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Adaptations to MICROPEP and ROCKET to allow performance evaluation of multiple grain and/or airbreathing motors

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THESIS

ADAPTATIONS TO "MICROPEP" AND "ROCKET" TO ALLOW PERFORMANCE EVALUATION OF MULTIPLE GRAIN AND/OR AIRBREATHING MOTORS

by

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June 1993

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19 Abstract

Adaptations to two existing rocket motor performance computer programs were made. MICROPEP, a FORTRAN program developed by the Naval Air Warfare Center Weapons Division, China Lake, California to evaluate theoretical performance of various propellants in rocket motors, was modified to allow calculation of the effects of non-ideal expansion and mixed shifting equilibrium-frozen composition nozzle flow on performance. In addition, the ability to handle vitiated air heaters, to calculate combustion chamber Mach number and to calculate stagnation pressure for airbreathing engines was incorporated.

ROCKET, an internal ballistics program written by the Lockheed Corporation and modified by the Naval Air Warfare Center Weapons Division, was updated to purge the program of unused code and allow input of performance losses in both the combustor and nozzle flows.

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Adaptations to "MICROPEP" and "ROCKET" to Allow Performance Evaluation of Multiple Grain and/or Airbreathing Motors

by

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Submitted in partial fulfillment
of the requirements for the degree of

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from the

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ABSTRACT

Adaptations to two existing rocket motor performance computer programs were made. MICROPEP, a FORTRAN program developed by the Naval Air Warfare Center Weapons Division, China Lake, California to evaluate theoretical performance of various propellants in rocket motors, was modified to allow calculation of the effects of non-ideal expansion and mixed shifting equilibirium-frozen composition nozzle flow on performance. In addition, the ability to handle vitiated air heaters, to calculate combustion chamber Mach number and to calculate stagnation pressure for airbreathing engines was incorporated.

ROCKET, an internal ballistics program written by the Lockheed Corporation and modified by the Naval Air Warfare Center Weapons Division, was updated to purge the program of unused code and allow input of performance losses in both the combustor and nozzle flows.

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I. INTRODUCTION

Many factors enter into the design of a rocket motor (required thrust, specific impulse, operation envelope, susceptibility, safety, cost, flight time, weight, size). It is the job of the engineer to take the requirements and to choose a propellant and motor configuration that best meet these needs. In order to do this, predictions or calculation of performance must be made. Because of the high cost of test firing, it is desirable to use computer codes that will accurately predict the theoretical performance of various compounds, thereby eliminating the need to conduct test firings on all but a few acceptable candidates. In recent years these codes have become available in PC versions.

After the propellants are selected, performance losses must be estimated. With these losses, actual pressure-time and thrust-time profiles and specific impulse can be calculated for various solid propellant grain designs and or ramjet configurations.

It was the intent of this investigation to modify two existing computer programs to cover a wider variety of performance and design problems. Specifically, MICROPEP [Ref. 1] (an equilibrium thermochemical "propellant evaluation code" developed by the Naval Air Warfare Center

Weapons Division, China Lake, California) was to be modified to allow input of the desired nozzle area ratio and ambient pressure so that effects of non-ideal expansion could be accurately calculated. The performance value for shifting equilibrium flow to the nozzle throat and frozen composition flow afterwards is often a good approximation to the actual flow and was also to be incorporated.

In order to incorporate airbreathing applications the inlet air temperature and composition, motor static pressure, nozzle contraction ratio and nozzle discharge coefficient are required inputs. With these inputs the program should calculate the vitiated air composition and heat of formation as well as the actual combustion chamber Mach number and stagnation pressure and the associated performance values.

ROCKET is a solid propellant rocket motor internal ballistics code orginally developed by the Lockheed corporation. With igniter, propellant and insulation geometry and physical porperties input it calculates the pressure-time and thrust-time profiles. Some of the subroutines have never worked correctly and many unused portions of the code had never been removed. Documentation for the code is also very limited. Modifications to ROCKET were required to make the nozzle loss coefficient an input, to update the basic algorithm so that multiple grains could be burned at the same time and to incorporate plot routines for the pressure-time and thrust-time profiles. Average thrust, average pressure and total impulse were also desired output values.

II. MICROPEP

A. BACKGROUND

The MICROPEP program is a PC based computer program developed by the Naval Air Warfare Center Weapons Division, China Lake, California and is used to estimate the performance of solid and liquid propellant rockets. It also has the capability of determining equilibrium and thermochemical properties at a specified pressure-temperature point.

MICROPEP can be broken into three parts. The first part provides an evaluation of combustion product composition and chemical properties assuming constant pressure, equilibrium adiabatic combustion. The unmodified program allows input of up to ten ingredients and the output consists of the following combustion chamber properties: temperature, pressure, enthalpy, entropy, ratio of specific heats, chemical composition, molecular weight, heat content and speed of sound.

The second part of the program provides an evaluation of the throat and exhaust compositions and chemical properties assuming isentropic, adiabatic expansion through the nozzle. The unmodified program calculates these properties for two separate conditions:

1. shifting equilibrium flow - assumes that the reaction kinetics are fast enough to maintain chemical equilibrium throughout the expansion process

2. frozen composition flow - assumes that the reaction rates are so slow that the exhaust composition is the same as the chamber composition. The output for the throat and exhaust are the same as for the chamber.

The third part of the program provides an evaluation of nozzle performance parameters assuming one-dimensional flow, Mach 1 at the throat and exit pressure equal to ambient pressure. Output consists of the following for both frozen and shifting flow: specific impulse, ratio of specific heats for the chamber to throat process (the so-called "process gamma"), characteristic exhaust velocity, nozzle expansion ratio, density specific impulse, vacuum impulse, ratio of nozzle throat area to mass flow rate and nozzle thrust coefficient. An example of the output from the code is shown in Table 1. It should be noted that the units are a mix between English and SI.

B. MODIFICATIONS

None of the modifications made to the program used any new solution optimization algorithms. The existing subroutines were used, as needed, to affect the changes. A flow diagram of the MICROPEP program is shown in Figure1, with the modifications shown in bold. The changes made are as follows:

Table 1:
NEWPEP SAMPLE OUTPUT

```
1                         **** NEWPEP - Feb.  1990 ****
 * xx                  * 05/16/93  * DH ** DENS **** COMPOSITION *******

 OXYGEN (GAS)                                  0  0.00001    2O
 HYDROGEN (GASEOUS)                            0  0.00001    2H

 INGREDIENT WEIGHTS (IN ORDER) AND TOTAL WEIGHT          (LAST ITEM IN LIST)

    94.0000      6.0000    100.0000

 THE PROPELLANT DENSITY IS 0.00001 LB/CU-IN OR  0.0003 GM/CC

 NUMBER OF GRAM ATOMS OF EACH ELEMENT PRESENT IN INGREDIENTS

    5.952381 H      5.875000 O

 ***************************CHAMBER RESULTS FOLLOW*************************

  T(K)   T(F)   P(ATM)    P(PSI) ENTHALPY  ENTROPY   CP/CV   SGAMMA    RT/V
 3272.  5430.   34.01    500.00     0.00   293.21  1.2069  1.1361    7.284

 DAMPED AND UNDAMPED SPEED OF SOUND= 4061.859 AND 4061.860 FT/SEC

 SPECIFIC HEAT (MOLAR) OF GAS AND TOTAL=    11.590    11.590
 NUMBER MOLS GAS AND CONDENSED=    4.6693    0.0000

   2.63700 H2O          1.32936 O2          0.45880 HO          0.11383 O
  8.93E-02 H2          3.77E-02 H          3.32E-03 HO2        6.49E-06 O3

 THE MOLECULAR WEIGHT OF THE MIXTURE IS    21.417

 TOTAL HEAT CONTENT (298 REF)    =1722.111 CAL/GM
 SENSIBLE HEAT CONTENT (298 REF)=1393.949 CAL/GM

 ***************************EXHAUST RESULTS FOLLOW*************************
  T(K)   T(F)   P(ATM)    P(PSI) ENTHALPY  ENTROPY   CP/CV   SGAMMA    RT/V
 2192.  3486.    1.00     14.70   -86.91   293.21  1.2123  1.1733    0.225

 DAMPED AND UNDAMPED SPEED OF SOUND= 3252.018 AND 3252.018 FT/SEC

 SPECIFIC HEAT (MOLAR) OF GAS AND TOTAL=    11.349    11.349
 NUMBER MOLS GAS AND CONDENSED=    4.4479    0.0000

   2.93879 H2O          1.43343 O2          0.06255 HO          0.00648 O
  5.62E-03 H2          8.50E-04 H          1.62E-04 HO2

 THE MOLECULAR WEIGHT OF THE MIXTURE IS    22.483
 TOTAL HEAT CONTENT (298 REF)    =1131.643 CAL/GM
 SENSIBLE HEAT CONTENT (298 REF)= 819.350 CAL/GM
```

Table 1: (cont.)
NEWPEP SAMPLE OUTPUT

```
**********PERFORMANCE:  FROZEN ON FIRST LINE, SHIFTING ON SECOND LINE********

An exact method for determining throat conditions was used
The frozen & shifting STATE gammas for the throat are:  1.2063  1.1360
ISentropic EXponent shown below is the gamma for the chamber to throat
PROCESS.

IMPULSE  IS EX  T*      P*    C*      ISP*  OPT EX D-ISP   A*M.    EX T    ADH
 263.3  1.2089 2981.  19.83 5691.9          5.09     0.1 0.35390 1728.  584778.
 275.0  1.1360 3096.  19.63 5815.9  222.9   5.77     0.1 0.36161 2192.  770299.

****************************THROAT RESULTS FOLLOW**************************

 T(K)  T(F)  P(ATM)   P(PSI) ENTHALPY  ENTROPY  CP/CV   SGAMMA    RT/V
3096.. 5114.   19.63   288.61   -16.14   293.21  1.2063  1.1360    4.250

DAMPED AND UNDAMPED SPEED OF SOUND= 3929.313 AND 3929.314 FT/SEC

SPECIFIC HEAT (MOLAR) OF GAS AND TOTAL=    11.621     11.621
NUMBER MOLS GAS AND CONDENSED=    4.6196     0.0000

  2.70089 H2O          1.35026 O2           0.38104 HO          0.08796 O
 7.01E-02 H2          2.71E-02 H           2.28E-03 HO2        3.74E-06 O3

THE MOLECULAR WEIGHT OF THE MIXTURE IS    21.647

TOTAL HEAT CONTENT (298 REF)    =1618.754 CAL/GM
SENSIBLE HEAT CONTENT (298 REF)-1297.611 CAL/GM

                    **** NEWPEP - Feb. 1990 ****
```

