Specify propellant parameters
 FORMAT: (6E12.5)

Column	Format	Variable	Description
1--12	E12.5	TS	Initial estimate of burning surface temperature, deg K
13--24	E12.5	QS/LID	Heat from reaction of less than critical size AP with fuel, cal/gm
25--36	E12.5	QLIQ	Heat from liquid layer, cal/gm
37--48	E12.5	QAL	Aluminum heat absorption, cal/gm
49--60	E12.5	RHAL	Density of aluminum, gm/cm ³
61--72	E12.5	--	Not used
73--80	--	--	Not read - may be used to identify card



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CARD 10: DATA CARD

NO. REQUIRED: One card per run for NJOB=1 or NJOB=9

FUNCTION: Specify modality of AP particle size distribution

FORMAT: (12I6)

Column	Format	Variable	Description
1--6	I6	NN	Modality of AP particle size distribution
7--72	11I6	--	Not used
73--80	--	--	Not read - may be used to identify card



CARD 11: DATA CARD

NO. REQUIRED: One card for each two particle distribution
modes input for NJOB=1 or NJOB=9

FUNCTION: Describe AP particle size distribution

FORMAT: (6E12.5)

Column	Format	Variable	Description
1--12	E12.5	SIG(1)	Weight fraction of AP particles between DMIN(1) and DMAX(1)
13--24	E12.5	DMIN(1)	Minimum diameter of particles in this mode, microns
25--36	E12.5	DMAX(1)	Maximum diameter of particles in this mode, microns
37--48	E12.5	SIG(2)	Weight fraction of AP particles between DMIN(2) and DMAX(2)
49--60	E12.5	DMIN(2)	Minimum diameter of particles in this mode, microns
61--72	E12.5	DMAX(2)	Maximum diameter of particles in this mode, microns
73--80	--	--	Not read - may be used to identify card



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CARD 12: DATA CARD

NO. REQUIRED: One card per run for NJOB=1 or NJOB=9

FUNCTION: Specify weight fraction aluminum

FORMAT: (6E12.5)

Column	Format	Variable	Description
1--12	E12.5	EPS	Weight fraction of aluminum
13--72	E12.5	--	Not used
73--80	--	--	Not read - may be used to identify card



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CARD 13: DATA CARD

NO. REQUIRED: One card per run except for NJOB=105

FUNCTION: Specify print option

FORMAT: A4

Column	Format	Variable	Description
1--4	A4	IAN	Specifies printout option--YES blank in columns 1--4 implies printout only rate vs pressure. Any other entry will cause printout to include surface temperature, CRIT, n/Do, MØX, SØX, and XTAR vs pressure to be printed.



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CARD 14: TITLE CARD
NO. REQUIRED: One card per run
FUNCTION: Specify end of job or title of next run
FORMAT: (20A4)

Column	Format	Variable	Description
1--80	20A4	TIT1	79 columns (2--80) of alphanumeric data may be input to identify stacked run. END OF JOB in columns 1--10 implies end of job and computer will terminate normally.

NOTE: If stacked job is to be run, repeat input indicated for Cards 2 through 13 as required by NJOB value specified in Card 2.

RESULTS OBTAINED WITH EXAMPLE DATA

BURNING RATES - 7 MODAL AP - 86% SOLIDS - 0.3% ALUMINIUM

PROPELLANT DATA IS

WT PERCENT OXID = 85.7	MEAN DIAM OF 273.8 MICRON
WELD I = 0.0749	PROP DENSITY = 1.68
RINDER DENSITY = 0.91	OXID DENSITY = 1.95
QFUEL = 433.0	TF(DEG K) = 2908.
MOL WT = 33.00	PRI MOL WT = 42.00
DIFF PARAM = 0.5070E-05	RESS FUNCT = 0.1339
ST RAT = 2.83	PRI ST RAT = 2.90

OXIDIZER IGNITION AND BURNING DATA IS

CIGN = 190.0	POWIGN = 0.750	0.0
POWD = 0.8	LATENT HEAT =	

ACTIVATION ENERGIES AND RATE FACTORS ARE

EF = 16000.	FOX = 30000.
AF = 0.299E+03	AOX = 0.400E+08
ORDER, PF = 1.500	PT CON, PF = 0.300E+02
ORDER, LP = 1.800	PT CON, LP = 0.112E+01
ORDER, HP = 1.800	PT CON, HP = 0.213E+01

FLAME PROPERTIES ARE

OXID FLM TEMP = 1400.0	GAS CONDUCT = 0.00030
CP(AVE) = 0.3240	OFF = 700.9
QPF = 906.0	AV FLM HT FACT = 0.5000

PROPELLANT INITIAL TEMP IS 27.0 DEG CENTIGRADE

PT	ATMS	PT, PSIA	RR, CM/SFC	RR, IN/SFC	SURF T	CSIT
6.80	100.0	0.1732	0.0682	531.07	16.440	
8.16	120.0	0.1776	0.0689	532.14	14.228	
10.20	150.0	0.2007	0.0760	537.40	14.771	
13.61	200.0	0.2466	0.0971	546.64	12.563	
17.01	250.0	0.2928	0.1153	554.42	10.978	
20.41	300.0	0.3375	0.1329	560.97	9.841	
23.72	400.0	0.4309	0.1697	572.43	8.068	
27.01	500.0	0.5049	0.1988	580.04	7.082	
30.30	700.0	0.6357	0.2503	591.34	5.880	
33.59	1000.0	0.7926	0.3120	602.44	4.487	
36.88	1200.0	0.8770	0.3456	607.68	4.072	
40.17	1500.0	0.9854	0.3980	613.69	3.631	
43.46	2000.0	1.1287	0.4444	620.85	3.341	
46.75	2500.0	1.2445	0.4900	626.07	3.126	
50.04	3000.0	1.3430	0.5287	630.19	2.919	
53.33	4000.0	1.5156	0.5967	636.79		

PT	ATM	MDP	HDN	MCX	SNX
6.80	5000	-0.5000	0.5000	0.2813	0.8679
8.16	5000	-0.5000	0.5000	0.3285	0.8680
10.20	5000	-0.5000	0.5000	0.4019	0.8688
13.61	5000	-0.5000	0.5000	0.4779	0.8703
17.01	5000	-0.5000	0.5000	0.5514	0.8715
20.41	5000	-0.5000	0.5000	0.7048	0.8725
23.72	5000	-0.5000	0.5000	0.8263	0.8733
27.01	5000	-0.5000	0.5000	1.0414	0.8738
30.30	5000	-0.5000	0.5000	1.2996	0.8746
33.59	5000	-0.5000	0.5000	1.4400	0.8753
36.88	5000	-0.5000	0.5000	1.6172	0.8756
40.17	5000	-0.5000	0.5000	1.8534	0.8760
43.46	5000	-0.5000	0.5000	2.0443	0.8764
46.75	5000	-0.5000	0.5000	2.2069	0.8768
50.04	5000	-0.5000	0.5000	2.4910	0.8770
53.33	5000	-0.5000	0.5000		0.8772

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PT, PSIA	RP, IN/SEC	XTAR PD	XTAR PF	XTAR AP	XTAR D
100.0	0.0682	40.27	5.47	79.65	2.57
120.0	0.0699	40.94	4.27	58.82	2.60
150.0	0.0790	44.10	3.45	44.55	2.73
200.0	0.0971	50.31	2.76	32.67	2.98
250.0	0.1153	56.47	2.34	26.00	3.25
300.0	0.1329	62.32	2.05	21.61	3.51
400.0	0.1698	27.54	1.70	16.46	4.23
500.0	0.1988	31.12	1.43	12.91	4.78
700.0	0.2503	37.26	1.08	8.88	5.76
1000.0	0.3120	44.34	0.79	5.83	6.93
1200.0	0.3156	48.07	0.67	4.65	7.55
1500.0	0.3880	52.67	0.54	3.50	8.34
2000.0	0.4444	58.64	0.40	2.39	9.37
2500.0	0.4899	63.33	0.31	1.76	10.19
3000.0	0.5287	67.24	0.26	1.37	10.89
4000.0	0.5967	74.83	0.19	0.92	12.20



Combustion modeling studies will be continued during FY 1975. These further studies will be directed primarily toward addition of a mathematical treatment for heterogeneous catalysis of burning rate to the multiple-flame model.

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APPENDIX I

EM 72-09 ADVANCEMENT OF COMPREHENSIVE COMBUSTION MODELING

EM 73-05 SOLID PROPELLANT COMBUSTION MODELING

EM 72-09

ADVANCEMENT OF COMPREHENSIVE
COMBUSTION MODELING

By

G. D. Sammons

Presented to the JANNAF Interagency Propulsion Committee
9th JANNAF Combustion Meeting, held 11--15 September
1972 at U.S. Naval Postgraduate School, Monterey, California

ROCKETDYNE
North American Rockwell Corporation
Solid Rocket Division
McGregor, Texas

3 October 1972

I-1/R-4827

ADVANCEMENT OF COMPREHENSIVE COMBUSTION MODELING

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INTRODUCTION

Studies in many laboratories over the past 15 years on the mechanism of combustion of composite solid propellants have provided enough information that it has been possible recently to approach the goal of a truly comprehensive and practical mathematical combustion model. This paper is a progress report covering the first five months of effort under AFOSR Contract F44620-72-C-0046 with this goal as its aim.

After the pioneering effort of Prof. C. E. Hermance,¹ Beckstead, Derr and Price² advanced this type of modeling by introduction of their multiple-flame model. The purpose of the current work is to advance another step forward in comprehensive modeling.

In both of the earlier models, researchers found that a relatively large amount of condensed phase or surface reaction was necessary. This is entirely consistent with a large volume of experimental evidence gathered in recent years.^{3,4,5,6} A concept of critical particle size for ammonium perchlorate (AP) was presented recently³ that allows the actual calculation of condensed phase heat release. This theory is based on the concept that a critical particle size exists for AP such that all particles beneath this size are consumed in condensed phase reaction.

MATHEMATICAL TECHNIQUE

The critical particle size is arrived at by calculating at a specific pressure the thermal wave penetration into the solid phase sufficient to cause a very fast condensed phase reaction. Initially in this study, a simple limiting thermal gradient was calculated by dividing the burn rate by the propellant thermal diffusivity and multiplying by the difference between surface temperature and a temperature at which the rate of condensed phase reaction becomes rapid enough to occur in the residence time available.

Figure 1 shows the surface energy balance incorporating the critical particle size model. The symbols M_{ox} and S_{ox} are defined as the mass flux and burning surface of supercritical oxidizer. M_p is the mass flux of fuel binder plus subcritical oxidizer. Delta is the weight fraction of this interstitial propellant that is consumed in condensed phase reaction and is calculated based on stoichiometry considerations.

The flame heights are calculated by the Burke-Schuman treatment as modified for short flames by Beckstead.² A planned improvement in this calculation is to use more terms of the series solution. Use of the first term gives only a rough approximation.⁷

Equations actually used in the computer program are presented in

Fig. 2. The first is an equation for surface temperature that is derived from the surface energy balance using mass balance equations. The coefficient γ is the weight fraction of supercritical oxidizer in the propellant. The computer program iterates on surface

temperature with an estimated value of critical particle size and after convergence a critical size is calculated. The surface temperature is then recalculated if the initial and calculated critical particle sizes are different. This doubly iterative process is continued until convergence of critical particle size is obtained within 0.01 micrometers. The equations for the unit heat release in the primary and final flame are also shown in Fig. 2. They also include the calculation of condensed phase heat release and the coefficient δ .

$$\begin{array}{c}
 \begin{array}{l} \text{ENERGY TO RAISE} \\ \text{PROPELLANT TO } T_s \end{array} + \begin{array}{l} \text{ENERGY TO VAPORIZE} \\ \text{OXIDIZER} \end{array} + \begin{array}{l} \text{ENERGY TO VAPORIZE} \\ \text{FUEL} \end{array} + \begin{array}{l} \text{ENERGY FROM} \\ \text{CONDENSED PHASE} \end{array} \\
 m_t c_p (T_s - T_0) + m_{ox} \frac{S_{ox}}{S_0} Q_L + (1 - \delta) m_p \frac{S_p}{S_0} Q_f + \delta m_p \frac{S_p}{S_0} Q_s \\
 \begin{array}{l} \text{ENERGY FROM PRIMARY} \\ \text{DIFFUSION FLAME} \end{array} + \begin{array}{l} \text{ENERGY FROM AP FLAME} \end{array} + \begin{array}{l} \text{ENERGY FROM FINAL} \\ \text{DIFFUSION FLAME} \end{array} \\
 + \beta_F Q_{PF} m_t \exp(-\xi_{PF}^*) + (1 - \beta_F) m_{ox} \frac{S_{ox}}{S_0} \left[Q_{AP} \exp(-\xi_{AP}^*) + Q_{FF} \exp(-\xi_T^*) \right]
 \end{array}$$

Figure 1. Critical Particle Size Model Energy Balance

$$\begin{array}{c}
 \text{SURFACE TEMPERATURE} \\
 T_s = T_0 + \frac{\gamma}{C_p} Q_L + \frac{(1 - \delta)(1 - \gamma)}{C_p} Q_f + \frac{\delta(1 - \gamma)}{C_p} Q_s + \\
 \frac{\beta_F Q_{PF}}{C_p} \exp(-\xi_{PF}^*) + (1 - \beta_F) \frac{\gamma}{C_p} \left[Q_{AP} \exp(-\xi_{AP}^*) + \right. \\
 \left. Q_{FF} \exp(-\xi_T^*) \right] \\
 \text{PRIMARY FLAME} \\
 Q_{PF} = C_p (T_f - T_0) + \gamma Q_L + (1 - \delta)(1 - \gamma) Q_f + \delta(1 - \gamma) Q_s \\
 \text{FINAL FLAME} \\
 Q_{FF} = \frac{C_p}{\gamma} \left[(T_f - T_0) + \gamma (T_{AP} - T_0) \right] + \frac{(1 - \delta)(1 - \gamma)}{\gamma} Q_f + \frac{\delta(1 - \gamma)}{\gamma} Q_s
 \end{array}$$

Figure 2. Equations Used in Computer Program

COMPUTER PROGRAM

There are several reasons that a time share computer was used for this work. One is speed of turnover; for instance, 15 or 20 turnovers are obtained within 30 minutes as opposed to one or two a day with conventional hardware. It allows direct communication with a large, fast computer and the editing software is extremely versatile. Additionally, it provides a way for an engineer not versed in computer technology to easily run a complex program with varying inputs. It is hoped that this program will eventually be a tool for engineers and chemists.

