SCAP Spray Combustion Analysis Program

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FOREWORD

This report was prepared by Software and Engineering Associates, Inc., Carson City NV, under contract F29601–91–C–0099, for Operating Location AC, Phillips Laboratory, Edwards AFB, CA 93524–7660. Project Manager for Phillips Laboratory was John Pan.

This report has been reviewed and is approved for release and distribution in accordance with the distribution statement on the cover and on the SF Form 298.

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A computer program (SCAP) has been developed which determines the state of a propellant combustion mixture at any point along the axis of a bipropellant rocket engine. The combustion model is based upon the work of Priem and Heidmann and has been extended to handle generalized propellant and gas property data. The primary assumption of this method is that the propellant vaporization is the rate governing mechanism of the combustion process and that the vaporization of the drops can be expressed by a Ranza and Marshall type correlation.

The governing equations consider mass, momentum, and heat transfer between the gas and liquid phases; and are cast in one dimension. The equations are represented by a set of ordinary differential equations and are solved simultaneously using the 4th order Runge-Kutta Adams-Moulton method.

This report describes the program inputs and engineering methods for the SCAP computer code.
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1.0 TECHNICAL DISCUSSION

1.1 Introduction

The steady-state Spray Combustion Analysis computer Program (SCAP) determines the state of the propellant combustion product mixture at any point along the axis of a liquid bipropellant rocket engine based on the evaporation rates of the propellants. The model is based on the vaporization model of Priem and Heidmann\(^1\), with the exception that gasdynamics is treated in greater detail. The Computer Program also differs from the one presented in Reference 1 in that; 1) the different equations are integrated simultaneously rather than in nested loops and; 2) the program accepts general propellant and gas property data.

This version of SCAP is run as a module of both the VIPER\(^2\) and TDK\(^3\) computer programs.

Necessary inputs to the program are propellant flow rate, temperature, injector velocity, physical properties, and drop size distribution of each propellant, and also the chamber pressure at the injector. Assuming steady-state operation, the program computes the condition of the propellants and combustion products by integrating (from the initial conditions at the injector) the continuity, momentum, and energy equations along the length of the chamber. The derivatives of all variables are determined explicitly using Euler integration. All physical properties are either input as tables, or computed automatically by subroutines.

The output of the steady-state program includes the annular stability parameters, i.e., burning rate parameter, drag parameter, relative velocity between droplets and gases, and the Reynolds number based on the speed of sound, that are required by the combustion instability model computer program described in Reference 4. This combustion instability model is an extension of the nonlinear analysis of combustion instability based on propellant vaporization that was originally developed by Priem and and Guentert, Reference 5. Using the stability parameters provided by the steady-state program as a starting point, the combustion instability program will determine the minimum threshold disturbance required to trigger instability.

The methods of analysis used by the steady-state program are described below.

1.2 Method of Analysis

The basic model used in the Steady-State Combustion Program is an extension of the original work of Priem and Heidmann, Reference 1. The model considers the conservation equations governing the heat, mass, and momentum transfer of a spray of liquid oxidizer and fuel drops traveling through a channel filled with gas phase combustion products. The assumption is made that propellant vaporization is the rate governing mechanism of the combustion process and that vaporization of the drops can be expressed by a Ranz and Marshall type correlation,
Reference 6. The drops are injected at specified temperature and velocity, as a distribution about a mass median drop size into a quiescent chamber of combustion gases. As the drops vaporize mass into the combustion chamber the gas velocity increases. During this period the liquid temperature increases to its "wet bulb" value and the droplet velocities decrease because of drag forces. After the drops pass through the zero relative velocity region they are accelerated by the combustion gases.

1.2.1 Propellant Properties

An extensive set of properties must be provided to the program for each oxidizer/fuel combination. This is accomplished by reading the appropriate propellant properties deck, as described in Section 3. The required properties include: 1) the equilibrium composition of the combustion products, average molecular weight, and specific heat ratio as a function of pressure, temperature, and mixture ratio, 2) viscosity and specific heat for each species vs. temperature, 3) species molecular weight, 4) species and propellant interaction energies, 5) species and propellant molecular diameters, and 6) oxidizer and fuel liquid and vapor properties. At present the following propellant property combinations are provided with the program:

\[ \begin{align*}
&\text{N}_2\text{O}_4 / \text{N}_2\text{H}_4 , \\
&\text{N}_2\text{O}_4 / \text{MMH} , \\
&\text{N}_2\text{O}_4 / \text{A50} , \\
&\text{N}_2\text{O}_4 / \text{UDMH} , \\
&\text{LOX} / \text{RP-1} , \\
&\text{LOX} / g \text{C}_3\text{H}_8 , \\
&\text{Air} / \text{JP4} , \\
&\text{LOX} / g \text{H}_2 , \\
&\text{LOX} / g \text{CH}_4 , \\
&\text{and}
\end{align*} \]