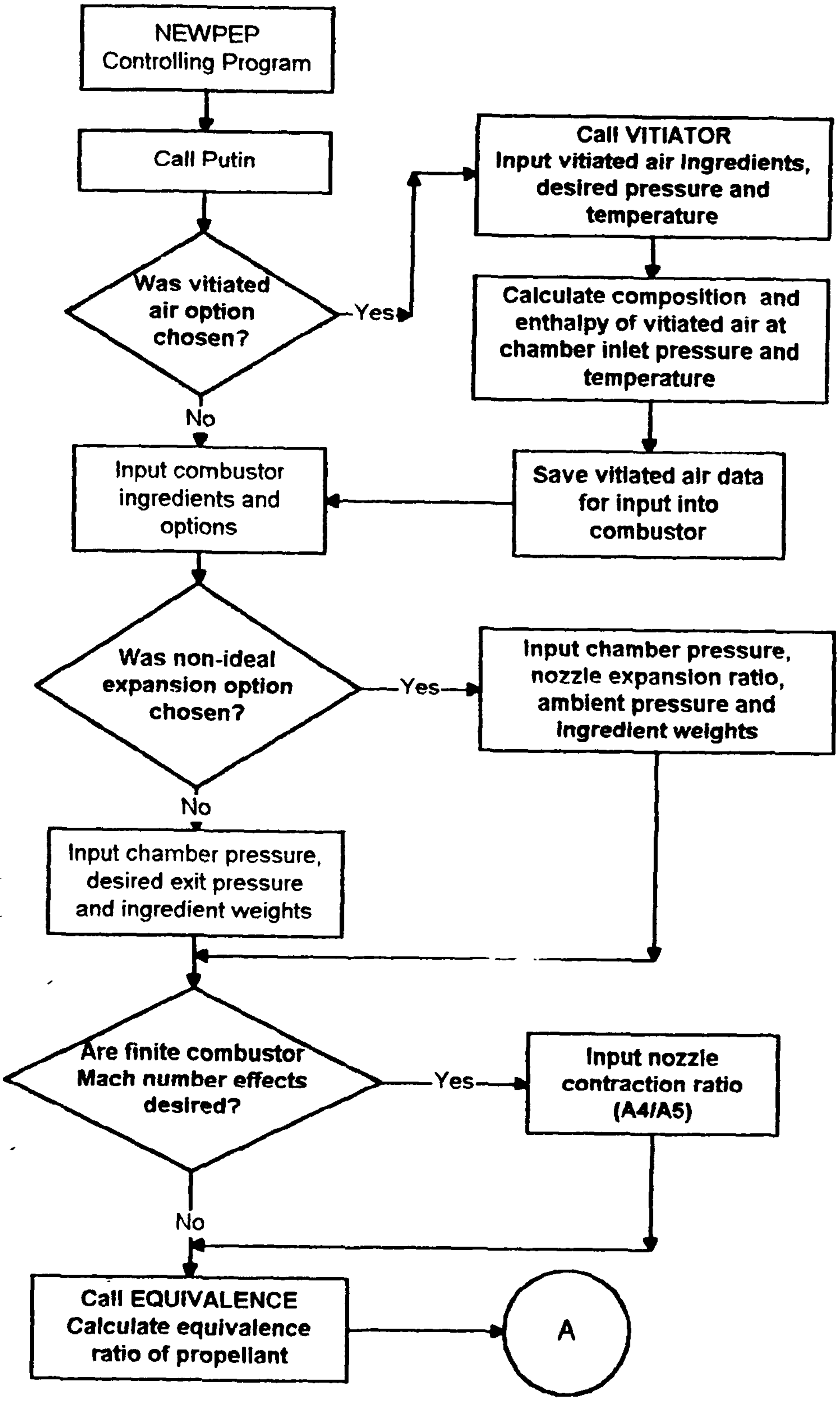


Figure 1:
PEP93 Flow Diagram

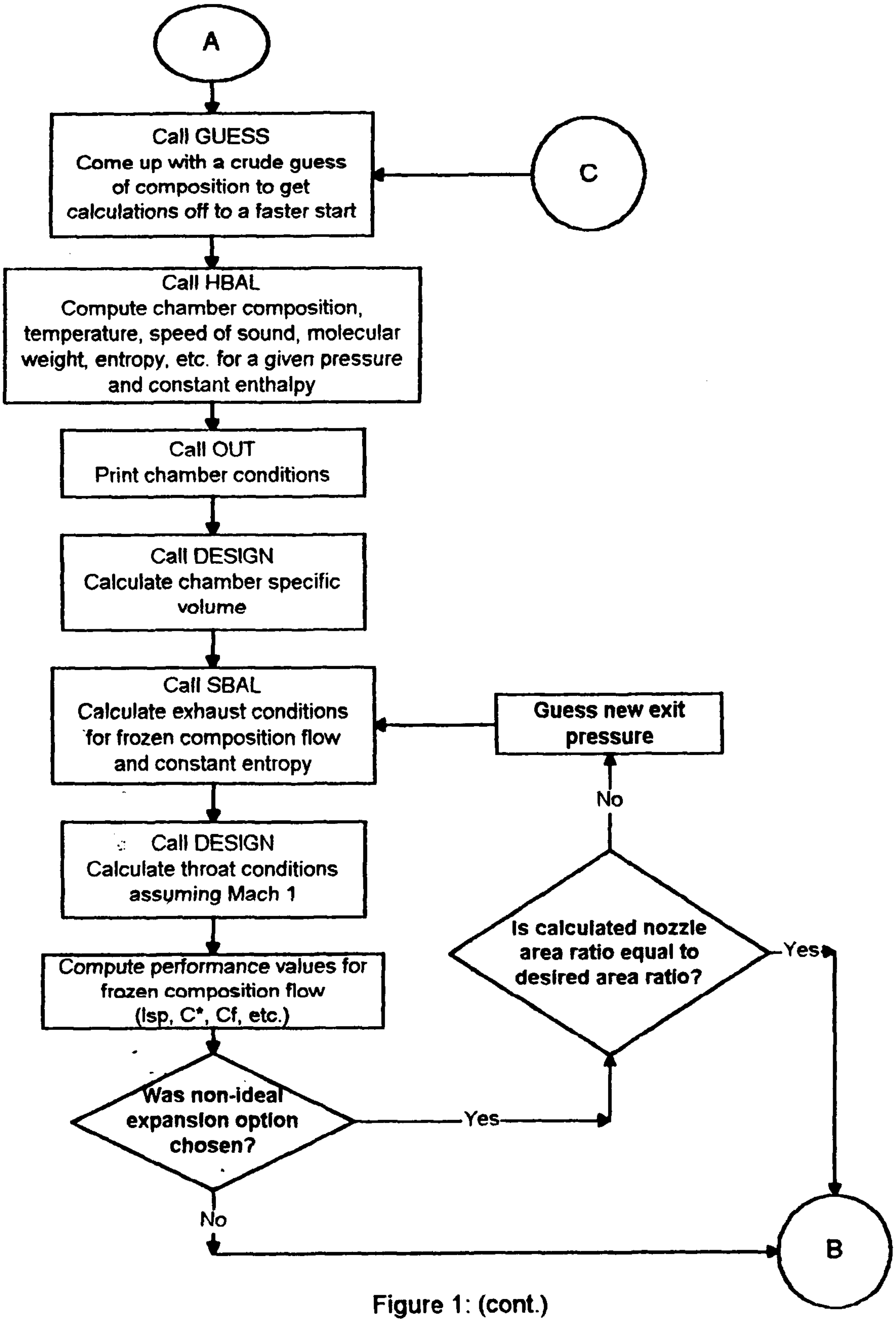


Figure 1: (cont.)
PEP93 Flow Diagram

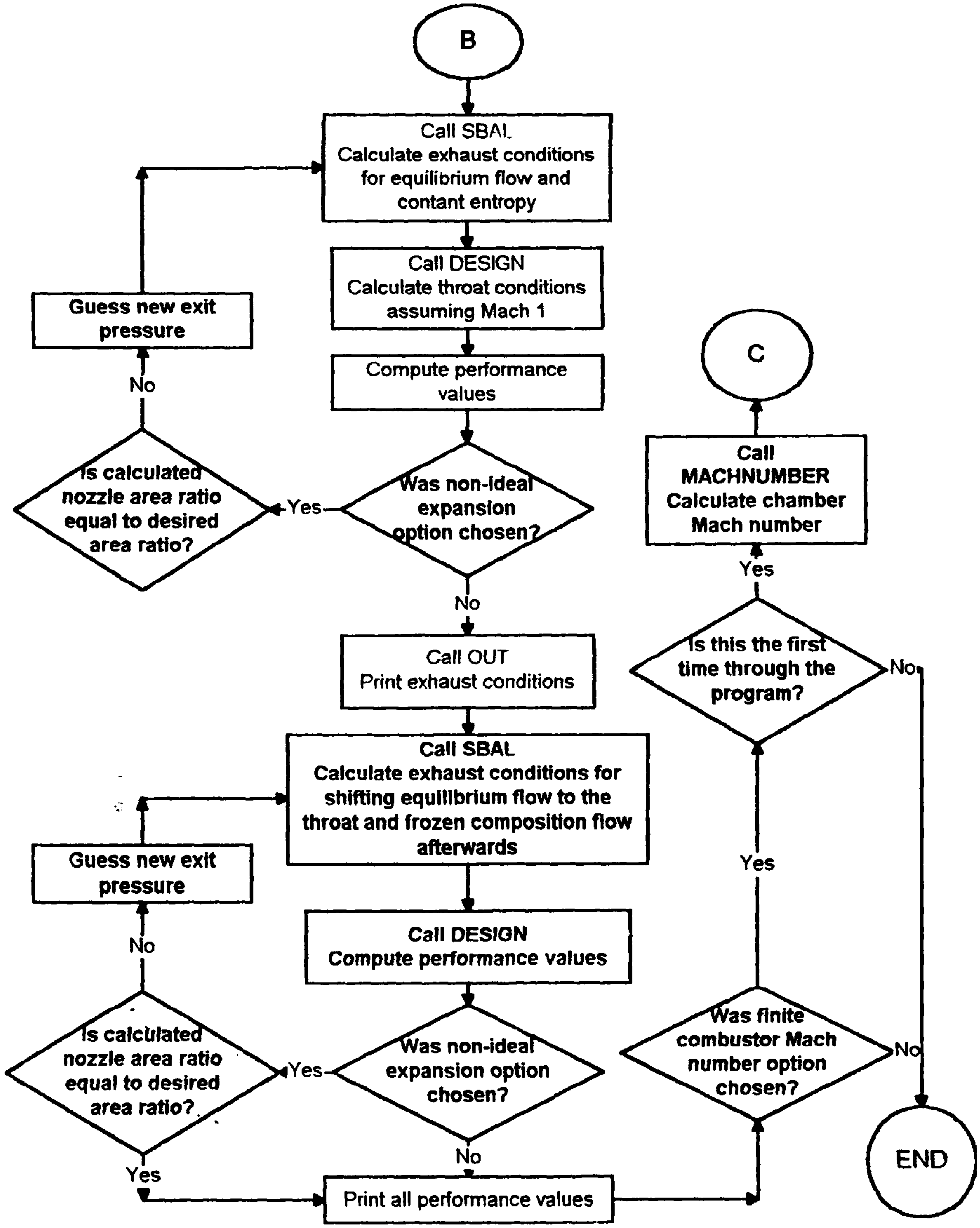


Figure 1: (cont.)
PEP93 Flow Diagram

1. The maximum allowable number of input ingredients has been increased to fifteen and the gas constant for the mixture is calculated.

$$R = \overline{R}/\overline{M}$$

2. The original program was extremely concise, leaving off units. Choosing clarity over brevity, units were added for all data.

3. Performance calculations:

a. Shifting equilibrium versus frozen composition flow- The theoretical performance of a rocket engine varies with the two assumptions. If the reaction rates of the chemicals are fast enough to maintain equilibrium throughout the nozzle then the additional energy gained by the reassociation of molecules and atoms will be reflected in an increased kinetic energy at the exhaust nozzle exit. Looking at the thrust and specific impulse equations

$$F = \dot{m}V_e/g_c - (p_e - p_o)A_e$$

$$I_{sp} = Fg_c/\dot{m}g_o$$

it is apparent that theoretical performance would be highest for shifting flow and lowest for frozen flow. Since actual performance has been measured between these two conditions, modifications have been made to MICROPEP to calculate shifting flow to the throat and frozen flow afterwards. This accounts for the higher reaction rates due to higher temperatures and pressures coupled with a flow Mach number less than one prior to the throat. After passing through the throat the flow accelerates past Mach 1 and the pressure drops rapidly to near ambient pressure, making it unlikely that the reaction kinetics will keep up with the flow velocity. Therefore, the assumption of frozen flow is reasonable.

b. Non-Ideal Expansion - It can be easily shown that the maximum thrust occurs when the exit pressure is equal to ambient pressure [Ref. 2]

$$F = \dot{m}V_e/g_c - (p_e-p_o)A_e$$

Taking the derivative of thrust with mass flow rate and ambient pressure constant gives

$$dF = \dot{m}dV_e/g_c + (p_e-p_o)dA_e + A_e dp_e$$

Using the continuity equation and the momentum equation for ideal flow

$$dF = (\rho AV)_e dV_e + (p_e-p_o)dA_e + A_e(-\rho VdV)_e$$

$$dF = (p_e-p_o)dA_e$$

therefore

$$dF/dA_e = 0 \quad \text{if } p_e=p_o$$

In an actual rocket motor the exit area is constant, so the expansicn will only be ideal for one operating altitude. An option was added to input nozzle expansion ratio and the ambient pressure. Performance values for non-ideal expansion can now be calculated for different ambient pressures.