Figure 3 shows two types of input that are most commonly used. There are many other optional inputs what can be used if desired. The input on the left uses a data file called FLEXI to input about 30 ingredient parameters. For this option a description of oxidizer must be typed in, which includes modality and weight fraction and minimum and maximum particle size for each mode. At this point either output can be asked for or any single parameter can be changed; for instance, in this example the unit heat

release in the condensed phase was changed. Only the information after each question mark is typed, as input all the rest is output by the computer.

RUN

NRCOMB 14:53 NR T/S JULY 21, 1972

NJOB, IPL0T, IPLT
? 1,0,0

TITLE LENGTH, IDENTIFY THE RUN
? 02TEST

IS DATA FILE TO BE USED ? YES

FILE NAME ? FLEX1

MODALITY OF OXIDIZER ? 5

SIG(J), DMIN(J), DMAX(J)
? .21, 230, 450,
? .35, 150, 210,
? .12, 75, 142,
? .25-6, 15.4, 62.2,
? .06, 3.8, 8.9

NRCOMB 08:47 NR T/S AUG. 09, 1972

NJOB, IPL0T, IPLT
? 11,1,0

FILE NAME ? FLEX1

NJOB, IPL0T, IPLT
? 4,0,0

NJOB, IPL0T, IPLT
? 10,1,0

QSOLID= ? 750

NJOB, IPL0T, IPLT
? 10,1,0

Figure 3. Computer Printout of Theoretical Data for CTPB Propellant

The input on the right of Fig. 3 is a minimum input where all data are entered by the computer. Again, if any one parameter change is desired it can be input as was done with QSOLID in the other input. This is the input that is used for the study of parametric variations.

The simplest form of output is shown in Fig. 4. Only burn rate pressure and critical particle size are given. Particle size is in micrometers. If no subcritical AP is calculated, the critical particle size column does not appear. Additional data can be obtained without any recalculations simply by inputting the proper index. Some of the tables of parameters are shown in Fig. 5 through 8. Figure 5 lists the coefficients used in the surface temperature and other equations shown in Fig. 2. The parameters SIGC and SIGSC are the weight fractions of subcritical and supercritical AP, respectively. The

RATES ONLY ? YES		
PT, PSIA	BR IN/SEC	CRIT
100.0	0.1799	10.000
120.0	0.1929	9.635
150.0	0.2081	9.208
200.0	0.2247	8.789
250.0	0.2353	8.522
300.0	0.2369	8.522
400.0	0.2521	8.168
500.0	0.2603	7.948
700.0	0.2832	7.395
1000.0	0.3336	6.465
1200.0	0.3710	5.955
1500.0	0.4289	5.280
2000.0	0.5246	4.457
2500.0	0.6171	3.887
3000.0	0.7066	3.470
4000.0	0.8685	2.899
NJOB, IPL0T, IPLT ? 7,0,0		
IX= ? 3		
NJOB, IPL0T, IPLT ? 100,0,0		

Figure 4. Continuation of Printout

sum of these is always one. Figure 6 and 7 show the calculated contributions to surface temperature in degrees Kelvin. The oxidizer and fuel vaporization are negative contributions. Figure 8 gives the flame heights in micrometers. The computer time of 30.5 seconds shown in this figure is the total time for about twice the output given in Fig. 5 through 8.

PT, PSIA	BR, IN/SEC	BETAF	DELTA	SIGC	SIGSC	GAMMA	CRIT
100.0	0.1799	1.0000	0.266	0.060	0.940	0.790	10.000
120.0	0.1929	1.0000	0.261	0.058	0.942	0.791	9.635
150.0	0.2081	1.0000	0.252	0.056	0.944	0.793	9.208
200.0	0.2247	1.0000	0.243	0.053	0.947	0.795	8.789
250.0	0.2353	1.0000	0.236	0.052	0.948	0.797	8.522
300.0	0.2369	0.8090	0.236	0.052	0.948	0.797	8.522
400.0	0.2521	0.5028	0.228	0.049	0.951	0.799	8.168
500.0	0.2603	0.3444	0.222	0.048	0.952	0.800	7.948
700.0	0.2832	0.2007	0.207	0.044	0.956	0.803	7.395
1000.0	0.3336	0.1209	0.176	0.036	0.964	0.810	6.465
1200.0	0.3710	0.0952	0.157	0.031	0.969	0.814	5.955
1500.0	0.4289	0.0734	0.127	0.025	0.975	0.819	5.280
2000.0	0.5246	0.0548	0.081	0.015	0.985	0.827	4.457
2500.0	0.6171	0.0456	0.041	0.007	0.993	0.834	3.887
3000.0	0.7066	0.0407	0.005	0.001	0.999	0.839	3.470
4000.0	0.8685	0.0247	0.000	0.000	1.000	0.840	2.899

NJOB, IPL0T, IPLT
 ? 7.0,0

 IX= ? 2

 NJOB, IPL0T, IPLT
 ? 100,0,0

Figure 5. Continuation of Printout

PT, PSIA	BR, IN/SEC	OXID VAP	FUEL VAP	CP HEAT	CRIT
100.0	0.1799	0.0	0.2	104.9	10.000
120.0	0.1929	0.0	0.2	102.2	9.635
150.0	0.2081	0.0	0.2	97.8	9.208
200.0	0.2247	0.0	0.2	93.2	8.789
250.0	0.2353	0.0	0.2	90.1	8.522
300.0	0.2369	0.0	0.2	90.1	8.522
400.0	0.2521	0.0	0.2	85.9	8.168
500.0	0.2603	0.0	0.2	83.3	7.948
700.0	0.2832	0.0	0.2	76.1	7.395
1000.0	0.3336	0.0	0.2	62.9	6.465
1200.0	0.3710	0.0	0.2	54.8	5.955
1500.0	0.4289	0.0	0.2	42.9	5.280
2000.0	0.5246	0.0	0.2	26.2	4.457
2500.0	0.6171	0.0	0.2	12.7	3.887
3000.0	0.7066	0.0	0.2	1.5	3.470
4000.0	0.8685	0.0	0.2	0.0	2.899

Figure 6. Continuation of Printout

Figure 9 shows the sigmoid distribution curve usually obtained with commercial oxidizer. From this curve it is easy to see that the use of 50 percent point does not give a true representation of particle size. To improve realism in oxidizer input, a spline fit was made to the sigmoid curve and the data input as a multimodal oxidizer. The curve in Fig. 9 was input as four modes. The oxidizer handling subroutine separates the modes into supercritical and subcritical particle sizes and will divide a single mode if necessary.

PT, PSIA	BR, IN/SEC	PF HEAT	APF HEAT	FF HEAT	CRIT
100.0	0.1799	432.9	0.0	0.0	10.000
120.0	0.1929	441.4	0.0	0.0	9.635
150.0	0.2081	452.5	0.0	0.0	9.208
200.0	0.2247	464.5	0.0	0.0	8.789
250.0	0.2353	472.5	0.0	0.0	8.522
300.0	0.2369	472.2	2.3	0.1	8.522
400.0	0.2521	461.0	22.2	0.8	8.168
500.0	0.2603	419.4	67.9	1.8	7.948
700.0	0.2832	316.9	182.0	2.6	7.395
1000.0	0.3336	218.4	305.1	1.0	6.465
1200.0	0.3710	179.3	359.4	0.3	5.955
1500.0	0.4289	143.4	416.4	0.1	5.280
2000.0	0.5246	111.1	478.5	0.0	4.457
2500.0	0.6171	94.4	519.6	0.0	3.887
3000.0	0.7066	85.5	549.0	0.0	3.470
4000.0	0.8685	53.1	597.9	0.0	2.899

NJOB, IPL0T, IPLT
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IX= ? 1

NJOB, IPL0T, IPLT
? 100.0,0

Figure 7. Continuation of Printout

PT, PSIA	BR, IN/SEC	XTAR PD	XTAR PF	XTAR AP	XTAR D
100.00	0.1799	11.79	14.16	205.99	25.53
120.00	0.1929	12.41	11.54	162.44	27.22
150.00	0.2081	13.01	8.91	120.59	29.39
200.00	0.2247	13.76	6.25	80.57	32.12
250.00	0.2353	14.25	4.68	58.00	34.06
300.00	0.2369	14.59	3.59	42.93	34.82
400.00	0.2521	15.02	2.48	27.66	37.16
500.01	0.2603	15.11	1.83	19.18	38.29
700.00	0.2832	15.06	1.20	11.28	40.86
000.00	0.3336	14.86	0.83	6.82	46.27
200.00	0.3710	14.72	0.70	5.37	50.25
500.00	0.4289	14.26	0.58	4.07	56.47
2000.01	0.5246	13.25	0.46	2.88	66.87
2500.03	0.6171	12.08	0.39	2.22	77.16
3000.01	0.7066	10.83	0.34	1.81	87.34
4000.02	0.8685	12.40	0.27	1.29	104.33

NJOB, IPL0T, IPLT
? S

RUNNING TIME: 30.5 SECS I/O TIME : 18.4 SECS

READY
BYE

OFF AT 13:50

Figure 8. Continuation of Printout

RESULTS

The initial test of the computer program was made with the data of Bastress primarily because both Hermance and Beckstead used these data. It, therefore, provides a point of correlation between the models (Ref Fig. 10). The theoretical data from the critical particle size model are shown as points. Data for the 20-micron AP (monomodal, 70% loading) fits Bastress' data within experimental error. The fit is not as good with the 200-micron AP but it is a considerable improvement over Beckstead's last published results.⁵ One of the major factors making the 200-micron monomodal propellant a better fit was to use the entire oxidizer distribution curve as input, as

was described previously. No further work is planned with this propellant, as it is not one currently in wide use. All subsequent comparisons of theoretical data will be with production or development propellants.

Figure 11 shows the theoretical data obtained for an 84% AP-loaded propellant with a carboxy-terminated polybutadiene (CTPB) binder. Experimental data shown are for an 86% AP loading. This line would swing down, pivoting at high pressure if there were only an 84% loading. The fit of data is, therefore, much better than it appears to be in Fig. 11.

All experimental data in Fig. 10 and 11 are strand rates, which are not necessarily predictive of motor rates. In the future only motor rates will be used for correlation if at all possible.

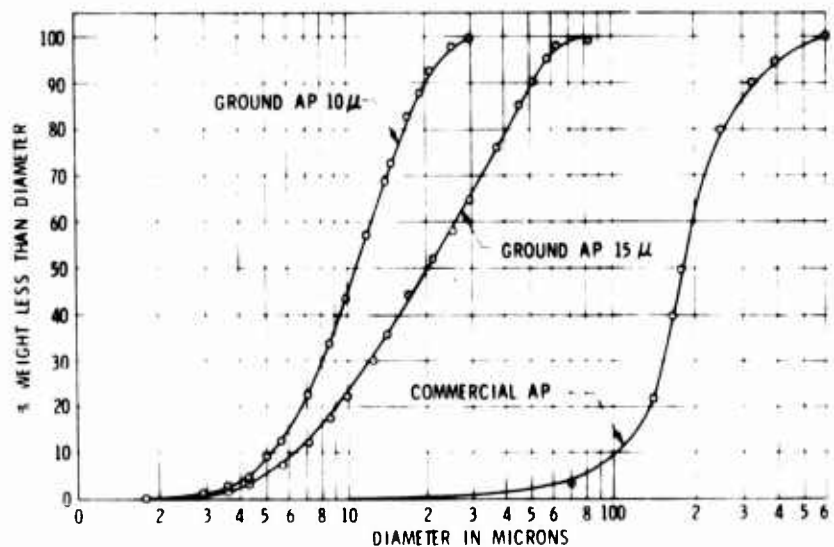


Figure 9. Particle Size Distribution of Ground and of Commercial 200-micron AP

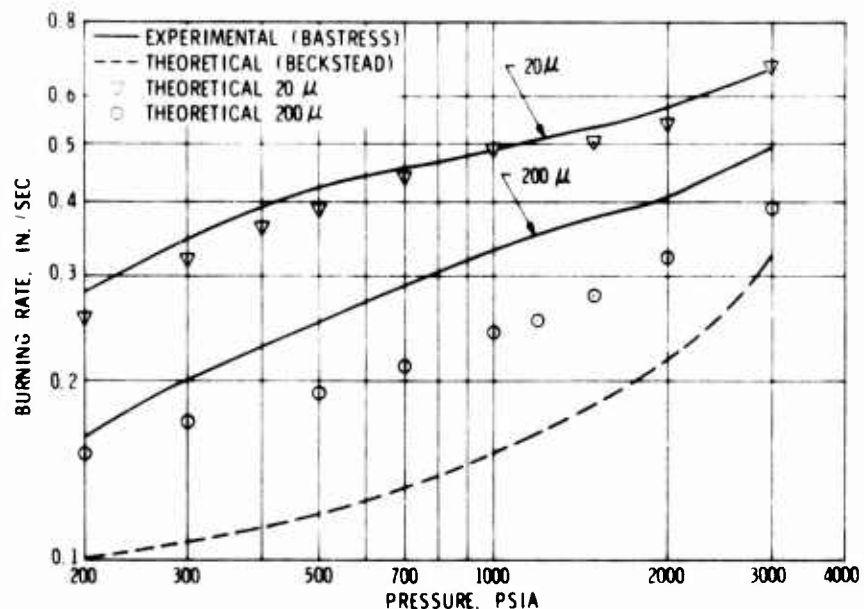


Figure 10. Correlation of Theoretical Burn Rate with Bastress Data for Polysulfide Propellants

CONCLUSIONS

Work completed thus far indicates that a comprehensive and predictive steady-state combustion model of composite solid propellants is possible. These models are complex but modern computing techniques make these models easy to use and study. It is our philosophy in this study to be realistic and include as much known phenomenology of solid propellant combustion as possible but to avoid unnecessary complexity. It is also our purpose to program this model so that it can become a tool for propellant chemists and engineers.