1.2.2 Initial Conditions

The first step in the computer program is the establishment of the size and number distribution of the drops of each propellant to be used in the calculation. The drop size distribution for each propellant is determined by specifying the mass mean drop diameter, \( \bar{D} \), a standard deviation \( \sigma_D \), and the desired number of drop size groups, \( N \). A drop radius vector, \( r \), is then computed such that, assuming a log normal distribution as discussed in Reference 1, each propellant is divided into \( N \) groups of equal mass. Since the smallest drop group sometimes dominates a combustion instability analysis, it can be similarly subdivided into \( N_s \) groups, so that the total number of drop groups is \( N_i = N + N_s - 1 \).

Next, drop mass flux and number flux vectors are computed using the drop radius vector, the propellant density, and the injector mass flow rate for each propellant. Once these vectors have been determined, initialization of the calculation is essentially complete. The propellants
have each been divided into a large number of drops of different size groups with known mass, velocity, and temperature. With the other inputs to the program such as engine geometry and operating conditions, these drop properties are sufficient to calculate mass, heat, and momentum transfer between the drops and the combustion gases, and subsequent changes in conditions of combustion gases and drop properties as a result of these exchanges. Starting with the conditions at the injector, the calculations are integrated down the axis of the chamber to describe the conditions throughout.

1.2.3 Mass Transfer (Vaporization) for Drops

The rate of evaporation from a spherical drop of propellant A is assumed to be given by:

\[
w_A = \frac{4\pi k_m M_A P_A}{RT_f} \left( \ln \left( \frac{P}{P - P_A} \right) \right) \quad \text{(lbm/sec)} \tag{1}
\]

which is equivalent to the expression given by Priem in Reference 1. In the above equation:

\[
\begin{align*}
w_A &= \text{transfer rate, mass of A per unit time} \\
r &= \text{radius of drop} \quad \text{(ft)} \\
k_m &= \text{mass transfer coefficient, determined from the} \\
&\quad \text{Nusselt number, } Nu_m \\
k_m &= Nu_m D_A \frac{r}{2} \quad \text{(ft}^3/\text{sec}) \tag{2} \\
Nu_m &= \text{Nusselt number for mass transfer (Sherwood number)} \\
D_A &= \text{diffusivity of A at the conditions in the film} \quad \text{(ft}^2/\text{sec}) \\
M_A &= \text{molecular weight of A} \\
P_A &= \text{vapor pressure of A} \quad P_A < P_{crit} \\
P &= \text{chamber pressure} \quad \text{(lbf/ft}^2) \\
\tilde{R} &= \text{universal gas constant} \\
T_f &= \text{average absolute temperature in the vapor film} \\
&\quad \text{between the drop and the bulk gas} \\
T_f &= \frac{T_L + T_g}{2} \quad \text{(°R)} \\
T_L &= \text{liquid drop temperature} \quad \text{(°R)} \\
T_g &= \text{bulk gas temperature} \quad \text{(°R)}
\end{align*}
\]

The Nusselt number for mass transfer is determined from the Ranz and Marshall equation (see Reference 6, page 647):

\[
Nu_m = 2 + 0.6 \operatorname{Re}^{1/2} \operatorname{Sc}^{1/3} \quad \text{(unitless)}
\]

where
\[ \text{Re}_f = \frac{2 \rho_f |U - V|}{\mu_f} \]  
(Reynolds number, evaluated at film conditions, i.e. unitless)  
(4)

\[ \rho_f = \text{density of the gas in the film} \]  
\(\text{lbm/ft}^3\)  
\(\mu_f = \text{viscosity of the gas in the film} \)  
\(\text{lbm/ft-sec}\)  
\(U = \text{velocity of the combustion gas} \)  
\(\text{ft/sec}\)  
\(V = \text{velocity of the drop} \)  
\(\text{ft/sec}\)  
\[ Sc_f = \frac{\mu_f}{\rho_f D_A} \]  
(Schmidt number evaluated at film conditions, Reference 6, page 512, i.e. unitless)  
(5)

Knowing the Nusselt number, \(k_m\) can be evaluated and \(w_A\) for the drop determined.