4. Exhaust kinetic energy

One of the output values of NEWPEP was labeled adiabatic head. This value is calculated using the formula

$$V_e^2/2$$

and is therefore labeled kinetic energy of exhaust.

5. Total and sensible heat content

These were included in the original NEWPEP but the definitions were not clear. The present values are:

a. Total Heat Content = $\Sigma_P n_i h_{fi}^o - \Sigma_R n_i h_{fi}^o$ (without water condensation)

b. Sensible Heat Content = $\Sigma_P n_i h_{fi}^o - \Sigma_R n_i h_{fi}^o$ (with water condensed)

6. Air-breathing motors

a. Vitiated air

The theoretical performance of the combustor varies with the composition and temperature of the incoming air. The vitiated air option requires the user to select the vitiator ingredients, inlet stagnation temperature and pressure. Using this information a pressure-temperature point calculation is made for the inlet composition and heat of formation. This "vitiated" air is then automatically entered as a user defined ingredient for the combustor calculations.

b. Combustor Mach number

As combustor Mach number increases the difference between static and stagnation pressure increases

$$p_t/p = (1+((\gamma-1)/2)*M^2)^\wedge(\gamma/\gamma-1)$$

The unmodified program assumes the Mach number is zero and, therefore, stagnation pressure is equal to static pressure.

To account for finite Mach numbers, the nozzle contraction ratio can be input. If this option is chosen the program first calculates the nozzle and exhaust conditions for a chamber Mach number equal to zero. Then, using the calculated process gamma and given nozzle contraction ratio, the combustion chamber Mach number is solved for using an interval halving method. Using a lower bound of M = 0 and an upper bound of M = 1.001, the following equation is iterated until convergence is reached.

$$0 = M*(A_4/A_5)-[2/(\gamma+1)+(\gamma-1)/(\gamma+1)*M^2)]^\wedge[(\gamma+1)/2(\gamma-1)]$$

The bisection method was chosen because of its guaranteed convergence and the small range of Mach numbers to be considered.

c. Nozzle discharge coefficient

One of the basic assumptions of MICROPEP is one-dimensional, isentropic flow. In order to more accurately predict mass flow rate through the nozzle, a streamline curvature correction (C_d) is now an allowable input. With the nozzle discharge coefficient the continuity equation becomes

$$\dot{m}_5 = p_t A_t c_d [\gamma/RT_t]^{0.5}[2/(\gamma+1)]\hat{}[(\gamma+1)/2(\gamma-1)]$$
$$= p_t A_t c_d / C^*$$

If an accurate value is not known the program default is 1.0.

7. Equivalence Ratio

One definition of equivalence ratio is the ratio of oxidizer required for complete combustion of the fuel (to the highest oxidation state) to that available for combustion [Ref. 3]. Using this definition, subroutine EQUIVALENCE solves the following equation

$$\Phi = [\Sigma_{i=1}^{k} n_i \text{ x } (n_o)_c]/\bar{n}_o$$

where K is number of reactant elements,

n_i is the number of moles of fuel element i,

$(n_o)_c$ is the number of moles of oxygen required for complete combustion of one mole of fuel element i,

$\bar{n}_o$ is the number of moles of oxygen available.

Note: The program attempts to account for all common fuel species. See Appendix C: Subroutine EQUIVALENCE for a complete list of the elements incorporated.

C. REVISED INPUT AND OUTPUT

Appendix A contains the revised "users guide" for PEP93. A sample output is shown in Table 2.

Table 2:
PEP93 SAMPLE OUTPUT

```
                         **** NEWPEP - Jan.     1993 ****
* xx                  *
INGREDIENT                          MASS     HF       DENSITY      COMPOSITION
                                    (gm)  (kcal/kg)  (kg/m**3)
OXYGEN (GAS)                        94.00      .0      .0000      20
HYDROGEN (GASEOUS)                   6.00      .0      .0000      2H

VOLUME PERCENT OF INGREDIENTS (IN ORDER)
   94.0000      6.0000

THE PROPELLANT DENSITY IS  .00001 LB/CU-IN OR    .0003 GM/CC
THE EQUIVALENCE RATIO IS    .5066

NUMBER OF GRAM ATOMS OF EACH ELEMENT PRESENT IN INGREDIENTS

   5.952381 H      5.875000 O

****************************CHAMBER RESULTS FOLLOW************************

TEMP          PRESSURE              ENTHALPY   ENTROPY    CP/CV   SGAMMA     Pi/ni
(K)        (MPa/ATM/PSI)            (kJ/kg)   (kJ/kg-K)                  (MPa/kmol)
3271.9   3.447/ 34.02/ 500.00         .0000     12.268    1.2069   1.1361 73831.150

DAMPED AND UNDAMPED SPEED OF SOUND- 1238.061 AND 1238.062 m/sec

SPECIFIC HEAT (MOLAR) OF GAS AND TOTAL=   484.92      484.922 J/kg K
NUMBER MOLS GAS AND CONDENSED=    4.6693     .0000

(*=liquid,&=solid)
  2.63700 H2O          1.32935 O2            .45881 HO            .11383 O
 8.93E-02 H2          3.77E-02 H           3.32E-03 HO2         6.49E-06 O3

THE MOLECULAR WEIGHT OF THE MIXTURE IS    21.417 gm/mole
THE GAS CONSTANT IS    388.22 J/kg K

TOTAL HEAT CONTENT (298 REF)     -     7205.281 kJ/kg
SENSIBLE HEAT CONTENT (298 REF)=       5832.259 kJ/kg

****************************EXHAUST RESULTS FOLLOW************************

TEMP          PRESSURE              ENTHALPY   ENTROPY    CP/CV   SGAMMA     Pi/ni
(K)        (MPa/ATM/PSI)            (kJ/kg)   (kJ/kg-K)                  (MPa/kmol)
2191.9    .101/  1.00/  14.70    -3636.2370    12.268    1.2123   1.1733   2278.684

DAMPED AND UNDAMPED SPEED OF SOUND=  991.215 AND  991.215 m/sec

SPECIFIC HEAT (MOLAR) OF GAS AND TOTAL=   474.82      474.822 J/kg K
NUMBER MOLS GAS AND CONDENSED=    4.4479     .0000
```

Table 2: (cont.)
PEP93 SAMPLE OUTPUT

```
 (*=liquid,&=solid)
   2.93879 H2O          1.43343 O2            .06255 HO             .00647 O
  5.62E-03 H2          8.50E-04 H           1.62E-04 HO2

 THE MOLECULAR WEIGHT OF THE MIXTURE IS    22.483 gm/mole
 THE GAS CONSTANT IS    369.81 J/kg-K

 TOTAL HEAT CONTENT (298 REF)    =    4734.795 kJ/kg
 SENSIBLE HEAT CONTENT (298 REF)=    3428.162 kJ/kg
*******************************************************************************

 An exact method for determining throat conditions was used
 The frozen & shifting STATE gammas for the throat are:  1.2063  1.1360
 GAMMA NU shown below is the gamma for the chamber to throat PROCESS.

 **********PERFORMANCE:  FROZEN ON FIRST LINE, SHIFTING ON SECOND LINE,******
 **************SHIFTING TO THROAT/FROZEN AFTERWARDS ON THIRD LINE************

 SPECIFIC GAMMA  T*       P*    C*      ISP*  Ae/A*    D-ISP    A*/m     Te      Cf
 IMPULSE   NU                                        (gm-s/   (cm**2/
  (sec)          (K)   (MPa) (m/s)   (sec)            cm**3)   kg/s)   (K)
  263.3   1.2088 2962. 1.938 1733.3          5.099     2.017   5.0272 1728.1.4895
  275.0   1.1360 3096. 1.990 1772.7 222.9   5.768     2.107   5.1415 2192.1.5215
  267.2   1.1360 3096. 1.990 1772.7 222.9   5.110     2.047   5.1415 1816.1.4781
 ****************************THROAT RESULTS FOLLOW**************************

 TEMP          PRESSURE               ENTHALPY   ENTROPY   CP/CV  SGAMMA    Pi/ni
 (K)         (MPa/ATM/PSI)            (kJ/kg)   (kJ/kg-K)                (MPa/kmol)
3096.5    1.990/ 19.64/ 288.61      -675.5011    12.268    1.2334  1.1441  2193.979

 DAMPED AND UNDAMPED SPEED OF SOUND= 1211.075 AND 1211.075 m/sec

 SPECIFIC HEAT (MOLAR) OF GAS AND TOTAL=    439.30     439.299 J/kg-K
 NUMBER MOLS GAS AND CONDENSED-    4.6196    .0000

 (*=liquid,&-solid)
   2.70090 H2O          1.35026 O2            .38103 HO             .08795 O
  7.01E-02 H2          2.71E-02 H           2.28E-03 HO2          3.74E-06 O3

 THE MOLECULAR WEIGHT OF THE MIXTURE IS    21.647 gm/mole
 THE GAS CONSTANT IS    384.09 J/kg-K

 TOTAL HEAT CONTENT (298 REF)    -    6772.908 kJ/kg
 SENSIBLE HEAT CONTENT (298 REF)=    5429.259 kJ/kg

 FROZEN & SHIFTING KINETIC ENERGY OF EXHAUST  584773.  770295.  m**2/s**2
```

III. ROCKET

A. BACKGROUND

1. ROCKET is a PC based program originally written by the Lockheed Corporation and then modified by the Naval Air Warfare Center Weapons Division. The intent of the original program was to calculate the pressure-time and thrust-time profiles of a multiple grain rocket motor using the following assumptions:

   a. Combustion products are ideal gases.

   b. Burning rate follows Veille's Law

   $\dot{r} = ap_c{}^n$

   c. Effects of mass addition and erosive burning are negligible.

   d. Inertia of the chamber gases is negligible.

   e. Variation of C* with pressure is described by

   $C^* = C^*_{pref}[p_{ref}/1000]^x$

   f. Propellant burning rate temperature sensitivity is described by

   $\dot{r} = \dot{r}_{70F}\exp[0.01\sigma_p(T_c-70)]$, where $\sigma_p = (1-n)\Pi_k$

   g. Properties of the chamber gases are mass averages of the individual gases.

2. Allowable inputs were:

   a. Number and type of grains

   (1) Igniter

(2) Insulation

(3) Propellant

(4) Igniter Motor (for large rockets)

b. Motor parameters

(1) Nozzle throat and exit areas

(2) Total motor volume

(3) Ambient temperature and pressure

(4) Throat closure blowout pressure

(5) Initial motor pressure

(6) Nozzle discharge coefficient and half angle correction

(7) Ratio of specific heats

(8) Throat area design pressure

(9) Throat erosion rate(radial)

c. Grain Parameters

(1) Burning rate

(2) Burning rate exponent

(3) Temperature sensitivity

(4) Reference pressure for C* correction

(5) Characteristic exhaust velocity

(6) Pressure correction exponent for C*

(7) Density

(8) Ignition time

(9) Flame spread ignition delay time

(10) Burning surface area

3. Using these inputs the program calculates chamber pressure by integrating the following mass conservation equation:

$$dp_c/dt = (1/\upsilon_o)[RT(\Sigma\rho_p A_b a p_c{}^n - p_c A_{th} g_c/C^*) - p_c(d\upsilon_o/dt)]$$

where υ_o is the instantaneous gas volume. Then the thrust coefficient is calculated using

$$c_F = \{2\gamma^2/(\gamma-1)*(2/(\gamma+1))\hat{}[(\gamma+1)/(\gamma-1)]$$
$$*[1-(p_e/p_c)\hat{}(\gamma-1)/\gamma]\}^{0.5}\lambda + (p_e - p_{amb})A_e/(p_c c_d A_{th})$$

With the values of pressure and thrust coefficient known, thrust was solved for using

$$F = c_F p_c A_{th} \lambda c_d$$

B. MODIFICATIONS

A flow diagram of the program is shown in Figure 2 and a modified user's guide is given in Appendix B.