The next step in this program is to add aluminum. The equations have already been written and the treatment will be much the same as is used by Cohen, Derr and Price.⁸

Currently, gas phase conductivities are calculated using Chapman-Enskog theories and then input to the program. Later these calculations will be written into the program.

The flame height calculations will be improved by using more terms of the series solution.

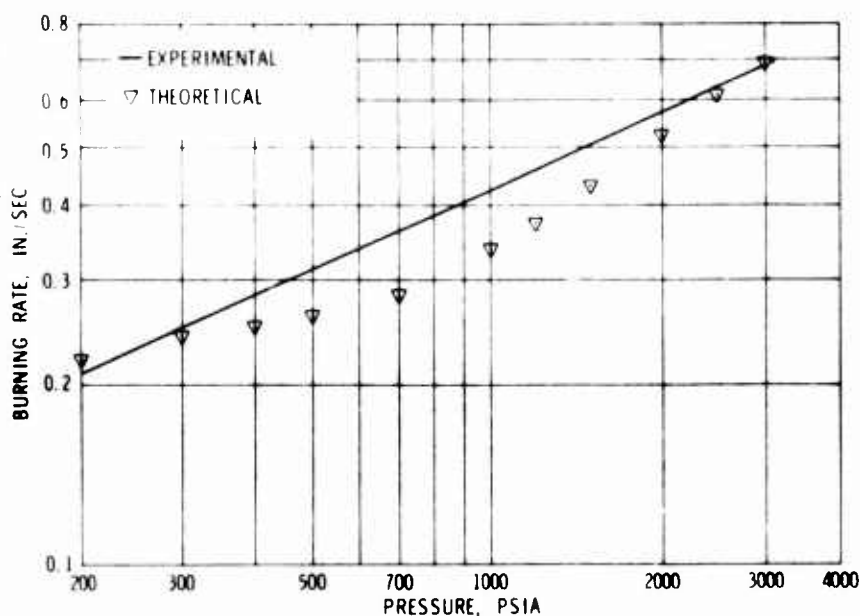


Figure 11. Theoretical Burning Rates for an 84 Percent Oxidizer Loaded Propellant with CTPB Binder

Parametric studies run continuously with this program are indicating that the exothermic liquid layer on AP during burning is very important. A treatment should be added based on the surface area of the burning supercritical oxidizer. This surface area is calculated within the program.

The effect of catalyst is to be added by changes in activation energies for the various chemical reactions treated by this model.

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NOMENCLATURE

T_s	- surface temperature
T_o	- initial propellant temperature
γ	- weight fraction of supercritical AP particles in total propellant
C_p	- specific heat of gas phase
Q_L	- latent heat of vaporization of AP
δ	- weight fraction of binder/critical AP particles consumed in condensed phase reaction
Q_f	- energy of fuel decomposition
Q_s	- energy of condensed phase heat release
β_F	- fraction of reactants reacting in primary flame
ξ_{AP}^* , ξ_{PF}^* , ξ_T	- nondimensional flame standoff distances for monopropellant flame, primary flame and total oxidizer flame

EM 73-05

SOLID PROPELLANT COMBUSTION MODELING

G. D. Sammons

August 1973

Paper presented at 10th JANNAF Combustion Meeting
6--10 August 1973, U.S. Naval War College, Newport,
Rhode Island (presentation made by B. M. Corley).

I-10/R-4827

SOLID PROPELLANT COMBUSTION MODELING

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ABSTRACT

This progress report covers the first 15 months of a continuing study on construction of a comprehensive mathematical model of composite solid propellant combustion, with emphasis on work during the past 12 months since reporting on the early efforts at the meeting last year.

The liquid layer believed to exist on burning ammonium perchlorate has been treated in a manner similar to that described last year. Depth of penetration of a thermal wave is calculated and this value is multiplied by the surface area of oxidizer on the burning propellant surface. The surface is calculated in the computer program for use in other equations. Total volume of the liquid layer derived in this manner is then used to calculate the thermal contribution to surface temperature.

Treatment of aluminum has been added, and the treatment of multimodal oxidizer has been improved. Most internal parameters have been thoroughly checked to verify that they have realistic values. Considerable time was spent on the Burke-Schumann flame height calculations. It has been found that at least seven terms of the series solution must be considered. The single first-term calculations that have been used in the past do not give a good assessment of flame height; the flame height is expressed implicitly in the final equation, and it was necessary to solve it by a Newton-Raphson iteration. Improvement in a number of input parameters is described. Gas phase conductivities were calculated using Chapman-Enskog theories with the Hirschfelder-Eucken corrector. The same theories were used to calculate diffusion coefficients. Stoichiometric ratios were calculated using more realistic pyrolysis species. A thermogravimetric analysis was made of a polybutadiene propellant binder and a statistical method was used to derive kinetic parameters from the thermograms. The method used was the Zsake modification of Doyle's method, which is probably the most sophisticated way of treating TGA data. Some other improvements in programming and correlation with actual propellant motor firings are shown and future plans are given.

INTRODUCTION

Work continued during the past year on the comprehensive modeling of composite solid propellants.* The model being developed is based on the Beckstead, Derr, Price multiflame model (1,2) and utilizes a critical particle size theory (3) to provide a means of calculating condensed phase heat release. A number of improvements have been made to the model and the computer program that was described at the meeting last year (4); one of

* This work is being supported by AFOSR under Contract F44620-72-C-0046.

the major improvements being the addition of a treatment of the liquid layer on burning ammonium perchlorate (AP). These improvements, an example experiment and future plans are described in the following paragraphs.

MATHEMATICAL MODEL AND IMPROVEMENTS

The most recent surface energy balance is shown on Fig. 1. The new terms (not shown last year) are the energy to melt the aluminum and the energy from the liquid layer. In this equation m_{ox} is the mass flux of interstitial propellant; or, more specifically, the binder plus the sub-critical AP. The term for condensed phase heat release based on the critical particle size theory is included. The critical particle size theory, stated simply, is that there exists for a given propellant and pressure a particle size where all smaller particles will be consumed in condensed phase reaction. The terms for aluminum fusion and liquid layer on AP are also present. The treatment of aluminum used is somewhat different from that used in the BDP model; with the methodology explained later.

ENERGY TO RAISE PROPELLANT TO T_s	ENERGY TO VAPORIZE OXIDIZER	ENERGY TO VAPORIZE FUEL	ENERGY FROM CONDENSED PHASE	ENERGY TO MELT AL
$m_i c_p (T_s - T_0)$	$- m_{ox} \frac{s_{ox}}{s_0} Q_L$	$- (1 - \delta) m_p \frac{s_p}{s_0} Q_i$	$+ \delta m_p \frac{s_p}{s_0} Q_s$	$- m_{AL} \frac{s_p}{s_0} Q_{AL}$
ENERGY FROM PRIMARY DIFFUSION FLAME ENERGY FROM AP FLAME ENERGY FROM FINAL DIFFUSION FLAME ENERGY FROM AP LIQUID LAYER				
$+ \beta_F Q_{PF} m_i \exp\left(-\dot{\xi}_{PF}\right) + (1 - \beta_F) m_{ox} \frac{s_{ox}}{s_0} \left[Q_{AP} \exp\left(\dot{\xi}_{AP}\right) + Q_{FF} \exp\left(\dot{\xi}_T\right) \right] + \omega m_{ox} \frac{s_{ox}}{s} Q_{LIQ}$				

Fig. 1. Critical Particle Size Model Energy Balance

Figure 2 shows first the current equation for surface temperature. This was derived from the energy equation using mass balance equations in the same manner as originally used by Beckstead (2). The following three equations are for the heat release in the primary, final, and AP flames, as denoted by the subscripts (PF, FF, AP).

Flame Heights. The Burke-Schumann equation modified for short flames is shown in Fig. 3. In the past a single term of this expression has been used but we have found that at least seven terms should be used. The equation is really not as complicated as it first appears; it is nothing more than is shown in the second equation. By adding the extra terms the equation has been made implicit in flame height but it is solved easily by a Newton-Raphson iteration. Convergence is obtained rapidly when the initial guess for flame height is taken as one-tenth the value obtained from a single-term calculation. This table is the numerical value of the first five terms; and each term is about half the value of the preceding term. An actual check of flame heights when different numbers of terms are used shows that at least seven terms must be used to get the flame within 1 micron.

SURFACE TEMPERATURE

$$T_s = T_0 - \frac{\gamma}{C_p} Q_L - \frac{(1-\delta)(1-\gamma-\epsilon)}{C_p} Q_f + \frac{\delta(1-\gamma-\epsilon)}{C_p} Q_s + \epsilon Q_{AL} + \frac{\beta_F Q_{PF}}{C_p} \exp\left(-\dot{\xi}_{PF}\right) +$$

$$(1-\beta_F) \frac{\gamma}{C_p} \left[Q_{AP} \exp\left(-\dot{\xi}_{AP}\right) + Q_{FF} \exp\left(-\dot{\xi}_T\right) \right] + \frac{\omega\gamma}{C_p} Q_{LIQ}$$

HEAT RELEASE

$$Q_{PF} = C_p (T_f - T_0) + \gamma Q_L + (1-\delta)(1-\gamma-\epsilon) Q_f - \delta(1-\gamma-\epsilon) Q_s + \epsilon Q_{AL} - \omega\gamma Q_{LIQ}$$

$$Q_{FF} = \frac{C_p}{\gamma} \left[(T_f - T_0) - \gamma(T_{AP} - T_0) \right] + \frac{(1-\delta)(1-\gamma-\epsilon)}{\gamma} Q_f - \frac{\delta(1-\gamma-\epsilon)}{\gamma} Q_s + \frac{\epsilon Q_{AL}}{\gamma} - \omega Q_{LIQ}$$

$$Q_{AP} = C_p (T_{AP} - T_0) + Q_L - \omega Q_{LIQ}$$

Fig. 2. Current Equations for Surface Temperature
Used in Computer Program

FLAME HEIGHTS

$$\frac{\nu - (1+\nu)C^2}{2(1+\nu)C} = \sum_{n=1}^{\infty} \frac{1}{\phi_n} \frac{J_1(C\phi_n)}{[J_0(\phi_n)]^2} \exp \left[- \frac{\left(\left[1 + (2\psi\phi_n)^2 \right]^2 - 1 \right)}{2\psi^2} \eta \right]$$

$$A = B_1 \exp(-C_1 \eta) + B_2 \exp(-C_2 \eta) + \dots B_n \exp(-C_n \eta)$$

SIZE OF TERMS

1	- 0.072
2	- 0.046
3	- 0.024
4	- 0.011
5	- 0.005

SOLVED BY NEWTON-RAPHSON ITERATION

$$\eta_{n+1} = \eta_n - \frac{f(x)}{f'(x)}$$

Fig. 3. Burke-Schumann Equation Modified
for Short Flames

A number of other improvements have been made to the computer program for this model. During the past year all parameters have been thoroughly checked, particularly those used internally and normally not listed. We found that some of the volume and weight fractions would become unrealistic; e.g., greater than one. When this occurred it caused discontinuities in the burn rate curve. This was remedied by setting boundaries on these parameters.

Treatment of the oxidizer particle size has been improved. The spline fit of the particle size distribution curve is still used. A normal bi- or tri-modal oxidizer blend will usually be split into 10 modes by this technique. Calculation of the h/D ratios is handled in a different manner than that described by Cohen, Derr, and Price (5) last year (Fig. 4). Each mode of supercritical oxidizer is split into 50 parts; the ignition delay term in the equation for h/D is calculated for each part, summed and averaged. Each ignition term is then multiplied by the weight fraction of the mode and summed with similar terms produced from each mode. Then h/D and S_{ox} are calculated.

SURFACE DIMENSIONALITY

$$\frac{h}{D} = \frac{1}{2} \left(1 \pm \sqrt{\frac{1}{3}} \right) \left(1 - \frac{r_{ox}}{r_f} \right) + r_{ox} \frac{K_o D^n}{p^m}$$

DIFFUSION COEFFICIENT

$$D_{AB} = \frac{C \sqrt{r^3 \left(\frac{1}{M_A} + \frac{1}{M_B} \right)}}{P \sigma_{AB}^2 \Omega_{AB}}$$

LIQUID LAYER TREATMENT

$$\omega = \frac{S_{ox}}{S} \frac{D_c}{\gamma} \frac{\rho_{ox}}{\rho_p}$$

Fig. 4. Calculations for h/D Ratios

Oxidizer/fuel stoichiometric ratios are different in the primary flame and the final flame. At temperatures such as are found at the binder surface it is known that polybutadiene depolymerizes (6) with the major specie produced being butadiene. This is considered the major diffusing specie in the primary flame, giving a stoichiometric ratio of 3.7. The Chapman-Enskog equation in the center of Fig. 4 was then used to calculate the diffusion coefficient for the primary flame. In the final flame it was assumed that hydrocarbon fragments were the major diffusing species; a stoichiometric ratio of 8.0 was used, along with a larger diffusion coefficient.