The time rate of change of the mass of a drop is simply

\[ \frac{dm}{dt} = -w_A \]  
(lbm/sec)  
(6)

Knowing the evaporation rate, only the heat transfer rate is required to complete an energy balance for the drop and determine the effect of net energy exchange on the drop temperature.

1.2.4 Heat Transfer Model

The rate of heat transferred to the drop by convection is determined by the equation

\[ Q_c = 4\pi r^2 h^o (T_g - T_L) \]  
(BTU/sec)  
(7)

where

\[ Q_c = \text{heat per unit time transferred by convection} \]

\[ h^o = \text{convective heat transfer coefficient corrected for the effect of concurrent mass transfer} \]

From film theory (Preim, Reference 1, eq. 22 and 20) \(h^o\) can be related to \(h\), the heat transfer coefficient with no mass transfer by

\[ h = Nu_h k_f / 2r \]  
(BTU/sec-ft²-R)  
(8)

\[ h^o = h \left[ \frac{z}{e^z - 1} \right] \]

where (Reference 1, eq. 16)
\[ z = \frac{w_A C_{PAf}}{4 \pi^3 h} \quad \text{(unitless)} \quad (10) \]

\[ C_{PAf} = \text{specific heat of vapor of A at the film conditions.} \quad \text{(BTU/lbm-R)} \]

The heat transfer coefficient without mass transfer, \( h \), is determined from the Ranz-Marshall equation (Reference 1, eq. 22).

\[ \text{Nu}_h = 2 + 0.6 \text{Re}_f^{1/2} \text{Pr}_f^{1/3} \quad \text{(unitless)} \quad (11) \]

where \( \text{Re}_f \) is determined by equation (4), and

\[ \text{Pr}_f = \frac{\text{Pr} \text{at film conditions, i.e.}}{\text{Pr}} \]

\[ \text{Pr}_f = \frac{C_{PAf} \mu_f}{k_f} \quad (12) \]

\[ k_f = \text{thermal conductivity of the gas in the film} \quad \text{(BTU/ft-sec-R)} \]

When the convective heat transfer to the drop has been determined, an energy balance for the drop will give the rate of change of temperature of the drop.

1.2.5 Energy Balance for Drops

For any single drop the rate of accumulation of energy at any time must equal the net energy transferred to the drop. By equation this is expressed as

\[ m C_{pl} \frac{dT_L}{dt} = Q_c - w_A \lambda - \frac{w_A v^2 \text{rad}}{2 Jg} \quad \text{(BTU/sec)} \quad (13) \]

where

\[ m = \text{mass of drop} \]

\[ C_{PL} = \text{specific heat of liquid at } T_L \]

\[ \lambda = \text{latent heat of vaporization at } T_L \]

\[ v_{\text{rad}} = \text{radial velocity of vaporized propellant leaving the drop surface} \]

\[ v_{\text{rad}} = w_A / \rho_{\text{vap}} S \cdot S = 4 \pi r^2 \]

\[ J = \text{constant for conversion of mechanical energy to thermal energy} \]

In applying this equation it is assumed that the drop has uniform temperature throughout due to rapid internal convection. The third term on the right side of the equation is the kinetic energy imparted to the vapor leaving the surface. Most investigators have not included this term since it is usually relatively small. It has been included here since it could be important for small radii and/or when the drop is near or at the critical temperature of the propellant and \( \lambda \) approaches or equals zero.
From equation (13) the rate of change of the drop temperature with time, or distance, can be evaluated.

The procedure just described to determine the mass-transfer rate and then determine the change in temperature of the drop is the one normally employed in the program. However, when the drop temperature approaches the boiling point of the liquid, a second procedure is used in order to eliminate the numerical difficulties associated with \( P - P_A \) approaching zero in the denominator of equation (1). Under these circumstances the energy transfer to the drop determines the rate of vaporization, \( w \), which can be found by evaluating properties at \( T_L \) equal to the liquid boiling point at the chamber pressure and by setting \( \frac{dT_L}{dt} = 0 \). Equation (13) is then solved for \( w \).

The only remaining calculation is to determine the rate of change of velocity of the drop as a result of momentum exchange with the combustion gas.