1. Calculation of actual thrust and specific impulse. Several factors contribute to the reduction in theoretical thrust and specific impulse from the theoretical values (F', Isp'). In general these can be put into two separate categories; losses due to incomplete combustion in the chamber and nozzle losses (two-phase flow, divergence, etc.). The ROCKET program has been modified to allow these losses to be accounted for using two efficiencies, η_{C*} and η_{Cf}.

a. Combustion Loss Coefficient (η_{C*})

η_{C*} is primarily a function of the gas residence time and is determined empirically [Ref. 4]. Typical values

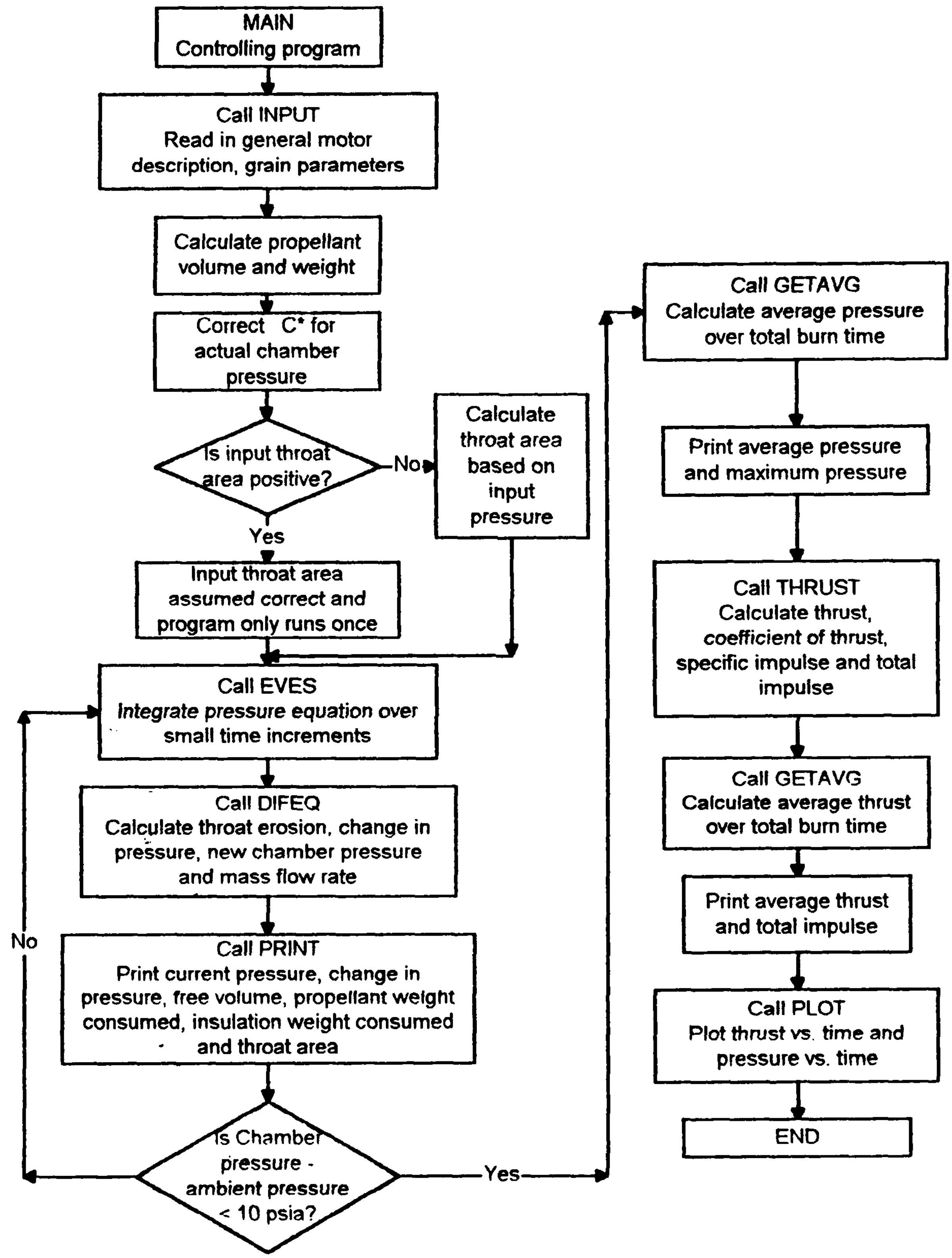


Figure 2:
ROCKET Flow Diagram

for aluminized solid propellants are between .96 and .995 for residence times greater than 10 seconds. For these propellants η_{C*} drops off rapidly for residence times below 10 seconds.

b. Nozzle Loss Coefficient (η_{Cf})

This can be expressed by [Ref. 5].

$$\eta_{Cf} = 1-(\epsilon_{div}+\epsilon_{kin}+\epsilon_{bl}+\epsilon_{sub}+\epsilon_{eros}+\epsilon_{tp})/100$$

where

ϵ_{div} = half angle correction for conical nozzles

ϵ_{kin} = correction for shifting equilibrium vs. frozen composition flow

ϵ_{bl} = boundary layer loss

ϵ_{sub} = correction for flow around submerged nozzles

ϵ_{eros} = losses due to nozzle throat erosion

ϵ_{tp} = velocity and thermal lag of condensed species in chamber

For use in ROCKET the input value of C* should be C* theoretical times η_{C*} . Allowable inputs of nozzle discharge coefficient and half-angle correction have been replaced by the nozzle loss coefficient, and thrust is calculated using

$$F = \eta_{Cf} c_f p_c A_{th}$$

2. Plotting routines

A plotting subroutine has been added which automatically takes the time and thrust values, determines the maximum value of thrust and plots the thrust-time profile scaled to maximum thrust. The same is done for the pressure-time profile. In addition, time, pressure and thrust are printed to a separate data file.

3. Total impulse is calculated using the following formula:

$$I_T = \bar{F}t_b$$

where

$\bar{F}$ is the average thrust

t_b is the total burn time.

4. Improved efficiency

Since the original program was written by Lockheed for use on a mainframe computer, ROCKET has undergone some modifications. These changes resulted in a program that was inefficient because several input variables were undefined in the users manuals. In order to increase efficiency, more than 25 variables and over 300 lines of code associated with these variables were removed. The result is a program that still gives the output discussed above and does indeed work well for more than one grain.

C. REVISED INPUT AND OUTPUT

A sample input file is given in Appendix B with a rocket motor description shown in Figure 3. A sample output file is shown in Table 3.

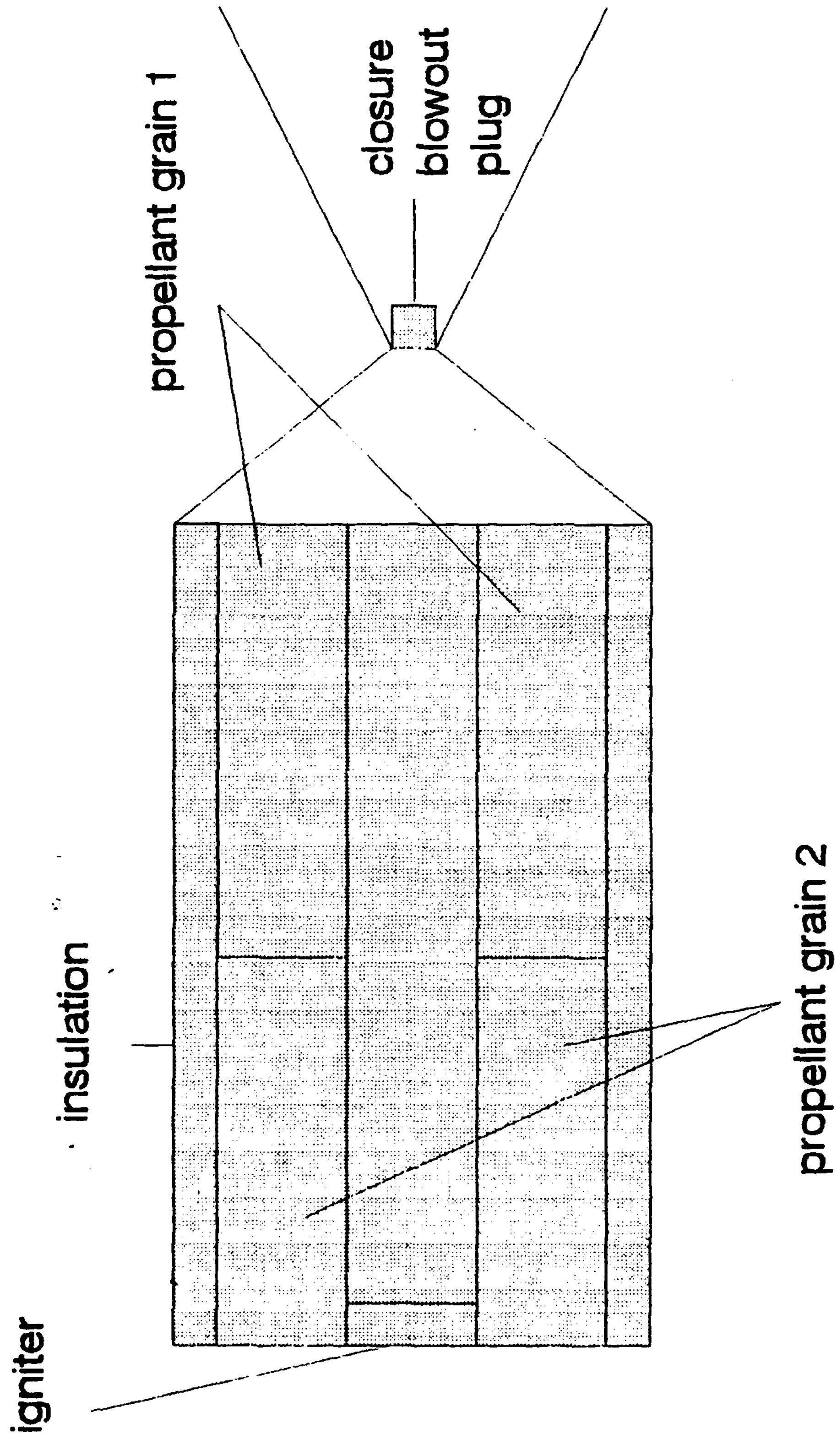


Figure 3:
ROCKET Description

Table 3:
ROCKET SAMPLE OUTPUT

```
1        15percent
         Motor Performance Program IBM-PC Version 1.0
                  INPUT DATA...
              Normal Input is finished
        General Configuration PARAMETERS are ...
          Throat AREA                          8.6577
          Exit AREA                          105.4500
          Expansion RATIO                     12.1799
          Total Motor VOLUME                   8042.5
          AMBIENT Temperature                    70.0
          AMBIENT Pressure                       10.1
          Closure BLOWOUT                        35.0
          Pzero                                  14.7
          CF Efficiency                         .9606
          Gamma                                1.1443
          Throat DESIGN Pressur                1030.0
          Throat EROSION                        .0005
        MOTOR HAS 4  GRAINS
        DESCRIPTION OF GRAIN   1
          BURN RATE                             .5800
          BURN RATE EXP.                        .3500
          PI SUB K                              .2000
          BURN REF. PRESS.                     1030.0
          C STAR                               5106.7
          C STAR EXP.                           .0450
          DENSITY                               .0623
          IGNITION TIME                         .0000
          DELTA IGN. TIME                       .0000
1
             WEB          BURN AREA
              .000          744.150
              .381          759.750
              .762          771.250
             1.143          778.650
             1.524          781.950
             1.905          781.150
             2.286          776.250
             2.666          767.250
             3.047          754.100
             3.428          736.900
             3.809          715.600
```