Liquid Layer. The AP liquid layer was not treated as a melt but as an exothermic layer. We have always assumed this layer to be a solution of

AP and perchloric acid. A thermal wave penetration is calculated in the same manner as for the critical particle size. This volume is converted to weight fraction of AP in the propellant that is available for exothermic surface reaction (Ref equation at bottom of Fig. 4).

EXPERIMENTAL RESULTS

The combustion model with the improvements noted above was applied to several smokeless propellants for which experimental data were available. Theoretical calculations for three of the propellants (based on carboxy-terminated polybutadiene binders) were made at two initial propellant temperatures and temperature sensitivities of burning rates were calculated. As shown in Table I, agreement of 77 F burn rates is good. Slopes of the burn rate curves are identical. The σ_k values were calculated using the one over one minus "n" relationship. The theoretical σ_k values are all low and should be two to three times higher; and we will look into this further.

Table I. Temperature Sensitivity

EXPERIMENTAL				THEORETICAL			
r at 1000 psi, in./sec	Slope	σ_p , %/deg F	σ_k , %/deg F	r at 1000 psi, in./sec	Slope	σ_p , %/deg F	σ_k , %/deg F
0.43	0.38	0.10	0.16	0.38	0.36	0.04	0.06
0.29	0.50	0.07	0.13	0.27	0.50	0.02	0.05
0.45	0.50	0.10	0.21	0.40	0.50	0.03	0.07

Figure 5 shows a burning rate vs pressure plot; the upper line represents a least squares fit to rocket motor firings; the lower line, the theoretical. This is a two cycle-by-two cycle log-log plot. The scales are the same as those widely used in industry to plot rocket motor rate; therefore, the data are presented in a realistic, practical manner. As noted last year we did not use strand data for correlative purposes since strand rates are not necessarily predictive of motor rates. Propellant used in the motor from which the plotted data were taken has a Butarez CTL-type binder and an 86% solids loading. The trimodal oxidizer is comprised of commercial 200- and 80-micron fractions and Majac-ground

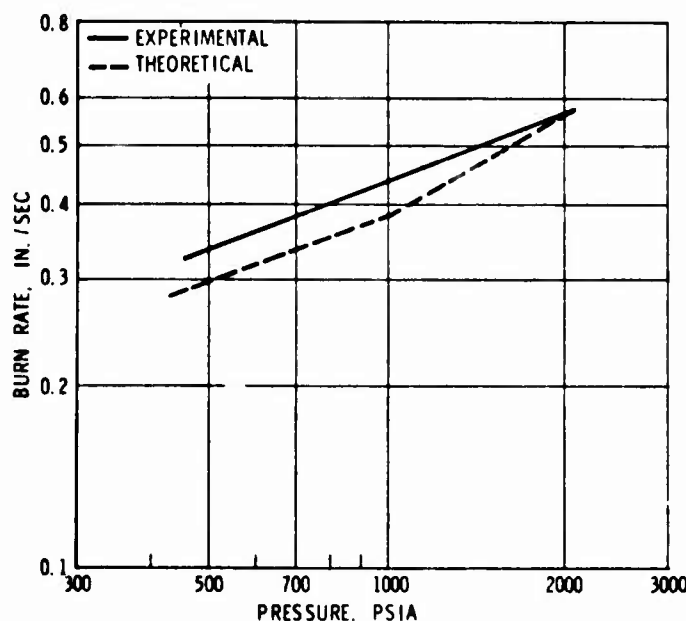


Fig. 5. Propellant with Butarez CTL Type with 86% Solids and Trimodal Oxidizer

10-micron AP at weight percent levels 35/26/25. The theoretical curve is identical in slope up to 1000 psi.

Comparable data with a propellant containing a trimodal mixture of 400-, 200-, and 80-micron AP at weight percent levels 51/20/15, respectively, are shown in Fig. 6. The break at 1000 psi is well verified by motor firings. No curve fitting was used to obtain these results; i.e., they were obtained on the first computer run. Fig. 7 shows data from a hydroxy-terminated polybutadiene (HTPB)-based propellant with a large amount of fine oxidizer; i.e., a trimodal blend of 200-, 80-, and 10-micron at weight percent levels of 31/15/40, respectively. Again, we are comparing motor data; and, although the burn rate is somewhat lower, the two lines have identical slopes. Data from a propellant that has a tetramodal oxidizer, i.e., 400-, 200-, 80-, and 10-micron at weight percent levels of 56/13/12/5, respectively, are shown in Fig. 8. We would like to emphasize again that no manipulation of parameters was required; the curve represents the first run made for the oxidizer blend with the current computer program.

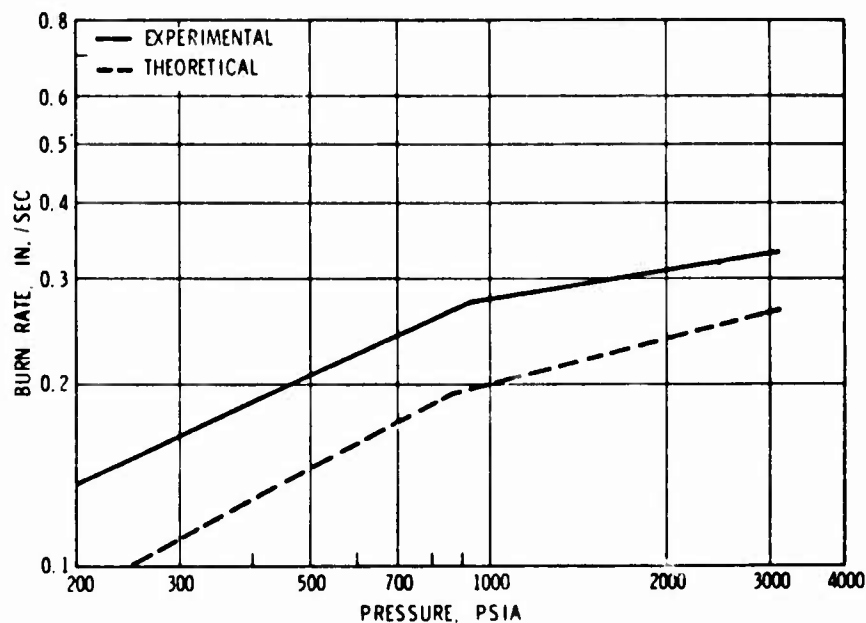


Fig. 6. Propellant with Butarez CTL Type Binder with 86% Solids and Trimodal Oxidizer

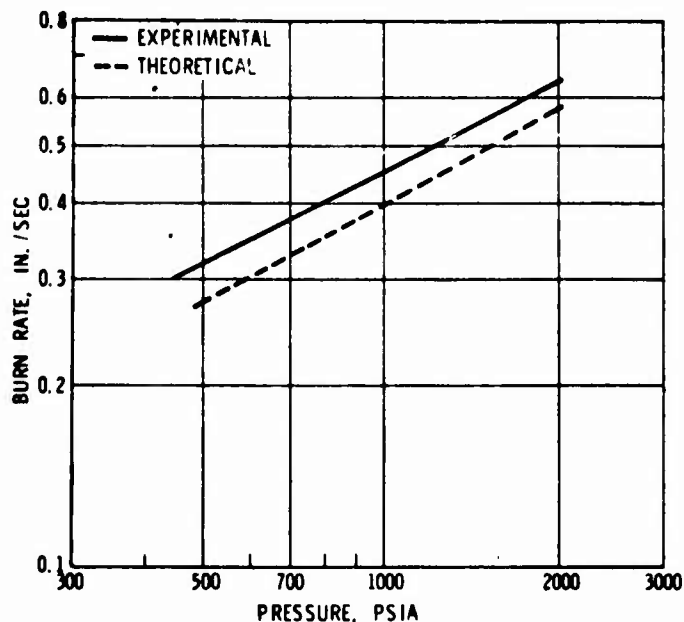


Fig. 7. Propellant with HTPB-Type Binder with 86% Solids and Trimodal Oxidizer

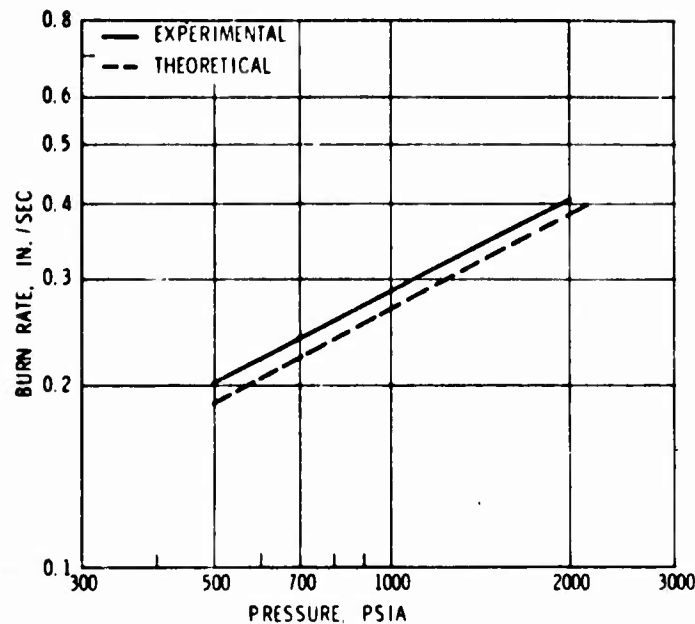


Fig. 8. Propellant with HTPB-Type Binder with 86% Solids and Trimodal Oxidizer

FUTURE PLANS

In the ensuing months, we plan to further study the possibilities of a two surface temperature model, add a treatment for the catalyst, and continue studying the effects of particle size. We will also establish possible maximum and minimum burn rates and continue to make improvements in the computer program.

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Rocketdyne Division
Rockwell International

APPENDIX II

COMPUTER PRINTOUT OF THE
PROGRAM NRComb

II-i


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48 CALL OUTPUT
49 IF(P-STOP)31,32,32
50 INT=1
51 CALL CONCAL
52 CONTINUE
53 GO TO 3
54 M1=2
55 CALL OUTPUT
56 GO TO 2
57 END
58 SUBROUTINE INPUT1
59
60 COMMON A1, A2, A3, AFH, C3P, ALFA, FHAL
61 COMMON AOX, RESS, AFH, BSQR, CSURP, DELDI, DZERN
62 COMMON FF, CIGN, CON1, CSURP, GAMMA, GMW, HDN
63 COMMON HOP, IJIM, IPLOT, K, KAP1, KAP2
64 COMMON KPF, FPS, MOX, MT, NP1, P
65 COMMON POWD, QFUEL, QPWIGN, PSTOP, QAP, QFF
66 COMMON QHOF, RHOP, QPF, RQN, RAP, PF
67 COMMON TAV, TF, PHOX, RQN, SOX, TAP
68 COMMON XLAMB, XN1, XN2, TIT1(20), TZERO, IS, XNUI
69 COMMON XSTAP, XSTARD, XN3, XSTPF, XNUP, ETAP
70 COMMON PMW, IPLT, GAM, XSTPD, DEL, XNUU, WAP
71 COMMON PRI, DR2, PR3, PR4, PR6, PR7
72 COMMON PRA
73 COMMON DMIN(20), DZERC1(20), DMAX(20), SLP(20), SIG(20)
74 COMMON NN, RHOP1, XNUSC, RQNI, RQNN
75 COMMON C7ERO, SIGC, CRIT, QSOLO
76 COMMON SIGSC, IX, LLL, RN, AH, C10, C15, C20
77 COMMON AFH1, ME, XSPD, XSAP, ISI
78 COMMON C25(20), NJOR, IJX
79 COMMON SII(20), QLIO
80 COMMON INI, M1
81 COMMON OAI
82
83 REAL KAP1, KAP2, KPF, MOX, MT
84 INTEGER AH
85
86 DATA XEND/'END'/'
87
88 ISI=1
89 READ (5,800) TIT1
90 FORMAT(20A4)
91 IF(TIT1(1).NE.XEND) GO TO 16
92 CALL EXIT
93 STOP
94
95 READ (5,100) NJOR, IPLOT, IPLT
96 FORMAT(12I6)
97 IF(NJOR.EQ.100)GO TO 13
98 IF(NJOR.EQ.105)GO TO 11
99 GO TO 12
100 M1 = 2
101 CALL OUTPUT
102 GO TO 1