1.2.6 Force Balance for Drops

A force balance on the drop yields the equation

\[
\rho_L \frac{4}{3} \pi r^3 \frac{dV}{dt} = \pi r^2 C_D \rho \frac{(U - V)(U - V)}{2} \tag{14}
\]

\( \rho_L \) = drop density

\( V \) = drop velocity

\( C_D \) = drag coefficient

\( \rho \) = gas density

\( U \) = gas velocity

The drag coefficient is found as a function of Reynolds number:

\[
\begin{align*}
C_D &= \min(27 \text{ Re}_f^{-0.84}, 50) \quad & 0 \leq \text{Re}_f < 80 \\
C_D &= 0.271 \text{ Re}_f^{0.17} \quad & 80 \leq \text{Re}_f < 10^4 \\
C_D &= 2 \quad & \text{Re}_f \geq 10^4
\end{align*} \tag{15}
\]

From equations (7), (13), and (14), and since \( \frac{dt}{dx} = \frac{dV}{V} \), the differential equations governing drop mass, drop temperature, and drop velocity, are found to be:

\[
\frac{dm}{dx} = -\frac{w}{V} \tag{16}
\]
\[
\frac{dT_l}{dx} = \frac{Q_c - w\lambda \cdot \frac{w v^2_{rad}}{2J}}{mVC_{pl}}
\]  

(17)

and

\[
\frac{dV}{dx} = \frac{3}{8} \frac{\rho |U - V|(U - V)}{\rho_L V} C_O
\]  

(18)

1.2.7 Equations for Steady State Combustion

For one-dimensional steady state flow, consideration of fluxes in and out of an incremental length, \(dx\), along the combustion chamber lead to expressions for continuity, momentum, and energy at any point.

The continuity equation can be expressed as

\[
\Phi + \sum n_i m_i = F_T
\]  

(19)

where

\[
\Phi = \rho UA, \text{ gas mass flux}
\]

\[
\rho = \text{ gas density}
\]

\[
U = \text{ gas velocity}
\]

\[
A = \text{ the local cross-sectional area of the chamber}
\]

\[
n_i = \text{ number flux, i.e., the number of drops of mass } m_i \text{ flowing per unit time past position } x. \ (1/\text{sec})
\]

\[
m_i = \text{ mass of the } i\text{th drop}
\]

\[
F_T = \text{ total propellant feed rate, lbs/sec.}
\]

\[F_T = F_{ox} + F_{fuel}\]  

(20)

It follows that

\[
\frac{d\Phi}{dx} + \sum n_i \frac{dm_i}{dx} = 0
\]  

(21)

so that

\[
\frac{dU}{dx} = -\left(\frac{U}{A} \frac{dA}{dx}\right) - \left(\frac{U}{\rho} \frac{dp}{dx}\right) - \left(\frac{1}{\rho A} \sum n_i \frac{dm_i}{dx}\right)
\]  

(22)

The momentum equation can be expressed as
\[
- \frac{\text{d}P}{\text{d}x} = \frac{\text{d}P}{\text{d}x}^{\text{(gas \ mom.)}} + \sum n_i \frac{\text{d}m_i}{\text{d}x}^{\text{(part \ mom.)}}
\]

where

\begin{align*}
  g &= \text{gravitational constant, } 32.174 \text{ ft/sec}^2 \\
  P &= \text{pressure} \\
  V_i &= \text{velocity of the } i\text{th drop}
\end{align*}

Since equation (21) gives

\[
\frac{\text{d}\Phi}{\text{d}x} = -\sum n_i \frac{\text{d}m_i}{\text{d}x}
\]

it follows that

\[
\frac{\text{d}P}{\text{d}x} = \frac{U}{A_g} \sum n_i \frac{\text{d}m_i}{\text{d}x} - \frac{\rho U \text{d}U}{g \text{d}x} - \frac{1}{A_g} \left[ \sum n_i m_i \frac{\text{d}V_i}{\text{d}x} + \sum n_i V_i \frac{\text{d}m_i}{\text{d}x} \right]
\]

The energy equation used by the steady-state program is simply:

\[
T = T_o - \frac{\gamma - 1}{2\gamma} \frac{U^2}{g R}
\]

where

\begin{align*}
  T &= \text{gas temperature} \\
  T_o &= \text{gas total temperature} \\
  \gamma &= \text{gas specific heat ratio} \\
  R &= \text{gas constant, } \tilde{R} / M_w \\
  M_w &= \text{gas molecular weight}
\end{align*}

It follows that

\[
\frac{\text{d}T}{\text{d}x} = \frac{\text{d}T_o}{\text{d}x} \frac{1}{g R} \left[ \frac{\gamma - 1}{\gamma} \frac{\text{d}U}{\text{d}x} + \frac{\gamma - 1}{2\gamma M_w} \frac{U^2}{\text{d}x} \right]
\]