Table 3: (cont.)
ROCKET SAMPLE OUTPUT

```
DESCRIPTION OF GRAIN    2
  BURN RATE                          .5800
  BURN RATE EXP.                     .3500
  PI SUB K                           .2000
  BURN REF. PRESS.                  1030.0
  C STAR                            5106.7
  C STAR EXP.                        .0450
  DENSITY                            .0623
  IGNITION TIME                      .0000
  DELTA IGN. TIME                    .0000
     WEB          BURN AREA
      .000         744.150
      .381         759.750
      .762         771.250
     1.143         778.650
     1.524         781.950
     1.905         781.150
     2.286         776.250
     2.666         767.250
     3.047         754.100
     3.428         736.900
     3.809         715.600
DESCRIPTION OF GRAIN    3
1
  BURN RATE                          .5800
  BURN RATE EXP.                     .3500
  PI SUB K                           .2000
  BURN REF. PRESS.                  1030.0
  C STAR                            5106.7
  C STAR EXP.                        .0450
  DENSITY                            .0623
  IGNITION TIME                      .0000
  DELTA IGN. TIME                    .0000
THIS GRAIN IS INSULATION WITH AN ABLATION RATE OF          .05000
     WEB          BURN AREA
      .000        1488.300
      .381        1519.500
      .762        1542.500
     1.143        1557.300
     1.524        1563.900
     1.905        1562.300
     2.286        1552.500
     2.666        1534.500
     3.047        1508.200
     3.428        1473.800
     3.809        1431.200
```

Table 3: (cont.)
ROCKET SAMPLE OUTPUT

DESCRIPTION OF GRAIN 4

BURN RATE	1.0000
BURN RATE EXP.	.0000
PI SUB K	.0000
BURN REF. PRESS.	1000.0
C STAR	5106.7
C STAR EXP.	.0450
DENSITY	.0623
IGNITION TIME	.0000
DELTA IGN. TIME	.0000

THIS GRAIN IS AN IGNITER

TIME	WDOT
.0000	1.4000
.2500	1.9000

TOTAL PROPELLANT WEIGHT= 362.478 IGNITER WEIGHT= .41

1

TIME	PC	PDOT	FREE VOL	P WEIGHT	WDOTP	INS WT	WDOT	AT
.000	14.70	22173.60	2217.59	.00	13.55	.00	.00	8.65770
.001	27.75	27381.44	2217.75	.01	16.58	.00	.00	8.65770
.001	38.26	27371.20	2217.88	.01	18.39	.00	2.42	8.65770
.001	51.96	29634.08	2218.07	.02	20.31	.01	3.24	8.65770
.002	66.64	31490.92	2218.27	.03	22.03	.01	4.11	8.65771
.002	76.89	32543.34	2218.41	.04	23.09	.01	4.71	8.65771
.002	87.46	33467.93	2218.55	.05	24.09	.01	5.32	8.65771
.003	98.30	34278.57	2218.70	.06	25.04	.01	5.95	8.65771
.003	109.38	34986.84	2218.86	.06	25.94	.01	6.59	8.65771
.003	120.68	35602.51	2219.02	.07	26.80	.02	7.24	8.65772
.004	132.16	36134.02	2219.18	.08	27.62	.02	7.90	8.65772
.004	143.80	36588.74	2219.35	.09	28.41	.02	8.56	8.65772
.004	155.57	36973.17	2219.52	.10	29.16	.02	9.23	8.65772
.005	167.45	37293.06	2219.70	.11	29.89	.02	9.90	8.65772
.005	191.48	37759.36	2220.06	.13	31.26	.02	11.25	8.65773
.006	215.74	38023.35	2220.43	.15	32.53	.03	12.61	8.65773
.007	240.11	38114.57	2220.82	.17	33.72	.03	13.97	8.65773
.007	264.49	38057.92	2221.22	.19	34.83	.03	15.32	8.65774
.008	288.80	37874.59	2221.63	.22	35.88	.04	16.66	8.65774
.009	312.95	37582.82	2222.05	.24	36.86	.04	17.99	8.65774
.009	336.89	37198.40	2222.48	.26	37.79	.04	19.30	8.65774
.010	360.55	36735.09	2222.92	.29	38.67	.05	20.59	8.65775
.010	383.89	36204.92	2223.37	.31	39.50	.05	21.86	8.65775
.011	406.88	35618.45	2223.83	.34	40.28	.05	23.11	8.65775
.012	451.65	34312.61	2224.77	.39	41.73	.06	25.53	8.65776
.014	494.66	32879.32	2225.74	.44	43.04	.06	27.85	8.65777
.015	535.78	31366.61	2226.73	.50	44.22	.07	30.06	8.65777
.016	574.94	29811.89	2227.74	.56	45.30	.08	32.15	8.65778
.018	612.09	28244.19	2228.78	.62	46.27	.08	34.13	8.65779
.019	647.24	26685.84	2229.83	.68	47.16	.09	36.00	8.65779
.020	680.42	25153.92	2230.91	.74	47.97	.09	37.76	8.65780
.021	711.65	23661.14	2232.00	.80	48.71	.10	39.42	8.65781

Table 3: (cont.)
ROCKET SAMPLE OUTPUT

TIME	PC	PDOT	FREE VOL	P WEIGHT	WDOTP	INS WT	WDOT	AT
.023	741.01	22216.91	2233.10	.86	49.39	.11	40.97	8.65781
.024	768.55	20827.85	2234.22	.92	50.01	.11	42.42	8.65782
.025	794.35	19498.47	2235.34	.99	50.58	.12	43.78	8.65783
.026	818.49	18231.46	2236.48	1.05	51.10	.12	45.05	8.65783
.029	862.10	15889.49	2238.79	1.19	52.02	.13	47.34	8.65785
.032	900.05	13800.72	2241.14	1.32	52.80	.15	49.33	8.65786
.034	932.96	11954.15	2243.51	1.46	53.46	.16	51.05	8.65787
.037	961.43	10332.46	2245.91	1.59	54.02	.17	52.54	8.65789
.039	986.03	8916.11	2248.33	1.73	54.49	.18	53.82	8.65790
.042	1007.24	7684.14	2250.77	1.87	54.90	.19	54.93	8.65791
.044	1025.51	6616.43	2253.22	2.01	55.25	.21	55.88	8.65793
.047	1041.23	5693.39	2255.69	2.16	55.54	.22	56.69	8.65794
.050	1054.76	4897.45	2258.17	2.30	55.80	.23	57.40	8.65795
.052	1066.40	4212.11	2260.66	2.44	56.02	.24	58.00	8.65797
.055	1076.41	3623.16	2263.16	2.59	56.20	.25	58.52	8.65798
.060	1092.43	2683.66	2268.17	2.87	56.51	.28	59.35	8.65801
.065	1104.32	1993.59	2273.20	3.16	56.74	.30	59.97	8.65803
.073	1116.71	1288.38	2280.79	3.60	56.98	.34	60.61	8.65807
.083	1126.81	740.77	2290.94	4.19	57.20	.38	61.14	8.65813
.106	1137.17	266.38	2313.86	5.51	57.46	.49	61.68	8.65825
.183	1148.30	113.77	2390.75	9.94	57.95	.85	62.25	8.65865
.249	1155.79	-2965.13	2457.94	13.81	56.44	1.16	62.64	8.65900
.255	1140.96	-2095.53	2463.65	14.14	56.19	1.19	61.88	8.65903
.263	1128.01	-1334.14	2471.14	14.57	55.98	1.22	61.21	8.65907
.273	1117.77	-724.26	2481.10	15.15	55.82	1.27	60.68	8.65912
.311	1107.56	-36.76	2518.33	17.29	55.71	1.45	60.15	8.65932
.322	1107.41	2.71	2528.26	17.86	55.73	1.50	60.14	8.65937
.532	1118.03	55.27	2732.80	29.61	56.30	2.49	60.70	8.66047
.736	1128.33	42.24	2934.31	41.20	56.81	3.45	61.24	8.66154
.982	1138.41	41.30	3178.18	55.22	57.32	4.62	61.77	8.66282
1.228	1148.53	41.29	3424.17	69.37	57.83	5.80	62.31	8.66410
1.576	1158.84	26.43	3775.79	89.60	58.34	7.48	62.85	8.66592
2.006	1169.16	12.86	4213.94	114.82	58.86	9.56	63.40	8.66816
2.539	1175.18	11.30	4759.95	146.24	59.18	12.15	63.74	8.67094
2.600	1175.38	-1.67	4823.12	149.88	59.18	12.45	63.75	8.67126
3.112	1173.38	-4.36	5349.12	180.16	59.09	14.94	63.66	8.67393
3.645	1164.48	-19.20	5893.98	211.51	58.65	17.52	63.22	8.67671
4.054	1153.28	-33.32	6309.70	235.44	58.08	19.50	62.66	8.67885
4.382	1142.12	-33.88	6639.00	254.38	57.54	21.08	62.09	8.68056
4.648	1130.45	-48.58	6904.06	269.62	56.94	22.35	61.50	8.68195
4.894	1118.50	-48.41	7146.19	283.54	56.35	23.51	60.88	8.68324
5.099	1108.47	-55.57	7346.10	295.03	55.84	24.47	60.37	8.68430
5.283	1097.31	-61.91	7524.33	305.28	55.28	25.33	59.80	8.68527
5.447	1087.16	-61.81	7681.28	314.29	54.78	26.10	59.27	8.68612
5.611	1077.07	-61.42	7836.83	323.23	54.28	26.85	58.75	8.68698
5.774	1066.62	-70.73	7990.99	332.08	53.75	27.61	58.21	8.68784
5.938	1054.58	-74.37	8143.54	340.83	53.14	28.35	57.59	8.68869
6.102	1042.41	-74.03	8294.40	349.49	52.54	29.09	56.96	8.68955

Table 3: (cont.)
ROCKET SAMPLE OUTPUT

TIME	PC	PDOT	FREE VOL	P WEIGHT	WDOTP	INS WT	WDOT	AT
6.266	1030.32	-73.41	8443.60	358.05	51.94	29.83	56.34	8.69040
6.360	1019.22	-25894.06	8527.95	362.89	.00	30.25	55.75	8.69089
6.360	1006.86	-25580.20	8527.95	362.89	.00	30.25	55.07	8.69090
6.361	990.63	-25167.67	8527.95	362.89	.00	30.25	54.19	8.69090
6.361	974.65	-24761.79	8527.95	362.89	.00	30.25	53.31	8.69090
6.362	958.93	-24362.40	8527.95	362.89	.00	30.25	52.45	8.69091
6.363	928.25	-23582.91	8527.95	362.89	.00	30.25	50.77	8.69092
6.365	898.54	-22828.35	8527.95	362.89	.00	30.25	49.15	8.69092
6.366	869.79	-22097.94	8527.95	362.89	.00	30.25	47.58	8.69093
6.368	815.03	-20706.56	8527.95	362.89	.00	30.25	44.58	8.69094
6.371	763.71	-19402.71	8527.95	362.89	.00	30.25	41.77	8.69096
6.376	670.56	-17036.25	8527.95	362.89	.00	30.25	36.68	8.69098
6.381	588.77	-14958.36	8527.95	362.89	.00	30.25	32.21	8.69101
6.386	516.95	-13133.84	8527.95	362.89	.00	30.25	28.28	8.69104
6.391	453.90	-11531.85	8527.95	362.89	.00	30.25	24.83	8.69106
6.397	398.53	-10125.25	8527.95	362.89	.00	30.25	21.80	8.69109
6.402	349.92	-8890.23	8527.95	362.89	.00	30.25	19.14	8.69112
6.407	307.24	-7805.84	8527.95	362.89	.00	30.25	16.81	8.69114
6.412	269.76	-6853.72	8527.95	362.89	.00	30.25	14.76	8.69117
6.417	236.86	-6017.73	8527.95	362.89	.00	30.25	12.96	8.69120
6.422	207.96	-5283.71	8527.95	362.89	.00	30.25	11.38	8.69122
6.427	182.60	-4639.22	8527.95	362.89	.00	30.25	9.99	8.69125
6.432	160.32	-4073.35	8527.95	362.89	.00	30.25	8.77	8.69128
6.438	140.77	-3576.49	8527.95	362.89	.00	30.25	7.70	8.69130
6.443	123.60	-3140.24	8527.95	362.89	.00	30.25	6.76	8.69133
6.448	108.52	-2757.20	8527.95	362.89	.00	30.25	5.94	8.69136
6.453	95.28	-2420.88	8527.95	362.89	.00	30.25	5.21	8.69138
6.458	83.66	-2125.58	8527.95	362.89	.00	30.25	4.58	8.69141
6.463	73.46	-1866.31	8527.95	362.89	.00	30.25	4.02	8.69144
6.473	56.63	-1438.77	8527.95	362.89	.00	30.25	3.10	8.69149
6.484	43.66	-1109.18	8527.95	362.89	.00	30.25	2.39	8.69154
6.494	33.65	-855.08	8527.95	362.89	.00	30.25	1.84	8.69160
6.509	22.78	-578.79	8527.95	362.89	.00	30.25	1.25	8.69168