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12      2      3      4      5      6      7      8      9      10      11      20      NJOB  
      READ (5,810) TZERO , ALFA , TF , GMW , XNU1 , DZERO  
      READ (5,810) QFUEL , RHOF , AF , EF , XNU2 , PMW  
      READ (5,810) QIGN , KAP1 , KAP2 , XN1 , XN2 , XN3  
      READ (5,810) KPF , KAPI , XLAMB , GAMMA , AFH  
      READ (5,810) CSUB , QSLID , QLIQ , QAL , PHAL  
      FORMAT(6E12.5)  
      GO TO (10,30),ISI  
20      CALL CXID(1)  
      GO TO 11  
3      READ (5,810) AF , ANX  
4      GO TO 11  
4      READ (5,810) QL  
5      GO TO 11  
5      READ (5,810) XNU1  
6      GO TO 11  
6      READ (5,810) AFH  
7      READ (5,810) PSTART,PSTOP  
8      READ (5,820) IX , TZERO  
820      FORMAT(16.5X,E12.5)  
9      GO TO 11  
9      READ (5,810) QFUEL  
      GO TO 11  
      CONTINUE  
13      READ (5,100) NN  
      READ (5,810) (SIG(J),DMIN(J),DMAX(J),J=1,NN)  
      CALL CXID(1)  
      READ (5,810) FPS  
      GO TO 11  
20      EPS=0.0  
      SIG(1)=.09394  
      SIG(2)=.24096  
      SIG(3)=.233  
      SIG(4)=.11039  
      SIG(5)=.09292  
      SIG(6)=.12269  
      SIG(7)=.05543  
      SIG(8)=.02919  
      SIG(9)=.0175  
      DMIN(1)=230.  
      DMIN(2)=140.  
      DMIN(3)=75.  
      DMIN(4)=35.  
      DMIN(5)=12.  
      DMIN(6)=4.  
      DMIN(7)=2.5
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10  REAL KAP1,KAP2,KPF,MNX,MT
11  DIMENSION RR(30),PT(30),ST(30),HDP1(30),HDN1(30),BRA(30)
12  DIMENSION PTA(30),MOXI(30),SOXI(30),XST1(30),XST2(30)
13  DIMENSION CIL(30)
14  DIMENSION XST3(30),XST4(30),RET1(30)
15  DIMENSION PTAL(30),RRAL(30)
16  REAL MDX1
17  INTEGER AH
18  DATA IYES/,YES,/,
19  GO TO (10,20),M1
20  RR(K)=R
21  WRITE(6,204) K,R,NN
22  WRITE(6,205) PAP
23  WRITE(6,205) RF
24  FFORMAT(5X,I3,5X,F12.5)
25  FFORMAT(10X,F7.3)
26  PT(K)=P
27  ST(K)=TS-273.2
28  HDPI(K)=HDP
29  HDN1(K)=HDN
30  BRA(K)=RR(K)/2.54
31  PTA(K)=PT(K)*14.7
32  MOXI(K)=MX
33  SOXI(K)=SOX
34  XST1(K)=XSTPD*10000.
35  XST2(K)=XSTPF*10000.
36  XST3(K)=XSTAP*10000.
37  XST4(K)=XSTARO*10000.
38  CIL(K)=CRIT
39  RET1(K)=RETAF
40  CALL ENERGY(1,0,0,0,0)
41  CALL FACTOR(1,0,0,0,0,0)
42  SOPSI=C20
43  CALL FLAHT(1,0,0,SOPSI,0)
44  CONTINUE
45  CONTINUE
46  IF(SIGC.GT.0.0)ISI=1
47  WRITE(6,210) AFH,AFH1
48  FFORMAT(10X,AFH=,E15.8,5X,AFH1=,E15.8)
49  KMAX=K
50  K=K+1
51  RETURN
52  IF(NJOR.EQ.105)GO TO 150
53  GO TO (13,16,17,18,19),IX
54  IF(PSSTART.EQ.PSTOP)GO TO 70
55  WRITE(6,101) TITI
56  GO TO 19
57  CONTINUE
58  GO TO 50
59  CONTINUE
60  CALL FLAHT(2,PTA,BRA,0,KMAX)
61  RETURN
62  XNUT=ALFA*100.
63  TZIP=TZERO-273.
64  IF(IPLT)6,11,6

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3      CALL ENERGY(2,PTA,BRA,CTL,KMAX)
      RETURN
16     CALL FACTOR(2,PTA,BRA,RET1,CTL,KMAX)
      RETURN
6      CONTINUE
      DO 4 K=1,KMAX
      PTA(K)=ALOG10(PTA(K))
      BRA(K)=ALOG10(BRA(K))
      WRITE(10)PTA(K),BRA(K)
      IF(IPLY.EQ.2) RETURN
      CONTINUE
      IF (IPLTOT) 15,15,40
15     CONTINUE
      WRITE(6,140) XNUT , DZERO
      WRITE(6,107) XNUT , DZERN
      WRITE(6,106) DELDI , RHDP
      WRITE(6,108) RHDF , TF
      WRITE(6,109) OFUEL , PMW
      WRITE(6,110) GMW , RESS
      WRITE(6,111) GAMMA , XNUP
      WRITE(6,112) XNUT , XNUP
      WRITE(6,145) CIGN , POWIGN
      WRITE(6,113) CIGN , OL
      WRITE(6,114) POWD , OL
      WRITE(6,154) EF , EQX
      WRITE(6,115) AF , AOX
      WRITE(6,116) XN1 , KDF
      WRITE(6,117) XN2 , KAP1
      WRITE(6,118) XN3 , KAP2
      WRITE(6,119) TAP , XLAMB
      WRITE(6,120) CSURP , QFF
      WRITE(6,121) QPF , AFH
      WRITE(6,122) TZIP
      WRITE(6,123)
      CONTINUE
      READ (5,134) IAN
      IF(IAN.EQ.1)YES) GO TO 70
      WRITE(6,124)
      DO 69 K=1,KMAX
      WRITE(6,125) PT(K), PTA(K), BRA(K), ST(K), CTL(K)
      CONTINUE
      WRITE(6,160)
      WRITE(6,129)
      DO 50 K=1,KMAX
      WRITE(6,126) PT(K),HDPI(K),MDN1(K),SOX1(K)
      CONTINUE
      WRITE(6,160)
      WRITE(6,127)

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CARD NO      INPUT LISTING      AUTOFLOW CHART SET -      COMBUSTION MODEL
****          ****          ****
310          DO 68 K=1,KMAX
311          WRITE(6,128)PTA(K), BPA(K),XST1(K),XST2(K),XST3(K),XST4(K)
312          GO TO 30
313          IF(151.EQ.0) GO TO 72
314          WRITE(6,130)
315          DO 71 K=1,KMAX
316          WRITE(6,131)PTA(K), BPA(K), CTL(K)
317          CONTINUE
318          GO TO 30
319          WRITE(6,132)
320          DO 73 K=1,KMAX
321          WRITE(6,133)PTA(K), BPA(K)
322          CONTINUE
323          GO TO 30
324          WRITE(6,151)
325          DO 152 K=1,KMAX
326          WRITE(6,153)HDN1(K),HDPI(K),SOX1(K)
327          CONTINUE
328          GO TO 30
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330          151
331          153
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131 FORMAT(F9.1,F14.4,F12.3)
132 FORMAT(IH1/2X'DT',PSTA*4X'HR IN/SEC'//)
133 FORMAT(F9.1,F14.4)
134 FORMAT(A4)
140 FORMAT(IH0/ 20X'PROPELLANT DATA IS'//)
145 FORMAT(IH0//13X'OXIDIZER IGNITION AND BURNING DATA IS'//)
154 FORMAT(IH0//12X'ACTIVATION ENERGIES AND RATE FACTORS ARE'//)
155 FORMAT(IH0//20X'FLAME PROPERTIES ARE'//)
160 FORMAT(IH0////)

C
RETURN
END
SUBROUTINE ENERGY(I,PTA,BRA,CTL,KMAX)

C
COMMON A1, A2, A3, AFH, C3P, ALFA, PHAL
COMMON A4P, C4P, CIGN, CON1, CSUBP, DELDI, DZERN
COMMON EF, EOX, IJIM, ETA, GAMMA, GMW, HDN
COMMON HDP, KPF, EPS, POWIGN, MX, NPI, KAP2
COMMON POWD, QFUEL, QHOP, PSTART, PSTOP, QAP, QFF
COMMON RHOF, TF, FHOX(20), RON, R, RQX, RF
COMMON TAV, XN1ARD, XN2, XN3, TZERO, TS, TAP
COMMON XLAMB, XSTAP, XN1, XN2, XN3, XN4, XN5, XN6, XN7
COMMON PMW, IPLT, GAM, PR3, DEL, XNUU, WAP
COMMON PR1, PR2, PR4, PR6, PR7
COMMON PRN(20), DZERN(20), DMAX(20), SLP(20), SIG(20)
COMMON NN, RHPI, XNUSC, RDN1, RONN
COMMON CZEPO, SIGC, CRIT, QSOLID
COMMON SIGSC, IX, LLL, RN, AH, C13, C15, C20
COMMON AFH1, ME, XSPD, XSAP, ISI
COMMON C25(20), NJOB, IJX
COMMON SII(20), QLIO
COMMON INI, MI
COMMON QAL

C
DIMENSION PA(30), PR(30), PC(30), PD(30), PE(30), PF(30)
DIMENSION PTA(30), BRA(30)
DIMENSION CTL(30), PG(30)

1
GO TO (1,2),I
PA(K)=PR1
PB(K)=PR2
PC(K)=PR3
PD(K)=PR4
PE(K)=PR6
PF(K)=PR7
PG(K)=PR8
RETURN
2
WRITE(6,I) KMAX
DO 4 J=1,KMAX
3
WRITE(6,P) PTA(J), BRA(J), PA(J), PB(J), PC(J), CTL(J)
4
CONTINUE

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COMMON ANX,
COMMON C40,
COMMON EF,
COMMON HDP,
COMMON KPF,
COMMON POWD,
COMMON QFUEL,
COMMON RHOF,
COMMON TAV,
COMMON XLAMB,
COMMON XSTAP,
COMMON PWH,
COMMON PR1,
COMMON PR8,
COMMON DMIN(20),
COMMON NN,RHOPI,
COMMON CZERO,
COMMON SIGSC,
COMMON AFH1,
COMMON C25(20),
COMMON SIT(20),
COMMON INI,M1,
COMMON QAL
BESS,
CIGN,
EUX,
IJIM,
EPS,
POWIGN,
QL,
RHOP,
TFI,
XNI,
XSTARD,
IPLT,
PR2,
PR9
DMIN(20),
NN,RHOPI,
CZERO,
SIGSC,
AFH1,
C25(20),
SIT(20),
INI,M1,
QAL
BETAF, HSQF, C3P
CON1, CSURP, DFLDI,
ETA, GAMMA, GMW,
IPLDT, K, KAPI,
MOX, MT, NPI,
PSTART, PSTCP, QAP,
RHOX, RPN, QAP,
TIT1(20), TZERO, SCX,
XSTPD, XN3, TS,
GAM, XSTPF, XNUJ,
PR3, DEL, XNUU,
PR4, PR6,
PR7
DZER0
HUN
KAP2
P
QFF
RF
TAP
XNU1
ETAP
WAP
PR7

REAL KAPI,KAP2,KPF,MOX,MT
DIMENSION FAC(10)
J=INI
IF (JJ)2,2,15
FAC(1)=1.36055
FAC(2)=1.7007
FAC(3)=1.04042
FAC(4)=2.7211
FAC(5)=2.4014
FAC(6)=3.4014
FAC(7)=4.75131
FAC(8)=6.90273
FAC(9)=8.16327
FAC(10)=10.20409
JJ=0
I=1
IF (JJ-1)15,20,20
XMULT=PSTART
JJ=1
I=8
IF (IJIM.EQ.0)GO TO 22
I=I-3
K=K-2
IJIM=0
IF (I-1)50,21,21
XMULT=XMULT*I*10.
I=2
P=XMULT*FAC(I)
I=I+1
LLL=1
RETURN
END

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SURFOUTLINE CONVR
EXTERNAL SURFAC
COMMON A1, A2, RESS, AF, BETAF, B500, AFH, C30, ALFA, RHAL
COMMON ANX, C4P, CIGN, CONI, CSHRP, GAMMA, KAP1, DZERP
COMMON FE, FDX, IJIM, IPLDT, K, NPI, P, OFF
COMMON HDP, KPE, EPS, POWIGN, PSTOP, OAB, RF
COMMON DWD, QHFL, RHOP, TF, TIT1(20), XN2, XNUP, ETAP
COMMON RHOF, TAV, XLAMB, XN1, XN2, XN3, XNUP, WAP
COMMON XSTAP, PMW, IDLT, GAM, PR3, PR4, PR7
COMMON PRI, PR2, PR3, PR4, PR5, PR6, PR7
COMMON PR9
COMMON DMIN(20), DZERO1(20), DMAX(20), SLP(20), SIG(20)
COMMON NN, RHAPI, XNUSC, RONI, RNN
COMMON CZERO, SIGC, CRIT, QSOLID
COMMON SIGSC, IX, LLL, RN, AH, C10, C15, C20
COMMON AFH1, ME, XSPD, XSAP, ISI
COMMON C25(20), NJOB, IJX
COMMON SIT(20), QLIQ
COMMON INI, M1
COMMON QAL
DIMENSION ARLST(2)
I7=0
I8=0
NE=1
XSPD=XSTPD
XSAP=XSTAP
ARLST(1)=CRIT
IF(ARS(1,-ACRIT/CRIT)-.01)2,2,3
IF(CRIT-ACRIT)4,2,5
I7=1
XLOW=ACRIT
GO TO 6
I8=1
XUP=AMIN1(ACRIT,50.)
IF(I7+I8-2)7,8,9
ARLST(1)=ACRIT
WRITE(5,100) NE, CRIT
FORMAT(10X,I5,5X,E15.8)
100 NE=NE+1
GO TO 1
ANS=0.02