The equation of state used by the steady-state program is

\[
P = \rho R T
\]

It follows that:

\[
\frac{\text{d}p}{\text{d}x} = \frac{1}{RT} \frac{\text{d}P}{\text{d}x} - \frac{P}{RT^2} \frac{\text{d}T}{\text{d}x} + \frac{P}{TRM_w} \frac{\text{d}M_w}{\text{d}x}
\]
1.2.8 Method of Numerical Solution

The differential equations previously described are solved as a set of \((1 + N_{ox} + N_{fuel})\) simultaneous ordinary differential equations using the 4th order Runge-Kutta Adams-Moulton integration method (see Subroutine RKAM). The form the equations take is given below.

For the gas phase, a single ordinary differential equation (the momentum equation) is given by equation 24, and is repeated here for convenience.

\[
\frac{dP}{dx} = \frac{U}{Ag} \sum n_i \frac{dm_i}{dx} - \frac{\rho U}{g} \frac{dU}{dx} - \frac{1}{Ag} \left[ \sum n_i m_i \frac{dV_i}{dx} + \sum n_i V_i \frac{dm_i}{dx} \right]
\]

The terms \(U, \rho, T, du/dx, dp/dx, \) and \(dT/dx\) are determined from equations 19, 27, 25, 22, 28, and 26, respectively.

\[
U = \frac{(F_T - \sum n_i m_i)}{\rho A}
\]

\[
\rho = \frac{P}{RT}, \quad R = R/M_w
\]

\[
T = \frac{T_o - \frac{\gamma - 1}{2\gamma} \frac{U^2}{gR}}
\]

\[
\frac{dU}{dx} = -\frac{U}{A} \frac{dA}{dx} - \frac{U}{\rho} \frac{dp}{dx} - \frac{1}{\rho A} \sum n_i \frac{dm_i}{dx}
\]

\[
\frac{dp}{dx} = -\frac{1}{RT} \frac{dP}{dx} - \frac{P}{RT^2} \frac{dT}{dx}
\]

\[
\frac{dT}{dx} = \frac{dT_o}{dx} - \frac{1}{gR} \frac{U}{\gamma - 1} \frac{dU}{dx}
\]

Note that the terms \(dM_w/dx\) and \(dy/dx\) in equations (26) and (28) are neglected. These terms have been found to be so small that no significant error results from their elimination.

For the condensed phase there are \(N_{ox} + N_{fuel}\) ordinary differential equations (ODE's) as given by equations (16), (17), and (18), as follows:

\[
i = 1, 2, ..., N_{ox}, ..., N_{ox} + N_{fuel}
\]

\[
\frac{dm_i}{dx} = \frac{w_i}{V_i}
\]

\[
\frac{dT_{L,i}}{dx} = \frac{Q_i - w_i \lambda_i - w_i v_{tel}^2 / 2J}{m_i V_i C_{PL,i}}
\]

\[
\frac{dV_i}{dx} = \frac{3}{8} \frac{1}{r_i \rho_{L,i}} \frac{(U - V_i) |U - V_i|}{V_i} C_D
\]
The methods used to obtain initial values for the above ODE's are described below. Initial values are required for the state variables, which are \( P, U, \rho, \) and \( T \) for the gas phase, and \( m_i, T_{\text{L,}i}, \) and \( V_i \) \((i = 1, 2, \ldots, N_{\text{ox}} + N_{\text{fuel}})\) for the condensed phase.

The initial values for the gas phase are set as:

\[
\begin{align*}
P & = \text{input} \\
U & = \text{input} \\
\rho & = \frac{P}{RT}
\end{align*}
\]

where

\[
\begin{align*}
R & = \frac{\tilde{R}}{M_w} \\
M_w & = M_w (O/F)
\end{align*}
\]

and

\[
\begin{align*}
(O/F) & = \text{input \ (default: \ (O/F) = F_{\text{ox}}/F_{\text{fuel}})} \\
T & = T(O/F)
\end{align*}
\]

From the above it can be seen that the initial value for the gas phase mass flow is

\[
\Phi = \rho \, U \, A
\]

The input feed rate to the system must be adjusted to provide mass conservation. The adjusted values are

\[
\begin{align*}
F_{\text{ox}}' & = F_{\text{ox}} - \left[ \frac{O/F}{O/F + 1} \right] \Phi \\
F_{\text{fuel}}' & = F_{\text{fuel}} - \left[ \frac{1}{O/F + 1} \right] \Phi \\
F_T' & = F_{\text{ox}}' + F_{\text{fuel}}' = F_T - \Phi
\end{align*}
\]