AVERAGE PRESSURE FROM .000 SEC. TO 6.509 SEC. WAS 1110.933 PSI
MAXIMUM PRESSURE WAS 1175.41 PSI

TIME	PC	PE	F	WEIGHT	CF	WDOT EX	ISP
.000	14.70	.00	.00	.00	.000	.00	.00
.001	27.75	.00	.00	.01	.000	.00	.00
.001	38.26	5.18	273.95	.02	.827	.00	113.34
.001	51.96	4.87	417.95	.03	.929	.00	120.14
.002	66.64	4.63	577.29	.04	1.001	.00	127.75
.002	76.89	4.50	690.88	.05	1.038	.00	132.32
.002	87.46	4.39	809.64	.06	1.069	.01	136.54
.003	98.30	4.29	933.04	.07	1.096	.01	140.41
.003	109.38	4.20	1060.59	.08	1.120	.01	143.99
.003	120.68	4.11	1191.83	.09	1.141	.01	147.30
.004	132.16	4.04	1326.36	.10	1.159	.02	150.38
.004	143.80	3.97	1463.80	.11	1.176	.02	153.24

Table 3: (cont.)
ROCKET SAMPLE OUTPUT

TIME	PC	PE	F	WEIGHT	CF	WDOT EX	ISP
.004	155.57	3.91	1603.81	.12	1.191	.02	155.91
.005	167.45	3.85	1746.08	.13	1.204	.02	158.41
.005	191.48	3.75	2036.21	.15	1.228	.03	162.96
.006	215.74	3.66	2353.98	.18	1.260	.04	167.19
.007	240.11	3.59	2676.77	.20	1.288	.05	171.24
.007	264.49	3.52	3002.53	.23	1.311	.06	175.05
.008	288.80	3.46	3329.74	.25	1.332	.07	178.61
.009	312.95	3.56	3674.16	.28	1.356	.08	181.99
.009	336.89	3.83	4033.64	.31	1.383	.09	185.31
.010	360.55	4.10	4389.03	.33	1.406	.10	188.54
.010	383.89	4.37	4739.64	.36	1.426	.12	191.66
.011	406.88	4.63	5084.88	.39	1.443	.13	194.63
.012	451.65	5.14	5757.28	.45	1.472	.16	200.10
.014	494.66	5.63	6403.28	.51	1.495	.20	204.95
.015	535.78	6.10	7020.91	.57	1.514	.23	209.24
.016	574.94	6.54	7609.00	.63	1.529	.27	213.03
.018	612.09	6.97	8167.05	.70	1.541	.31	216.40
.019	647.24	7.37	8695.02	.76	1.552	.36	219.40
.020	680.42	7.74	9193.27	.83	1.561	.41	222.08
.021	711.65	8.10	9662.43	.90	1.568	.46	224.49
.023	741.01	8.43	10103.34	.97	1.575	.51	226.66
.024	768.55	8.75	10517.02	1.04	1.581	.56	228.62
.025	794.35	9.04	10904.56	1.11	1.586	.62	230.40
.026	818.49	9.31	11267.14	1.18	1.590	.67	232.02
.029	862.10	9.81	11922.16	1.32	1.597	.79	234.86
.032	900.05	10.24	12492.06	1.47	1.603	.91	237.25
.034	932.96	10.62	12986.34	1.62	1.608	1.04	239.29
.037	961.43	10.94	13414.09	1.76	1.611	1.18	241.05
.039	986.03	11.22	13783.48	1.92	1.615	1.31	242.57
.042	1007.24	11.46	14102.08	2.07	1.617	1.45	243.90
.044	1025.51	11.67	14376.50	2.22	1.619	1.59	245.07
.047	1041.23	11.85	14612.75	2.37	1.621	1.74	246.10
.050	1054.76	12.00	14815.98	2.53	1.622	1.88	247.02
.052	1066.40	12.14	14990.82	2.68	1.624	2.03	247.84
.055	1076.41	12.25	15141.17	2.84	1.625	2.18	248.57
.060	1092.43	12.43	15381.87	3.15	1.626	2.48	249.83
.065	1104.32	12.57	15560.39	3.46	1.627	2.79	250.87
.073	1116.71	12.71	15746.61	3.94	1.629	3.25	252.12
.083	1126.81	12.82	15898.38	4.57	1.630	3.87	253.37
.106	1137.17	12.94	16054.16	6.00	1.631	5.29	255.19
.183	1148.30	13.07	16222.20	10.79	1.632	10.05	257.68
.249	1155.79	13.16	16335.24	14.97	1.632	14.21	258.55
.255	1140.96	12.99	16112.51	15.33	1.631	14.57	258.60
.263	1128.01	12.84	15918.07	15.80	1.630	15.05	258.66
.273	1117.77	12.72	15764.40	16.42	1.629	15.67	258.71
.311	1107.56	12.61	15611.44	18.74	1.628	17.99	258.83
.322	1107.41	12.61	15609.22	19.35	1.628	18.60	258.86
.532	1118.03	12.73	15770.64	32.10	1.629	31.29	259.19

Table 3: (cont.)
ROCKET SAMPLE OUTPUT

TIME	PC	PE	F	WEIGHT	CF	WDOT EX	ISP
.736	1128.33	12.85	15927.39	44.65	1.630	43.77	259.41
.982	1138.41	12.97	16081.13	59.84	1.631	58.89	259.61
1.228	1148.53	13.08	16235.53	75.17	1.632	74.14	259.79
1.576	1158.84	13.20	16393.98	97.08	1.632	95.92	259.99
2.006	1169.16	13.33	16553.22	124.37	1.633	123.08	260.21
2.539	1175.18	13.40	16649.05	158.39	1.634	156.92	260.41
2.600	1175.38	13.40	16652.59	162.32	1.634	160.84	260.43
3.112	1173.38	13.39	16627.51	195.09	1.634	193.46	260.56
3.645	1164.48	13.29	16498.77	229.04	1.633	227.24	260.63
4.054	1153.28	13.17	16334.23	254.94	1.632	253.02	260.65
4.382	1142.12	13.04	16169.36	275.45	1.631	273.46	260.65
4.648	1130.45	12.91	15996.25	291.97	1.630	289.91	260.62
4.894	1118.50	12.78	15818.51	307.05	1.629	304.95	260.59
5.099	1108.47	12.66	15669.43	319.51	1.628	317.37	260.56
5.283	1097.31	12.54	15503.05	330.61	1.627	328.44	260.52
5.447	1087.16	12.42	15351.63	340.39	1.626	338.20	260.48
5.611	1077.07	12.31	15200.99	350.08	1.625	347.86	260.43
5.774	1066.62	12.19	15045.10	359.68	1.624	357.45	260.38
5.938	1054.58	12.06	14865.09	369.19	1.622	366.93	260.33
6.102	1042.41	11.92	14683.13	378.59	1.621	376.32	260.27
6.266	1030.32	11.78	14502.43	387.88	1.620	385.60	260.21
6.360	1019.22	11.66	14335.84	393.14	1.618	390.85	260.17
6.360	1006.86	11.51	14149.64	393.14	1.617	390.87	260.17
6.361	990.63	11.33	13901.90	393.14	1.615	390.91	260.17
6.361	974.65	11.15	13664.10	393.14	1.613	390.94	260.17
6.362	958.93	10.97	13427.16	393.14	1.611	390.97	260.17
6.363	928.25	10.62	12964.72	393.14	1.607	391.04	260.17
6.365	898.54	10.28	12517.07	393.14	1.603	391.10	260.16
6.366	869.79	9.95	12083.74	393.14	1.599	391.17	260.16
6.368	815.03	9.32	11258.29	393.14	1.589	391.28	260.16
6.371	763.71	8.73	10484.76	393.14	1.580	391.40	260.16
6.376	670.56	7.67	9080.83	393.14	1.558	391.60	260.15
6.381	588.77	6.73	7848.10	393.14	1.534	391.77	260.15
6.386	516.95	5.91	6765.68	393.14	1.506	391.93	260.14
6.391	453.90	5.19	5815.28	393.14	1.474	392.06	260.13
6.397	398.53	4.56	4980.80	393.14	1.438	392.18	260.12
6.402	349.92	4.00	4248.10	393.14	1.397	392.29	260.11
6.407	307.24	3.51	3604.78	393.14	1.350	392.38	260.10
6.412	269.76	3.50	3085.91	393.14	1.316	392.46	260.09
6.417	236.86	3.60	2644.44	393.14	1.285	392.53	260.08
6.422	207.96	3.69	2261.16	393.14	1.251	392.59	260.07
6.427	182 60	3.79	1936.15	393.14	1.220	392.65	260.07
6.432	160.32	3.89	1667.17	393.14	1.196	392.70	260.06
6.438	140.77	3.99	1433.56	393.14	1.172	392.74	260.05
6.443	123.60	4.09	1230.77	393.14	1.146	392.78	260.04
6.448	108.52	4.20	1054.80	393.14	1.118	392.81	260.04
6.453	95.28	4.31	902.18	393.14	1.089	392.84	260.03
6.458	83.66	4.43	769.88	393.14	1.059	392.86	260.02

Table 3: (cont.)
ROCKET SAMPLE OUTPUT

TIME	PC	PE	F	WEIGHT	CF	WDOT EX	ISP
6.463	73.46	4.54	655.25	393.14	1.026	392.88	260.02
6.473	56.63	4.79	470.06	393.14	.955	392.92	260.01
6.484	43.66	5.04	331.44	393.14	.874	392.95	260.00
6.494	33.65	5.31	227.84	393.14	.779	392.97	259.99
6.509	22.78	5.74	119.40	393.14	.603	392.99	259.99

AVERAGE THRUST FROM .000 SEC. TO 6.509 SEC. WAS 15696.570 lbf
TOTAL IMPULSE= 102172.50 SEC.

THRUST VS. TIME
THRUST
(1000 lbf)