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CARD NO

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622      N=15
623      WRITE(6,110) CRIT, XUP, XLOW
624      FORMAT(10X,5E16.8)
625      CRIT=CONVR3(SURFAC,ARLST,XUP,XLOW,ANS,N)
626      WRITE(6,120) CRIT
627      FORMAT(10X,CRIT=,E15.9)
628      CONTINUE
629      RETURN
630
631      END
632      FUNCTION ROB(XNAME,ARLST)
633      EXTERNAL XNAME
634      DIMENSION ARLST(2)
635      ROB=XNAME(ARLST)
636      RETURN
637      END
638      FUNCTION SURFAC(ARLST)
639
640      COMMON A1, A2, BSQ, AFH, C3P, ALFA, PHAL
641      COMMON AOX, RESS, RETAF, BSQ, C3P, AFH, C3P, ALFA, PHAL
642      COMMON C4P, CIGN, RETAF, BSQ, C3P, AFH, C3P, ALFA, PHAL
643      COMMON EF, ENX, ETA, CIGN, RETAF, BSQ, C3P, AFH, C3P, ALFA, PHAL
644      COMMON HDP, IJIM, IPILOT, K, GAMMA, KAP1, KAP2
645      COMMON KPF, FPS, POWIGN, MOX, PSTOP, QAP, P
646      COMMON POWD, QFUEL, QPF, RHOX, RAD, QFF
647      COMMON RHOF, PHOP, TITL(20), XN1, XN2, XN3, XNUP, XNUI
648      COMMON TAV, TF, XSTAD, XSTPF, XNUP, XNUI
649      COMMON XLAMB, XN1, XN2, XN3, XNUP, XNUI
650      COMMON XSTAD, XSTPF, XNUP, XNUI
651      COMMON PMW, IPILOT, GAM, DEL, PR4, PR6, PR7
652      COMMON PRI, PR2, PR3
653      COMMON PRR
654      COMMON DMIN(20), DZERO(20), DMAX(20), SLP(20), SIG(20)
655      COMMON NN, RHOP1, XNUSC, RONI, RONN
656      COMMON C2EPN, SIGC, CRIT, QSOLID
657      COMMON SIGSC, IX, LLL, RN, AH, C10, C15, C20
658      COMMON AFH1, ME, XSPD, XAP, ISI
659      COMMON C25(20), NJOR, IJX
660      COMMON SII(20), QLIQ
661      COMMON INI, M1
662      COMMON QAL
663
664      DIMENSION ARLST(2)
665      CRIT=ARLST(1)
666      CALL OXID(2)
667      CALL STAMPI
668      ACRTT=CRITL(TS,R)
669      SURFAC=APLST(1)-ACRTT
670      WRITE(6,101) CRIT = ,E15.8)
671      FORMAT(10X,CRIT = ,E15.8)

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RETURN
END
FUNCTION CONVR3 (XNAME,ARGLST,XUP,XLOW,ANS,N)
EXTERNAL XNAME
DIMENSION ARGLST(20)
RT=XLOW
XINC=(XUP-XLOW)*0.5
TOP=XLOW+XINC
IVAL=N
ARGLST(1)=RT
AROT=XNAME(ARGLST)
ARGLST(1)=XUP
ATOP=XNAME(ARGLST)
IF ((ATOP-ANS)*(ABOT-ANS))>0.31
IF (ABS(ATOP-ANS)-ABS(ABOT-ANS))>32.32,33
CONVR3=XUP
GO TO 99
CONVR3=XLOW
GO TO 99
ARGLST(1)=TOP
ATOP=XNAME(ARGLST)
CONTINUE
IF ((ATOP-ANS)*(ABOT-ANS))>1.40,2
XINC=XINC*0.5
TOP=ROT+XINC
IVAL=IVAL-1
IF (IVAL)<12,12,11
CONVR3=TOP
GO TO 99
ARGLST(1)=TOP
ATOP=XNAME(ARGLST)
GO TO 50
XINC=XINC*0.5
BOT=TOP
TOP=BOT+XINC
AROT=ATOP
IVAL=IVAL-1
IF (IVAL)<22,22,21
CONVR3=TOP
GO TO 99
ARGLST(1)=TOP
ATOP=XNAME(ARGLST)
GO TO 50
IF (ATOP-ANS)>42,41,42
CONVR3=TOP
GO TO 99
CONVR3=BOT
CONTINUE
RETURN
END
FUNCTION CRIL(TE,RE)
COMMON A1, A2, A3, A4, A5, A6, A7, A8, A9, A10, A11, A12, A13, A14, A15, A16, A17, A18, A19, A20, A21, A22, A23, A24, A25, A26, A27, A28, A29, A30, A31, A32, A33, A34, A35, A36, A37, A38, A39, A40, A41, A42, A43, A44, A45, A46, A47, A48, A49, A50, A51, A52, A53, A54, A55, A56, A57, A58, A59, A60, A61, A62, A63, A64, A65, A66, A67, A68, A69, A70, A71, A72, A73, A74, A75, A76, A77, A78, A79, A80, A81, A82, A83, A84, A85, A86, A87, A88, A89, A90, A91, A92, A93, A94, A95, A96, A97, A98, A99, A100, A101, A102, A103, A104, A105, A106, A107, A108, A109, A110, A111, A112, A113, A114, A115, A116, A117, A118, A119, A120, A121, A122, A123, A124, A125, A126, A127, A128, A129, A130, A131, A132, A133, A134, A135, A136, A137, A138, A139, A140, A141, A142, A143, A144, A145, A146, A147, A148, A149, A150, A151, A152, A153, A154, A155, A156, A157, A158, A159, A160, A161, A162, A163, A164, A165, A166, A167, A168, A169, A170, A171, A172, A173, A174, A175, A176, A177, A178, A179, A180, A181, A182, A183, A184, A185, A186, A187, A188, A189, A190, A191, A192, A193, A194, A195, A196, A197, A198, A199, A200, A201, A202, A203, A204, A205, A206, A207, A208, A209, A210, A211, A212, A213, A214, A215, A216, A217, A218, A219, A220, A221, A222, A223, A224, A225, A226, A227, A228, A229, A230, A231, A232, A233, A234, A235, A236, A237, A238, A239, A240, A241, A242, A243, A244, A245, A246, A247, A248, A249, A250, A251, A252, A253, A254, A255, A256, A257, A258, A259, A260, A261, A262, A263, A264, A265, A266, A267, A268, A269, A270, A271, A272, A273, A274, A275, A276, A277, A278, A279, A280, A281, A282, A283, A284, A285, A286, A287, A288, A289, A290, A291, A292, A293, A294, A295, A296, A297, A298, A299, A300, A301, A302, A303, A304, A305, A306, A307, A308, A309, A310, A311, A312, A313, A314, A315, A316, A317, A318, A319, A320, A321, A322, A323, A324, A325, A326, A327, A328, A329, A330, A331, A332, A333, A334, A335, A336, A337, A338, A339, A340, A341, A342, A343, A344, A345, A346, A347, A348, A349, A350, A351, A352, A353, A354, A355, A356, A357, A358, A359, A360, A361, A362, A363, A364, A365, A366, A367, A368, A369, A370, A371, A372, A373, A374, A375, A376, A377, A378, A379, A380, A381, A382, A383, A384, A385, A386, A387, A388, A389, A390, A391, A392, A393, A394, A395, A396, A397, A398, A399, A400, A401, A402, A403, A404, A405, A406, A407, A408, A409, A410, A411, A412, A413, A414, A415, A416, A417, A418, A419, A420, A421, A422, A423, A424, A425, A426, A427, A428, A429, A430, A431, A432, A433, A434, A435, A436, A437, A438, A439, A440, A441, A442, A443, A444, A445, A446, A447, A448, A449, A450, A451, A452, A453, A454, A455, A456, A457, A458, A459, A460, A461, A462, A463, A464, A465, A466, A467, A468, A469, A470, A471, A472, A473, A474, A475, A476, A477, A478, A479, A480, A481, A482, A483, A484, A485, A486, A487, A488, A489, A490, A491, A492, A493, A494, A495, A496, A497, A498, A499, A500, A501, A502, A503, A504, A505, A506, A507, A508, A509, A510, A511, A512, A513, A514, A515, A516, A517, A518, A519, A520, A521, A522, A523, A524, A525, A526, A527, A528, A529, A530, A531, A532, A533, A534, A535, A536, A537, A538, A539, A540, A541, A542, A543, A544, A545, A546, A547, A548, A549, A550, A551, A552, A553, A554, A555, A556, A557, A558, A559, A560, A561, A562, A563, A564, A565, A566, A567, A568, A569, A570, A571, A572, A573, A574, A575, A576, A577, A578, A579, A580, A581, A582, A583, A584, A585, A586, A587, A588, A589, A590, A591, A592, A593, A594, A595, A596, A597, A598, A599, A600, A601, A602, A603, A604, A605, A606, A607, A608, A609, A610, A611, A612, A613, A614, A615, A616, A617, A618, A619, A620, A621, A622, A623, A624, A625, A626, A627, A628, A629, A630, A631, A632, A633, A634, A635, A636, A637, A638, A639, A640, A641, A642, A643, A644, A645, A646, A647, A648, A649, A650, A651, A652, A653, A654, A655, A656, A657, A658, A659, A660, A661, A662, A663, A664, A665, A666, A667, A668, A669, A670, A671, A672, A673, A674, A675, A676, A677, A678, A679, A680, A681, A682, A683, A684, A685, A686, A687, A688, A689, A690, A691, A692, A693, A694, A695, A696, A697, A698, A699, A700, A701, A702, A703, A704, A705, A706, A707, A708, A709, A710, A711, A712, A713, A714, A715, A716, A717, A718, A719, A720, A721, A722, A723, A724, A725, A726, A727

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AF, AFH, C3P, ALFA,
BETA, BSQR, CSUBP, DELDI,
CONI, GAMMA, GMW,
ETA, PHAL
DZERN
HGN

COMMON	HDP.	IJIM.	IPLOT.	K.	KAP1.	KAP2			
COMMON	KPF.	EPS.	MOX,IGN.	MT.	NPI.	P			
COMMON	POWD.	POWIGN.	PSTART.	PSTOP.	OAP.	OFF			
COMMON	QFUEL.	QL.	QPF.	R.	RAP.	RF			
COMMON	RHOF.	RHQP.	RHOX.	RON.	SOX.	TAP			
COMMON	TAV.	TF.	TIT1(20).	TZERO.	TS				
COMMON	XLAMB.	XN1.	XN2.	XN3.	XNU.	XNU1			
COMMON	XSTAP.	XSTART.	XSTOP.	XSTPF.	XNUP.	ETAP			
COMMON	PMW.	IPLT.	GAM.	DEL.	XNUU.	WAP			
COMMON	PR1.	PR2.	PR3.	PR4.	PR6.	PR7			
COMMON	PR8.								
COMMON	DMIN(20).	DZERO1(20).	DMAX(20).	SLP(20).	SIG(20)				
COMMON	NN.	RHOP1.	XNUSC.	RON1.	RONN				
COMMON	CZERO.	SIGC.	CAIT.	QSOLID					
COMMON	SIGSC.	IX.	LLL.	RN.	AH.	C10.C15.C20			
COMMON	AFH1.	ME.	XSPD.	XSAP.	ISI				
COMMON	C25(20).	NJOB.	IJX						
COMMON	SII(20).	QLIQ							
COMMON	INI.	MI							
COMMON	QAL								
COMMON	DELL=TE-TZERO								
COMMON	RR=DELL*REF/0011								
COMMON	IF(TE.GT.723.)GO TO 5								
COMMON	CRITL=0.0								
COMMON	SIGSC=1.0								
COMMON	RETURN								
COMMON	CONTINUE								
COMMON	DFLLL=TE-673.								
COMMON	CPITL=DELIL/RR*10000.								
COMMON	RETURN								
COMMON	END								
COMMON	SURROUTINE OXID (N)								
COMMON	A.	A2.	AF.	BETAF.	BSQR.	AFH.	C3P	ALFA.	RHAL
COMMON	ACAP.	ACIGN.	RECONI.	CSURP.	DELDI.	DZERO			
COMMON	EF.	ENX.	ETA.	GAMMA.	GMW.	HDN			
COMMON	HDP.	IJIM.	IPLOT.	K.	KAP1.	KAP2			
COMMON	KPF.	EPS.	MOX.	MT.	NPI.	P			
COMMON	POWD.	POWIGN.	PSTART.	PSTOP.	OAP.	OFF			
COMMON	QFUEL.	QL.	QPF.	R.	RAP.	RF			
COMMON	RHOF.	RHQP.	RHOX.	RON.	SOX.	TAP			
COMMON	TAV.	TF.	TIT1(20).	TZERO.	TS				
COMMON	XLAMB.	XN1.	XN2.	XN3.	XNU.	XNU1			
COMMON	XSTAP.	XSTART.	XSTOP.	XSTPF.	XNUP.	ETAP			
COMMON	PMW.	IPLT.	GAM.	DEL.	XNUU.	WAP			
COMMON	PR1.	PR2.	PR3.	PR4.	PR6.	PR7			
COMMON	PR8.								
COMMON	DMIN(20).	DZERO1(20).	DMAX(20).	SLP(20).	SIG(20)				