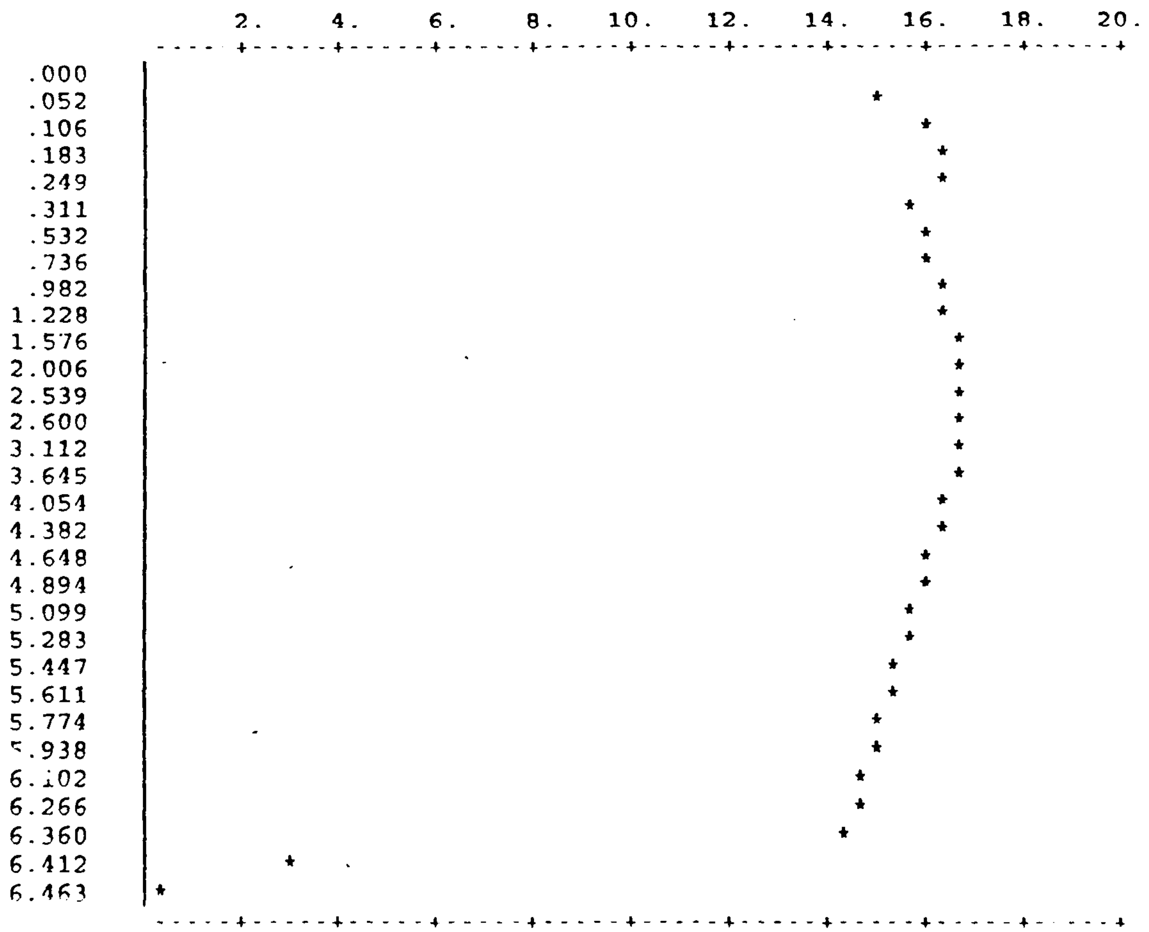
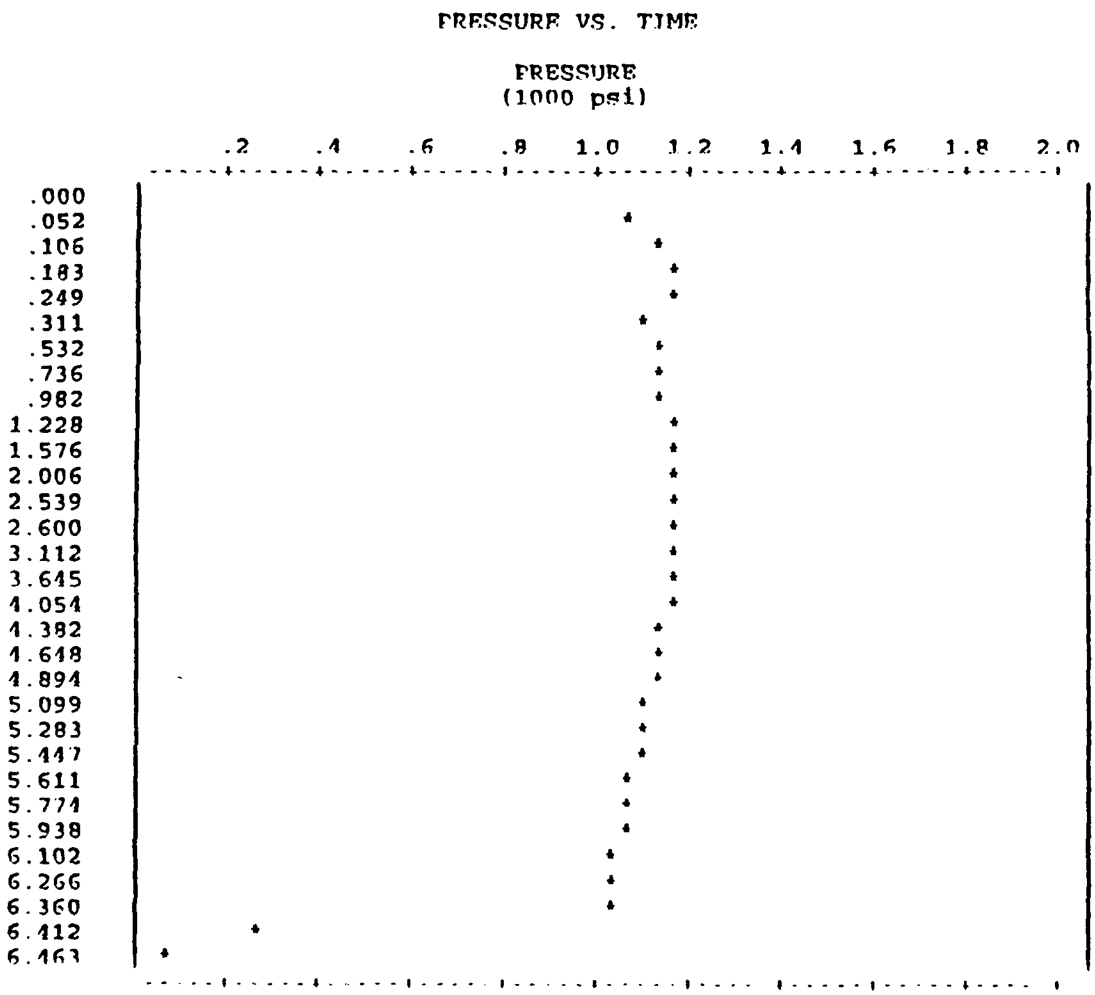


Table 3: (cont.)
ROCKET SAMPLE OUTPUT



IV. RESULTS AND CONCLUSIONS

A. RESULTS

In order to verify the accuracy of the modifications made to NEWPEP, several problems were run using the old version, the updated version and the NASA SP-273 code [Ref. 6]. The results for the following two problems are summarized in Table 4.

1. A mixture of 6% by weight H_2 and 94% by weight O_2 was burned at a chamber pressure of 3.447 MPa (500 psi) and expanded to an ambient pressure of 0.1014 MPa (14.7 psi).

2. A mixture of 85% by weight ammonium perchlorate and 15% HTPB (Sinclair) was burned at 6.8947 MPa (1000 psi) and expanded to an ambient pressure of 0.1014 MPa (14.7 psi). There were no significant differences in any of the output values.

B. CONCLUSIONS

PEP93 is an interactive program that works well on a personal computer. It allows the user to evaluate a wider variety of performance/design problems while using an existing, familiar program.

ROCKET was successfully modified to allow the use of multiple grains. This greatly enhances the ability to predict the performance of actual rocket motors.

Table 4:
SAMPLE COMPARISON OF NEWPEP/PEP93/NASA SP-273

Sample 1						Sample 2		
Ingredients						Ingredients		
	H2 6% by weight						AP 85% by weight	
	O2 94% by weight						HTPB 15% by weight	
		NEWPEP	PEP93	NASA SP-273		NEWPEP	PEP93	NASA SP-273
Chamber	P (MPa)	3.447	3.447	3.447		6.895	6.895	6.895
	T (K)	3272	3271.9	3273.05		2844	2844	2844.19
	H (kJ/kg)	0	0	0		-2132.58	-2132.79	-2133.15
	S (kJ/kg-K)	12.268	12.268	12.2631		10.15	10.15	10.146
Throat	P (MPa)	1.989	1.99	1.989		3.884	3.885	3.885
	T (K)	3096	3096.5	3097.35		2596	2595.8	2596.08
	H (kJ/kg)	-675.298	-675.501	-675.84		-2659.77	-2659.79	-2660.04
	S (kJ/kg-K)	12.268	12.268	12.2631		10.15	10.15	10.146
Exhaust	P (MPa)	0.101	0.101	0.101		0.101	0.101	0.101
	T (K)	2192	2191.9	2191.79		1324	1323.8	1323.67
	H (kJ/kg)	-3636.31	-3636.24	-3637.1		-4995.7	-4995.56	-4996.42
	S (kJ/kg-K)	12.268	12.368	12.2631		10.15	10.15	10.146
Performance								
Frozen								
Specific								
Impulse	(sec)	263	263.3	263.2		241.1	241.1	241
C*	(m/sec)	1734.9	1733.3	1734		1501.4	1501	1501
Ae/A*		5.09	5.099	5.099		8.09	8.091	8.0894
Cf		N/A	1.4895	1.489		N/A	1.575	1.575
Shifting								
Specific								
Impulse	(sec)	275	275	274.9		244	244	243.9
C*	(m/sec)	1772.7	1772.7	1773		1513.5	1513.5	1514
Ae/A*		5.77	5.768	5.7662		8.36	8.361	8.3596
Cf		N/A	1.5215	1.521		N/A	1.5812	1.581
Shifting/Frozen								
Specific								
Impulse	(sec)	N/A	267.2	267.1		N/A	242.5	242.4
C*	(m/sec)	N/A	1772.7	1773		N/A	1513.5	1514
Ae/A*		N/A	5.11	5.109		N/A	8.105	8.104
Cf		N/A	1.4781	1.478		N/A	1.5711	1.571

APPENDIX A

USER'S GUIDE FOR PEP93

(Changes in **Bold**)

A. GENERAL

1. The files NEWPEP.FOR, NEWEQUIL.FOR and NEWDSIGN.FOR are needed to create NEWPEP.EXE. In addition, several common blocks are needed. BLANK.INC, CHARA.INC, IBRIUM.INC, SCRATCH.INC and SIZE.INC.

2. The data files JANNAF.DAT and PEPCODED.DAT are needed to run PEP93.

B. INPUT

1. Up to **15** ingredients may be input by the user. These ingredients may be coded ingredients from the PEPCODED.DAT file or user defined ingredients, or both.

2. The user is prompted for the following inputs when PEP93 is run:

   a. File name (up to 30 characters)

   b. Run title (up to 17 characters)

   c. **Vitiated air option**

      (1) Number of coded ingredients for vitiator

      (2) Number of user defined ingredients for vitiator

      (3) Ingredient code numbers from PEPCODED.DAT

(4) User defined ingredient name, composition, heat of formation and density

(5) Chamber pressure

(6) Chamber inlet temperature

(7) Ingredient weights

d. Number of coded ingredients for combustor

e. Number of user defined ingredients for combustor

f. Number of runs

g. Density exponent used in calculating density (defaults to 1.0)

h. Propellant temperature to adjust the system enthalpy for heating or cooling
(default is 298K)

i. Quadratic coefficients for solid specific heat. Used to adjust the system enthalpy for heating or cooling (defaults to 0.3 cal/gm-K)

j. Nozzle discharge coefficient (defaults to 1.0)

k. Options

(1) Delete exit calculations

(2) Include ionic species in calculations

(3) Include boost velocities and nozzle design data

(4) Input pressures in psi instead of MPa

(5) Increase numerical precision of species concentrations

(6) Output a list of all combustion species considered

(7) Fix temperature

(8) Debug options

(a) Thermo data at every guess

(b) Values of J, M, VF, PR, VA in subroutine TWITCH

(c) Species composition every guess

(d) Log of equilibrium constant every guess

(e) Classification of species each iteration from TWITCH

(9) Exact or approximate throat calculations

(10) Normalize or not normalize to 100 grams

(11) Calculate non-ideal expansion performance

(12) Calculate chamber Mach number

l. Ingredient code numbers from PEPCODED.DAT

m. User defined ingredient name, composition, heat of formation and density

n. Chamber pressure **(MPa)**

o. Exhaust pressure **or area ratio and ambient pressure** (see note 2)

p. Ingredient weights

q. Ratio of chamber area to throat area

3. Notes:

a. Format for user defined ingredients

(1) Ingredient name - A30

(2) #atoms of element/symbol of element - 6(I3, A2)

(3) Heat of formation(cal/gram) - F5.0

(4) Density(gm/cm^3) - F6.0

b. If the non-ideal expansion option is not chosen, the exhaust pressure is used for input "o" and is also equal to the ambient pressure. If the non-ideal expansion option is chosen, the ratio (exit area/throat area) and the ambient pressure are input at "o".

C. SAMPLE INPUT

```
TYPE IN OUTPUT FILE NAME (DEFAULT: PEPOUT.DAT)
If you wish to direct to a printer, type in
printer name such as "LPT1" for the IBM PC
or "LPAO:" for the VAX.
To send output to screen, type "TT;" (VAX & IBM PC)


TYPE RUN TITLE (char*17) OR type quit.
sample
DO YOU WANT TO CALCULATE COMPOSITION AND ENTHALPY OF
VITIATED AIR?  1=YES,2=NO
1
INPUT NO. OF CODED ING., NO. OF USER DEFINED ING. FOR
VITIATOR
2,0

READ IN 2 INGREDIENT CODE NUMBERS SEP. BY COMMAS
44,729

READ IN CHAMBER PRESSURE (MPa), CHAMBER INLET TEMPERATURE
(K), wt1,wt2, +etc.  2.068,700.,96.,4.

BEGIN ENGINE DATA INPUT.

NO. OF CODED ING., NO. OF USER DEFINED ING., AND NO.OF RUNS
=
NOTE:  INPUT VITIATED AIR AS A USER DEFINED INGREDIENT.
1,1,1
DENSITY EXPONENT (DEFAULTS TO 1.0) =

PROPELLANT TEMPERATURE (DEFAULTS TO 298.0) =

 ENTER THREE VALUES FOR CSUBP FIT
 FIRST VALUE = 0.0 DEFAULTS TO 0.30

NOZZLE DISCHARGE COEFFICIENT (DEFAULTS TO 1.0) =

OPTIONS;    1-DELETE EXIT CALCULATIONS
            2-INCLUDE IONIC SPECIES IN CALCULATIONS
            3-INCLUDE BOOST VELOCITIES AND NOZZLE DESIGN DATA
            4-INPUT PRESSURES IN PSI INSTEAD OF MPA
            5-"N" ORDERS OF MAGNITUDE SPECIES PRECISION
              INCREASE
            6-OUTPUT A LIST OF ALL COMBUSTION SPECIES
              CONSIDERED
            7-DEBUG OPTIONS
            8-"P-T-H-S" MAP OPTION
            9-"0"=exact throat "1"=approx throat "2"=exact
              with throat composit.
            0-"1"=do not normalize weights to 100 gms
```

```
               "0"=normalize
             A-CALCULATE NON-IDEAL EXPANSION PERFORMANCE
             B-CALCULATE CHAMBER MACH NUMBER
1234567890AB**put 0-no or 1-yes under number (opt 5 takes 0
or"n")
000000000011

READ IN 1 INGREDIENT CODE NUMBERS SEP. BY COMMAS
714

VITIATED AIR IS AUTOMATICALLY ENTERED AS FIRST USER DEFINED
INGREDIENT

READ IN CHAMBER PRESSURE (MPa),AREA RATIO,AMBIENT PRESSURE
(MPa), WT1,WT2, +ETC.
INCLUDE DECIMAL POINT AND SEPARATE BY COMMAS
INPUT A ZERO CHAMBER PRESSURE TO ADD INGREDIENTS AGAIN
INPUT A -1.O TO END PROGRAM
1.379,5.,14.7,7.,93.

INPUT RATIO OF CHAMBER AREA TO THROAT AREA TO.
CALCULATE MACH NUMBER AT STATION 4
1.5

TYPE RUN TITLE (char*17) OR type quit
quit
Stop - Program terminated
```

D. SAMPLE OUTPUT

See Table 2.

APPENDIX B

USER'S GUIDE FOR ROCKET

A. INPUT

1. The data file CARD.DAT is needed to run ROCKET and consists of the following variables.

Title					
Ath	Ae	Vol	Tp	Po	Pb
Pi	η_{cf}	γ	Pd	td	
ET#					
pressure 1	erosion rate at pressure 1				
pressure 2	erosion rate at pressure 2				
etc.	etc.				
G#					
$\dot{r}$	n	Π_k	P_{ref}	C*	X
ρ_p	t_i	Δt_i	r_{ab}		
pts	id#				
Wb	Ab				
0	0	0			

where

Ath Throat area (in^2)

Enter a positive area if it is known

Enter a negative area for a first guess if unknown

Enter zero if you have no first guess (very slow)

Ae Nozzle exit area (in^2)

Vol Total motor volume without propellant or igniter (in^3)

Tp Ambient propellant temperature (^oF)

Po Ambient pressure (psia)

Pb Throat plug closure blowout pressure (psia){typically 35}

Pi Initial motor pressure (psia)

η_{cf} Nozzle loss coefficient

γ Generally use γ_v for shifting equilibrium flow (PEP93)

Pd Design pressure for sizing the throat (psia)

td Throat erosion delay time (sec)

Positive value: fixed rate from t=0 (i.e. 0.0005 in/sec)

Negative : equals the time delay for onset of erosion

Negative or 0: must include pressure vs. erosion rate table (Erosion rates are radial in in./sec)

ET# Number of points for throat erosion table

G# Number of grains

$\dot{r}$ Propellant burning rate at P_{ref} (in./sec)

n Burning rate exponent ($\dot{r}=aP_c^n$)

Π_k Propellant temperature sensitivity (%/^oF)

P_{ref} Reference pressure for the specified burning rate (psia)

C* Characteristic exhaust velocity at P_{ref} (ft/sec)

X Pressure correction exponent for C*

ρ_p Density of grain(lbm/in^3){propellant,igniter or insulation}

t_i Ignition time (sec) {0 if no igniter}

Δt_i Ignition time delay (sec) {0 if no igniter}

pts Number of points in web burned vs. burning surface area table

Wb Web distance burned (in)

Ab Propellant burning surface area (in^2)

Ab_i Exposed insulation area (in^2)

id# Identification number for grain

1:igniter

2:insulation

3:propellant

$\dot{r}_{ab}$ Insulation ablation rate

2. Notes:

   a. All input data is formatted F12.6 except:

      (1) Title - no format required

      (2) ET#,G# - format I3

   b. Enter 0 in columns 3,6 and 9 of the last row.

   c. Igniters:

      (1) $\dot{r}$ always equal to 1

      (2) pts is # of points in time vs. $\dot{m}$ curve

      (3) Wb=time (sec)

      (4) Ab= $\dot{m}$ (lbm/sec)

   d. Insulation:

      (1) $\dot{r}$,n,Π_k and P_{ref} refer to the propellant

grain, not to the insulation. They are used to calculate a reference web which can be used to describe the amount of insulation exposed during a firing. C^*, X, ρ_p, t_i and Δt_i are for the insulation.

(2) Wb is the web of the associated propellant grain. Ab is the exposed insulation area.

B. OUTPUT

1. Input data is printed with all values labeled.
2. Output data consists of the following:
   a. Total propellant weight and igniter weight.
   b. A table of time, chamber pressure, change in pressure, total motor volume, propellant weight consumed, rate of mass addition due to propellant burning, insulation weight consumed, rate of mass flow through the nozzle and throat area.
   c. Average and maximum pressure for run.
   d. A table of time, chamber pressure, exit pressure, thrust, coefficient of thrust, rate of mass flow through the nozzle and specific impulse.
   e. Average thrust and total impulse.
   f. Plots of thrust versus time and pressure versus time.
3. **Time, pressure, and thrust are also put into the data file PLOT.DAT**

C. SAMPLE INPUT

See Table 5.

D. SAMPLE OUTPUT

See Table 3.

Table 5:
ROCKET SAMPLE INPUT

```
15percent
  8.657700 105.450000 8042.477000   70.000000   10.130000   35.000000
 14.700000   0.960600    1.144300 1030.000000    0.000500
 3
  0.580000   0.350000    0.200000 1030.000000 5106.660000    0.045000
  0.062300   0.000000    0.000000
11   3
  0.000000 1448.300000
  0.380900 1519.500000
  0.761800 1542.500000
  1.142800 1557.300000
  1.523700 1563.900000
  1.904600 1562.300000
  2.285500 1552.500000
  2.666400 1534.500000
  3.047400 1508.200000
  3.428300 1473.800000
  3.809200 1431.200000
  0.580000   0.350000    0.200000 1030.000000 5106.660000    0.045000
  0.062300   0.000000    0.000000    0.050000
11   2
  0.000000 1488.300000
  0.380900 1519.500000
  0.761800 1542.500000
  1.142800 1557.300000
  1.523700 1563.900000
  1.904600 1562.300000
  2.285500 1552.500000
  2.666400 1534.500000
  3.047400 1508.200000
  3.428300 1473.800000
  3.809200 1431.200000
  1.000000   0.000000    0.000000    0.000000 5106.660000    0.045000
  0.062300   0.000000
 2   1
  0.000000   1.400000
  0.250000   1.900000
 0   0   0
```

APPENDIX C

PEP93 SUBROUTINE EQUIVALENCE

```
SUBROUTINE EQUIVALENCE(equiv)
  INCLUDE 'size.inc'
  INCLUDE 'blank.inc'
  INCLUDE 'chara.inc'
  INCLUDE 'scratch.inc'
  INCLUDE 'ibrium.inc'
  real ostoic,oin,equiv
  common/llist/atwt(100)
  ostoic=0.0
  do 10 j=1,is
       if(aspec(j) .eq. 'Ag') ostoic=ostoic+alp(j)
       if(aspec(j) .eq. 'Al') ostoic=ostoic+alp(j)*3.0/2.0
       if(aspec(j) .eq. 'B' ) ostoic=ostoic+alp(j)*3.0/2.0
       if(aspec(j) .eq. 'Ba') ostoic=ostoic+alp(j)*2.0
       if(aspec(j) .eq. 'Be') ostoic=ostoic+alp(j)
       if(aspec(j) .eq. 'Bi') ostoic=ostoic+alp(j)*3.0/2.0
       if(aspec(j) .eq. 'C' ) ostoic=ostoic+alp(j)*2.0
       if(aspec(j) .eq. 'Ce') ostoic=ostoic+alp(j)*2.0
       if(aspec(j) .eq. 'Cr') ostoic=ostoic+alp(j)*3.0
       if(aspec(j) .eq. 'Cs') ostoic=ostoic+alp(j)*3.0/2.0
       if(aspec(j) .eq. 'Cu') ostoic=ostoic+alp(j)
       if(aspec(j) .eq. 'Fe') ostoic=ostoic+alp(j)*3.0/2.0
       if(aspec(j) .eq. 'H' ) ostoic=ostoic+alp(j)/2.0
       if(aspec(j) .eq. 'Hg') ostoic=ostoic+alp(j)
       if(aspec(j) .eq. 'K' ) ostoic=ostoic+alp(j)*2.0
       if(aspec(j) .eq. 'Li') ostoic=ostoic+alp(j)
       if(aspec(j) .eq. 'Mg') ostoic=ostoic+alp(j)*2.0
       if(aspec(j) .eq. 'Mn') ostoic=ostoic+alp(j)*2.0
       if(aspec(j) .eq. 'Mo') ostoic=ostoic+alp(j)*3.0
       if(aspec(j) .eq. 'Na') ostoic=ostoic+alp(j)*2.0
       if(aspec(j) .eq. 'Ni') ostoic=ostoic+alp(j)
       if(aspec(j) .eq. 'P' ) ostoic=ostoic+alp(j)*5.0/2.0
       if(aspec(j) .eq. 'Pb') ostoic=ostoic+alp(j)*2.0
       if(aspec(j) .eq. 'Rb') ostoic=ostoic+alp(j)*2.0
       if(aspec(j) .eq. 'S' ) ostoic=ostoic+alp(j)*2.0
       if(aspec(j) .eq. 'Si') ostoic=ostoic+alp(j)*2.0
       if(aspec(j) .eq. 'Sn') ostoic=ostoic+alp(j)*2.0
       if(aspec(j) .eq. 'Th') ostoic=ostoic+alp(j)*2.0
       if(aspec(j) .eq. 'Ti') ostoic=ostoic+alp(j)*2.0
       if(aspec(j) .eq. 'U' ) ostoic=ostoic+alp(j)*2.0
       if(aspec(j) .eq. 'V' ) ostoic=ostoic+alp(j)*5.0/2.0
       if(aspec(j) .eq. 'W' ) ostoic=ostoic+alp(j)*3.0
       if(aspec(j) .eq. 'Zn') ostoic=ostoic+alp(j)
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```
     if(aspec(j) .eq. 'Zr') ostoic=ostoic+alp(j)*2.0
     if(aspec(j) .eq. 'O')oin=alp(j)
 10 continue
    equiv=ostoic/oin
    return
```

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