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INPUT LISTING

AUTOFLOW CHART SET -

COMBUSTION MODEL

CARD NO

CONTENTS

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779 COMMON NN,RHOP1,XNUISC,RONI,RQNN
779 COMMON CZERO,SIGC,CRIT,QSNLIO
780 COMMON SIGC,IX,LLL,PN,AM,C10,C15,C20
781 COMMON AFH1,MF,XSPD,XSAP,ISI
782 COMMON C25(20),NJDB,IJX
783 COMMON SII(20),QLIQ
784 COMMON INI,M1
785 COMMON QAL
786
787 DIMENSION A(20),CC(20)
787 DIMENSION SI(20)
788 DO 3 J=1,NN
789 SI(J)=0.0
790 A(J)=0.0
791 CC(J)=0.0
792 CONTINUE
793 RQNN=0.0
794 DZERO=0.0
795 SIGC=0.0
796 SIGSC=0.0
797 DO 10 J=1,NN
798 NM=J
799 IF(CRIT.LE.0.01) GO TO 10
800 IF(DMIN(J).LE.CRIT-0.01) GO TO 16
801 CONTINUE
802 DO 15 J=1,NN
803 B=DMIN(J)
804 D=DMAX(J)
805 CALL PART(R,D)
806 RQNN=RON+SIG(J)*RONI
807 DZERO=DZERO+SIG(J)*DZERO1(J)
808 SIGC=0.0
809 SIGSC=1.0
810 RETURN
811 CONTINUE
812 NMM=N4-1
813 J=NM
814 IF(DMAX(J).GT.CRIT) GO TO 25
815 SIGC=SIGC+SIG(J)
816 WRITE(6,100) SIGC
817 FORMAT(10X,'ONE',E16.8)
818 J=J+1
819 IF(J.LE.NN) GO TO 31
820 GO TO 28
821 CR=ALOG(CRIT)
822 DMI=ALOG(DMIN(J))
823 DMA=ALOG(DMAX(J))
824 D7E=ALOG(DZERO1(J))
825 AT(J)=(CR-DMI)/SLP(J)
826 WRITE(6,101) SLP(J), A(J)
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COMMON C25(20),NJOB,IJX
COMMON SII(20),OLIQ
COMMON INI,M1
COMMON OAL
PAR=DMI
RONI=(DMI*0.001)**POWD
DELZ=(DMA-DMI)/10.
DO 10 J=1,10
PAR=PAR+DELZ
DZF=(PAR*0.001)**POWD
DZF=DZF/P**POWIGN
RONI=RONI+DZF
CONTINUE
RONI=RONI/11.
RETURN
END
SUBROUTINE STAMP1
EXTERNAL DONI
COMMON A1, A2, BESS,
COMMON ANX, CIGN,
COMMON C4P, EOX,
COMMON FF, IJM,
COMMON HDP, EPS,
COMMON KPF, POWIGN,
COMMON POWD, OL,
COMMON QFUL, RHCP,
COMMON RHDF, TF,
COMMON TAV, XN1,
COMMON XLAMB, XSTARD,
COMMON XSTAP, IPLT,
COMMON PMW, PR2,
COMMON PRI,
COMMON PR8
COMMON DMIN(20),DZERO1(20),DMAX(20),SLP(20),SIG(20)
COMMON NN,RHDP1,XNUSC,RCN1,RCNN
COMMON CZERO,SIGC,CPII,QSOLIQ
COMMON SIGSC,IX,LLL,RN,AH,C10,C15,C20
COMMON AFH1,ME,XSPD,XSAP,ISI
COMMON C25(20),NJOB,IJX
COMMON SII(20),OLIQ
COMMON INI,M1
COMMON OAL
DIMENSION AN(4)
DIMENSION ARG1ST(20)
REAL KAP1,KAP2,KPF,MOX,MT
REAL MOX70
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AFH, C2P, ALFA, H-HAL
AFJAF, BSQR, CSURP, DELDI, DZFRD
CON1, GAMMA, GMM, HDN
IPLT, K, KAPI, KAP2
MOX, MT, NOI, P
PSTART, PSTOP, QAP, OFF
OPF, RAP, RF
PHOX, SOX, TAP
TITI(20), TZERO, TS, XNUI
XN2, XN3, XNUP, XTAP
XSTAP, XNUU, WAP
GAM, DEL, XNUU, PR6, PR7
PR3, PR4, PR5, PR6, PR7
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INPUT LISTING

AUTOFLOW CHART SET -

COMBUSTION MODEL

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034 REAL*8 ARG,AN
035 GAM=ALFA*(1.-SIGC)
036 WF=(1.-EPS-ALFA)/(1.-EPS-GAM)
037 IF(WF.GT.1.0)WF=1.0
038 XNUU=1./(1.+RHOF*(1.-WF)/(WF*RHOX))
039 IF(XNUU.GT.1.0)XNUU=1.0
040 RHOFI=RHOF*XNUU/WF
041 IF(RHOPI.LT.RHOI)RHOFI=RHOF
042 XNUSC=1./(1.+RHOF*(1.-EPS-GAM)/(GAM*RHOPI))
043 IF(XNUSC.GT.1.0)XNUSC=1.0
044 DEL=1.11*ALFA*SIGC/(1.-EPS-GAM)
045 C0=1.11*INUF
046 RHOPE=RHOX*XNU/ALFA
047 DELD=1+EPS*RHOX/(GAM*RHOI)+RHOX*(1.-GAM-EPS)/(RHOPI*GAM)
048 IF(DELD.LT.1.0)DELD=1.0
049 DELDI=(3.141592/6.*DELD)*((1./3.)-SQRT(2./3.))
050 ASQR=DELDE*2/6.*((1.+SQRT(1.5)*DELD))
051 CON1=1./(1.+SQRT(1.5)*DELD)
052 C=XNUP-(1.+XNUP)*CON1*CON1
053 C=C/(2.*(1.+XNUP)*CON1)
054 C10=C
055 C11=XNU1-(1.+XNU1)*CON1*CON1
056 C11=C11/(2.*(1.+XNU1)*CON1)
057 ARG=3.33*CON1
058 IRR=1
059 CALL RESSEL(0.DO,ARG,AN)
060 BESS=AN(1)
061 DUM1=CON1*BESS*(1.+XNU1)/(XNU1-(1.+XNU1)*CON1**2)
062 IF(DUM1)20,22,24
063 20 ETA=ALOG(-1.293*DUM1)
064 22 ETA=0.0
065 24 GO TO 26
066 26 ETA=ALOG(3.215*DUM1)
067 DUM1=CON1*BESS*(1.+XNUP)/(XNUP-(1.+XNUP)*CON1**2)
068 IF(DUM1)30,32,34
069 30 ETAP=ALOG(-1.293*DUM1)
070 32 ETAP=0.0
071 34 GO TO 36
072 36 ETAP=ALOG(3.215*DUM1)
073 34 IRR=2
074 36 CONTINUE
075 CON2=GAM*TA*TA**0.75/42.06*GMW
076 C3=2.*CON2*ETA*AFHI
077 C4=(7.55*CON2)**2/BSQR
078 XNC=XN2
079 RATC=RHOPI*P
080 XMT=0.
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01501990
01502000

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51 17=0
    18=0
    ARGLS(1)=TS
    ARGLS(2)=C3
    ARGLS(3)=C4
    ARGLS(4)=RATC
    ARGLS(5)=XNC
    ARGLS(6)=C
    ARGLS(7)=C
    ARGLS(8)=CON2
    ARGLS(9)=C11
    ARGLS(10)=IHR
    XTS=TS-RHR(00N1,ARGLS)
    IF(ABS(1.-XTS/TS)-.001)60,60,61
    IF (TS-XTS)85,50,95
    17=1
    XLOW=XTS
    GO TO 97
85 18=1
    XD=AMIN1(XTS,1400.)
    IF (17+18-2)98,89,89
    ARGLS(1)=XTS
    GO TO 80
89 ANS=0.0001
    N=15
    XTS=CONVR2(00N1,ARGLS,XUP,XLOW,ANS,N)
    CONTINUE
80 R=MT/RHOP
82 WRITE(6,100)
    C 100
    FORMAT(10X,TWO)
    RETURN
END
SUBROUTINE BESSEL(X,Y,ANS)
DIMENSION ANS(4)
REAL*8 X,Y,ANS,Z,FZERO,THZERO,FONE,THONE
IF(X-3.D0)2,2,4
Z=X*X/9.
IF(X)20,20,30
ANS(1)=1.
ANS(2)=1.
GO TO 6
CONTINUE
ANS(1)=((((0.0021*Z-.0039444)*Z+.0444479)*Z-.3163866)*
&Z+1.2656208)*Z-2.2499957)*Z+1.
ANS(2)=.63662031*DLG(.5*X)*ANS(1)+((((-.00024846*Z+
&.00427916)*Z-.04261214)*Z+.25300117)*Z-.74350384)*Z+.60
&.359366)*Z+.36746691
GO TO 5
Z=3./X
FZERO=((((0.0014476*Z-.00072805)*Z+.00137237)*Z-.0000
&9512)*Z-.0055274)*Z-.77E-6)*Z+.79788456
THZERO=X+((((0.0013558*Z-.00029333)*Z-.00054125)*Z+.00
&262573)*Z-.00003954)*Z-.04166397)*Z-.78539816
ANS(1)=FZERO*DCDS(THZERO)/DSQRT(X)
ANS(2)=FZERO*DSIN(THZERO)/DSQRT(X)
IF(Y-3.D0)8,8,10
Y=Y*Y/9.

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40 IF(Y)40,40,50
ANS(3)=0.
ANS(4)=0.
GO TO 80
50 CONTINUE
ANS(3)=((((00001109*Z-.0003176)*Z+.00443319)*Z-.0395
64289)*Z+.21033573)*Z-.5649985)*Z+.5)*Y
ANS(4)=(.63662031*Y*DL0G(.5*Y)*ANS(3)+((((0027873*Z-
8.0400976)*Z+.3123951)*Z-1.3164327)*Z+.1682709)*Z+.2212
8091)*Z-.6364198)/Y
RETURN
90 Z=3./Y
10 FONE=((((-0020033*Z+.00113653)*Z-.00249511)*Z+.00017
8105)*Z+.0153667)*Z+1.56E-6)*Z+.79788456
THONE=Y+(((((-00029166*Z+.00079824)*Z+.00074348)*Z-.00
5637879)*Z+.00005650)*Z+.12499612)*Z-2.3561945
ANS(3)=FONE*DCOS(THONE)/DSQRT(Y)
ANS(4)=FONE*DSIN(THONE)/DSQRT(Y)
RETURN
END
FUNCTION BOB(XNAME,ARGLST)
EXTERNAL XNAME
DIMENSION ARGLST(20)
BOB=XNAME(ARGLST)
RETURN
END
FUNCTION CONVR2 (XNAME,ARGLST,XUP,XLOW,ANS,N)
EXTERNAL XNAME
DIMENSION ARGLST(20)
BOT=XLOW
XINC=(XUP-XLOW)/0.5
TOP=XLOW+XINC
IVAL=N
ARGLST(1)=BOT
ARGLST(2)=XNAME(ARGLST)
ARGLST(1)=XUP
ATOP=XNAME(ARGLST)
IF ((ATOP-ANS)*(ABOT-ANS))30,30,31
IF ((ARS(ATOP-ANS)-ARS(ABOT-ANS))32,32,33
CONVR2=XUP
GO TO 99
CONVR2=XLOW
GO TO 99
30 ARGLST(1)=TOP
ATOP=XNAME(ARGLST)
CONTINUE
IF ((ATOP-ANS)*(ABOT-ANS))11,40,2
XINC=XINC*.5
TOP=BOT+XINC
IVAL=IVAL-1

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CA-D N(1)

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12 IF (IVAL)12,12,11
COMMON C4P
GO TO 99
11 ARGLS(1)=TOP
ATOP=XNAME(ARGLS)
GO TO 50
2 XINC=XINC*0.5
RAT=TOP
TOP=BOT+XINC
ARGT=ATOP
IVAL=IVAL-1
IF (IVAL)22,22,21
22 CONV2=TOP
GO TO 99
21 ARGLS(1)=TOP
ATOP=XNAME(ARGLS)
GO TO 50
40 IF (ATOP-ANS)42,41,42
41 CONV2=TOP
GO TO 99
42 CONV2=BOT
CONTINUE
RETURN
END
FUNCTION DNI(ARGLS)
C

COMMON A1, A2, BESS,
COMMON ANX, C4P, CIGN,
COMMON EF, ENX, IJIM,
COMMON HDP, EPS, PNWIGN,
COMMON KDF, QDWD, QFUEL,
COMMON QHOF, RHOF, RHOP,
COMMON TAV, TF, TIT1(20),
COMMON XLAMB, XN1, XN2, XN3,
COMMON XSTAB, XSTAR, XSTPD,
COMMON PMW, IPLT, PR2,
COMMON PR1, PR3, PR4,
COMMON PR5, PR6, PR7,
COMMON PR8,
COMMON DMIN(20), DZERR(20), DMAX(20), SLP(20), SIG(20)
COMMON NN, RHOP, XNUSC, RONI, RONY
COMMON C7ERO, SIGC, CRIF, QSOLID
COMMON SIGSC, IX, LLL, RN, AM, C10, C15, C20
COMMON AFH1, ME, XSPD, XSAP, ISI
COMMON C25(20), NJOB, IJX
COMMON SIT(20), QLIO
COMMON INI, MI
COMMON QAL
AFH, C3P, ALFA, PHAL
BETA, HSQR, CSUBP, DELDI,
CONI, GAMMA, GMW, HDN
ETA, K, KAP, KAP2
IPLOT, MT, NPI, P
MOX, PSTART, PSTOP, QAP, QFF
QPF, R, RAP, RF
RHOF, RHOP, SOX, TAP
TIT1(20), TZERN, TS
XN1, XN2, XN3, XNUP, XNUJ
XSTAB, XSTPD, XNUJ
GAM, DEL, XNUJ, WAP
PR3, PR4, PR6, PR7

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PEAL KAP1,KAP2,KPF,MUX,MT
PEAL MUX1,MUX2
INTERGR AH
DIMENSION A(20),B(20),O(20)
XSPF=XSTPF
XSPD=XSTPD
TS=ARGLIST(1)
C3=ARGLIST(3)
C4=ARGLIST(4)
RATC=ARGLIST(5)
XNC=ARGLIST(6)
C=ARGLIST(7)
C5P=ARGLIST(8)
C11=ARGLIST(9)
C2P=ARGLIST(10)
IAB=GAMMA*PMW*TS**.75/82.06
C15=C2P
C3P=2.*C2P*ETAP*AFH1
C4P=(7.56*C2P)**2/HSQR
MUX=AHX*EXP(-EQU/(1.0*7*TS))
SQPSI=C2P*C2P/(HSQR*MUX*MUX)
C20=SQPSI
CALL SXCL(TS,SOX)
OMEG=SOX*CRIT*1.E-4*RHOMX/(GAM*RHOP)
QAP=CSURP*(TAP-TZERQ)+QL-OMEG*QLIQ
QFF=CSURP*(TF-TZERQ)-GAM*(TAP-TZERQ)/(GAM*(1.-DEL))*
&(1.-EPS-GAM)/GAM*QFUEL-DEL*(1.-EPS-GAM)/GAM*QSOLID
&+EPS*QAL/GAM-OMEG*GAM*QLIQ
&QPF=CSURP*(TF-TZERQ)+GAM*QL*(1.-EPS-GAM)*(1.-DEL)*QFUEL-DEL
&(1.-EPS-GAM)*QSOLID
&+EPS*QAL-OMEG*QLIQ
&MT=MUX*SOX/GAM
XSTPF=MT/(KPF*P**XN1)
DUM2=1.+C4P/(MUX**2)
IF(DUM2.GT.1.0)GO TO 122
DUM3=0.5*C4P/(MUX**2)
GO TO 124
DUM3=SQRT(DUM2)-1.
XSTPD=C3P/(MUX*DUM3)
CALL FLAVF(SQPSI,A,IPB,0)
CALL NEWRAF(XSTPD,A,B,C,D,C2P,XSTAR)
XSTPD=XSTAR*AFH1
CONTINUE
XSTAR=MUX/(RATC*P**XNC)
BETAF=AFH1*(XSTAR-XSTPF)/XSTPD
IF(BETAF.GE.1.0) BETAF=1.0
IF(BETAF.LE.0.0) BETAF=0.0
CONTINUE
SQPSI=C5P*(HSQR*MUX*MUX)
DUM2=1.+C4/(MUX**2)
IF(DUM2-1.0)GO TO 10,11
DUM3=SQRT(DUM2)-1.
GO TO 91
DUM3=0.5*C4/(MUX**2)
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01 XSTARD=C2/(MNX#DIUM3)
IR=IBR
IRR=2
CALL FLAME(SJPSI,A,IRH,D)
CALL NEWPAF(XSTAFD,A,R,C11,D,C5P,XSTA)
XSTARD=XSTA*.05
CONTINUE
130 IRR=IR
ZAP=CSURP*MNX*XSTAP/XLAMR
95 WRITE(6,200) ZAP
C 200 FORMAT(10X,'ZAP=',F15.8)
96 ZAP=ZAP+CSURP*MNX*XSTARD/XLAMH
C 210 WRITE(6,210) ZAT
C 210 FORMAT(10X,'ZAT=',F15.8)
C ZPF=XSTPD+XSTPF
IF(RETAF.LT.1.0) ZPF=XSTAP*AFH1+XSTIPE
ZPF=3ETAF*(XSTPD+XSTPF)+(1.-RETAF)*(XSTAP*AFH1+XSTIPE)
ZPF=CSURP*MT/XLAMR*7PF
C 220 WRITE(6,220) ZPF
C 220 FORMAT(10X,'FOR B<1 ZPF=',F15.8)
PR1=GAM*QL/CSURP
PR2=(1.-EPS-DEL)*(1.-EPS-GAM)/CSURP*QFUEL
PR3=DEL*(1.-EPS-GAM)/CSURP*QSLID
IF(ZPF.LE.174.5) GO TO 230
PR4 = 0.0
GO TO 235
230 PR4=RETAF*EXP(-ZPF)
235 PR5=(1.-RTAF)*GAM/CSURP
IF(ZAP.LE.174.5) GO TO 240
PR6 = 0.0
GO TO 245
240 PR6=PR5*QAP*EXP(-ZAP)
245 IF(ZAT.LE.174.5) GO TO 250
PR7 = 0.0
GO TO 255
250 PR7=PR5*QFF*EXP(-ZAT)
255 PR8=OMEG*GAM*QLI/CSURP
PR9=EPS*(1.-GAM-EPS)*QAL
XTS=TZERO-PR1-PR2+PR3+PR4+PR5+PR6+PR7+PR8-PR9
XTS=AMAX1(XTS,500.)
DNI=ARGLS(1)-XTS
RETURN
100 END
SUBROUTINE SOXCL(TSI,SOXI)
C
COMMON AI, A2, AESS, AFH, C3P, ALFA, RHAL
COMMON C4P, CIGN, CON1, RSQR, CSUBP, OFLDI, DZERO
COMMON EFF, EOX, ETA, GAMMA, K, KAP1, KAP2
COMMON HDP, IJIM, IPLDT, K

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INPUT LISTING

AUTOFLOW CHART SET -

COMBUSTION MODEL

CARD NO

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COMMON KDF, EPS, POWIGN, MDX, PSTART, MT, NPI, P OFF
COMMON POWD, POWIGN, PSTOP, R, RAP, RF
COMMON QFUEL, QL, RHP, RHOX, T7ERO, TS, XNU1
COMMON PHOF, TAV, XLAMB, XN1, XSTAP, GAM, PR3, XNU2, ETAP
COMMON XLAMB, XN1, XSTAP, GAM, PR3, XNU2, ETAP
COMMON PMW, IPLT, PR2, PR4, XNUU, WAP
COMMON PRI, PR1, PR2, PR3, PR4, PR6, PR7
COMMON PR8
COMMON DM1V(20), DZER01(20), DMAX(20), SLP(20), SIG(20)
COMMON NN, ZHNP1, XNUISC, RQNI, RQNN
COMMON CZERO, SIGC, CRIT, QSOLID
COMMON SIGSC, IX, LLL, RN, AH, C10, C15, C20
COMMON AFH1, XE, XSPD, XSAP, ISI
COMMON C25(20), NJOR, IJX
COMMON SIT(20), QLIO
COMMON INI, MI
COMMON QAL
C
REAL KAP1, KAP2, KPF, MDX, MT
RF=RHOF#AF#EXP(-FF/(1.987*TS1))
KAP=MDX/RHOX
RQNN=RQNN#RAP#CIGN
HDP=A1*(1.-RAP/RF)+RQNN
HON=A2*(1.-RAP/RF)+RQNN
IF(HDP.GT.0.5)HDP=0.5
IF(HDN.LT.-0.5)HDP=-0.5
IF(HDN.GT.0.5)HON=0.5
IF(HDN.LT.-0.5)HDN=-0.5
HDP2=HDP#HDP
HON2=HON#HON
SX1=3.*XNUISC*(HDP2+HDN2+1./3.)/(1.+3.*XNUISC
S*(HDP2+HDN2))
RETURN
END
SUBROUTINE NEWRAE(XI,A,B,C,D,C2P,XSTAR)
COMMON A1, A2, RESS, AF, AF, BSQR, AFH, C3P, ALFA, PHAL
COMMON C4P, CIGN, CON1, HETAF, CSURP, DELDI, DZER0
COMMON EF, EX, IJIM, ETA, GAMMA, GW, HON
COMMON HDP, HDP, IJIM, IPLT, K, KAP1, KAP2
COMMON KPF, EPS, MOX, MT, NPI, P
COMMON POWD, POWIGN, PSTART, QAP, P OFF
COMMON QFUEL, QL, RHP, RHOX, RQNI, RAP, RF
COMMON PHOF, TAV, XLAMB, XN1, XSTAP, TS, XNU1
COMMON XLAMB, XN1, XSTAP, XN2, XSTPD, XNU2, XNU, XNUU, ETAP

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COMMON DMW, IPLT, GAM, DEL, XNUU, WAP  
COMMON PFI, PR2, PR6, PL7  
COMMON PRF  
COMMON DMIN(20), DZERO1(20), DMAX(20), SLP(20), SIG(20)  
COMMON NA, RHPI, XNUSC, RONI, RGN  
COMMON C7F4C, SIGC, CRTT, QSOLIT  
COMMON SIGSC, IX, LLL, RN, AH, C10, C15, C20  
COMMON AFH1, ME, XSPD, XSAP, ISI  
COMMON C25(20), NJDR, IJX  
COMMON STI(20), QLIO  
COMMON INI, MI  
COMMON QAL  
C  
REAL MDX  
DIMENSION A(20), R(20), D(20)  
WRITE(6,100) C  
C 100 FORMAT(10X, C = ,E15.8)  
C 101 WRITE(6,101) XI  
C 101 FORMAT(10X, XI = ,F15.8)  
XI=XI*CDP/(MDX*RSQR*AFH1)  
PD=.01E-4*CDP/(MDX*RSQR*AFH1)  
I=0  
NNN=7  
XI=XI*.5  
SUM2=0.0  
SUM1=0.0  
DO 5 J=1,NNN  
SUM3=A(J)/EXP(D(J)*XI)  
IF(SUM3.LT.1.0E-4)GO TO 6  
C 102 WRITE(6,102) SUM3  
C 102 FORMAT(10X, SUM3 = ,F15.8)  
SUM1=SUM1+SUM3  
SUM2=SUM2-A(J)*D(J)/EXP(D(J)*XI)  
CONTINUE  
XI=XI-(SUM1-C)/SUM2  
XI=XI-XI-XI  
XI=XI  
IF(AHS(XIX).LT.EPI)GO TO 6  
I=I+1  
XSTAR=XI*MDX*RSQR/C2P  
C 104 WRITE(6,104) I, XSTAR  
C 104 FORMAT(10X, I5, , = ,F15.8)  
IF(I.LT.10)GO TO 1  
GO TO 10  
XSTAR=XI*MDX*RSQR/C2P  
CONTINUE  
RETURN  
END  
SUBROUTINE FLAME(SQPSI,A,IBB,D)  
C  
COMMON A1, A2, BESS, AF, AF, RSQR, AFH, C3P, ALFA, RHAL  
COMMON ANX, ANX, BESS, BE, AF, RSQR, CSUBP, DELDI, DZERO  
COMMON C4P, C4P, CIGN, CIGN, ETA, GAMMA, GMW, HDN  
COMMON EF, EF, FOX, IJIM, IJIM, K, KAPI, KAP2  
COMMON HDP, HDP, IJIM, IJIM, K, KAPI, KAP2  
COMMON KPF, KPF, EPS, EPS, MT, MT, NPI, NPI, P
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COMMON POWN, POWN, PSTART, PSTOP, QAP, QFF
COMMON QFUEL, QFUEL, QPF, QPF, QAP, QFF
COMMON TAV, TAV, TIT1(20), TIT1(20), R, R, R
COMMON XLAMB, XLAMB, XN1, XN2, XN3, XN4, XN5, XN6, XN7
COMMON XSTAP, XSTAP, XSTARD, XSTPD, XSTPF, XSTP, XSTP, XSTP
COMMON PWT, PWT, IPLT, IPLT, PR3, PR3, PR3, PR3
COMMON PRI, PRI, PR2, PR2, PR3, PR3, PR3, PR3
COMMON PRA, PRA, PRA, PRA, PRA, PRA, PRA, PRA
COMMON PWIN(20), PWIN(20), DMAX(20), SLP(20), SIG(20)
COMMON NN, NN, NN, NN, NN, NN, NN, NN
COMMON C7ER, C7ER, C7ER, C7ER, C7ER, C7ER, C7ER, C7ER
COMMON SIGSC, SIGSC, SIGSC, SIGSC, SIGSC, SIGSC, SIGSC, SIGSC
COMMON AFH1, AFH1, AFH1, AFH1, AFH1, AFH1, AFH1, AFH1
COMMON C25(20), C25(20), NJOR, NJOR, NJOR, NJOR, NJOR, NJOR
COMMON SII(20), SII(20), OLIO, OLIO, OLIO, OLIO, OLIO, OLIO
COMMON INI, INI, INI, INI, INI, INI, INI, INI
COMMON QAL, QAL, QAL, QAL, QAL, QAL, QAL, QAL
C
DIMENSION A(20), D(20)
DIMENSION ANN(4)
REAL*8 ANN, ROOT, AUG, NSQPSI, CB, R
DSQPSI=SQPSI
DO 5 J=1,9
  ROOT=ROOT*(J)
  AUG=ROOT*CON1
  CALL BESSEL(ROOT, AUG, ANN)
  IF (IAB.FO.2) GO TO 10
  A(J)=ANN(3)/(ANN(1)*ROOT)
  A(J)=-A(J)
  GO TO 15
10 15
  A(J)=ANN(3)/(ANN(1)*ANN(1)*ROOT)
  B=1.00+4.00*DSQPSI*ROOT*ROOT
  IF (B.GT.1.01) GO TO 20
  IF (IJB.NE.1) GO TO 35
  CB=DSQRT(B)-1.00
  IJB=0
  CB=CB/(ROOT*ROOT*NSQPSI)
  R=CB*ROOT*ROOT*NSQPSI
  GO TO 30
20 30
  B=DSQRT(B)-1.00
  D(J)=B/(2.00*DSQPSI)
  C25(J)=D(J)
  CONTINUE
  WRITE(6,100)A
  WRITE(6,100)B
  FORMAT(10X,F15.4)
C 100
  RETURN
END
FUNCTION BROTT(NI)

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02200100
02200110
02200120
02200130
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02200150
02200160
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02200180
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02200200
02200210
02200220
02200230
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02200250
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02200270
02200280
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02200300
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02200370
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02200390
02200400
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02200500
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02200560
02200570
02300010

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03/12/74

INPUT LISTING

AUTOFLOW CHART SET -

COMPISTION MODEL

CARD NO

CONTENTS

1402	GO TO (1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17),NI	02300020
1403	RETURN=3.8317	02300020
1404	RETURN	02300020
1405	RETURN=7.0156	02300020
1406	RETURN	02300020
1407	RETURN=10.1735	02300020
1408	RETURN	02300020
1409	RETURN=13.3237	02300020
1410	RETURN	02300020
1411	RETURN=16.4705	02300020
1412	RETURN	02300020
1413	RETURN=19.625	02300020
1414	RETURN	02300020
1415	RETURN=22.7765	02300020
1416	RETURN	02300020
1417	RETURN=25.9181	02300020
1418	RETURN	02300020
1419	RETURN=29.0597	02300020
1420	RETURN	02300020
1421	RETURN=32.2013	02300020
1422	RETURN	02300020
1423	RETURN=33.7573	02300020
1424	RETURN	02300020
1425	RETURN=35.3428	02300020
1426	RETURN	02300020
1427	RETURN=36.9002	02300020
1428	RETURN	02300020
1429	RETURN=38.4845	02300020
1430	RETURN	02300020
1431	RETURN=40.0428	02300020
1432	RETURN	02300020
1433	RETURN=41.6261	02300020
1434	RETURN	02300020
1435	RETURN=43.1853	02300020
1436	RETURN	02300020
1437	END	02300020