The initial values for the condensed phase \( m_i, T_{\text{L,}i}, \) and \( V_i \) are obtained as described below. A single initial value of temperature and of velocity is input for each propellant; \( T_{\text{L,ox}}, T_{\text{L,fuel}}, V_{\text{ox}}, \) and \( V_{\text{fuel}}. \) These initial values apply to all oxidizer drops and to all fuel drops, respectively. A single mass median drop size is also input for each propellant; \( \overline{D}_{\text{ox}} \) and \( \overline{D}_{\text{fuel}}. \) A drop size distribution for the oxidizer and for the fuel is then calculated as discussed in Section 1.2.2. Since the radius of the drops in the \( i \)th group is now known, drop volumes for the \( i \)th group are calculated as

\[
\text{VOL}_i = \frac{4}{3} \pi r_i^3
\]

The mass of each drop is

\[
m_i = \rho_i \text{VOL}_i
\]
where

$$\rho_i = \rho_i \left( T_{L,i} \right).$$

Initial values are also needed for the drop group number flux, $n_i$, which is the number of drops of mass $m_i$ flowing per second past the initial position. The adjusted feed rate for each propellant, $F_{ox}$ and $F_{fuel}$, is used to calculate the $n_i$. For the oxidizer

$$n_{ox,i} = \frac{F_{ox,i}}{m_{ox,i}} \text{ (sec}^{-1}\text{)}$$

where

$$F_{ox,i} = \text{(mass fraction of oxidizer in group i) } F_{ox}$$

Values for the fuel are calculated in the same manner.

1.2.9 Analysis with 2D Droplet Velocity

TRW Inc. has developed a class of engines which feature a pintle injector design in which the spray pattern is not directed axially. The figure given below illustrates the injection process for a typical pintle injector design.

![Figure 1. Schematic, TRW Pintle Injector Spray](image)

The injector produces a cylindrical fuel sheet that is axially directed along the outer wall of the pintle. Oxidizer is injected near the end of the pintle in the radial direction as a planar sheet. It can be assumed that the impingement of these streams produces a single sheet of oxidizer and fuel directed along the resultant momentum path, and is, therefore, shaped as a conic frustum.
A method has been provided in the code by which this type of flow can be approximated. The method assumes that gas velocity, $U$, is directed axially, as before. However, the oxidizer and fuel sprays are assumed directed initially along a common, non-axial, path (the path of resultant momentum). Thus, each drop group velocity, $V_i$, is represented by two components, $u_i$ and $v_i$. The velocity and distance vectors are represented as shown in the figure given below.

\[
\begin{align*}
\theta_i &= \arctan \frac{v_i}{u_i} \\
t_i &= \frac{1}{V_i} dS_i \\
dS_i &= \frac{dx}{\cos \theta_i} \\
dt_i &= \frac{dS_i}{V_i} = \frac{dx}{V_i \cos \theta_i}
\end{align*}
\]

**Figure 2. 2D Model: Velocity, Distance, and Time of Flight for the $i$th Drop Group**

The equations given previously are then modified as shown below.

- $\sqrt{V_i^2} = u_i^2 + v_i^2$

and

- $\theta_i = \arctan \left( \frac{v_i}{u_i} \right)$

- In equation (24), $u_i$ replaces $V_i$

- In equation (29) and (30), $V_i \cos \theta_i$ replaces $V_i$

For example:

\[
\frac{dm_i}{dx} = -\frac{w_i}{V_i \cos \theta_i}
\]

Equation (31) is replaced by

\[
\frac{du_i}{dx} = \frac{3}{8} \frac{1}{r_i \rho_{ti}} \frac{|U-u_i|}{|U-u_i|} \left( U-u_i \right)
\]
and

\[
\frac{dv_i}{dx} = \frac{3}{8} \frac{1}{r_i \rho_{i1}} \frac{\rho}{|v_i|} \left| v_i \right|
\]

The TRW LM Descent Engine (LMDE), and its derivative, the TR-201, feature a pintle injector in which the oxidizer is injected as radial spokes, rather than as a sheet. A photograph of the LMDE pintle tip is shown below (from Reference 7).

Figure 3. Post Test Photograph of Injector and Pintle Tip for Engine No. I/No. 3, HEA (S/N 023) - After Approximately 2390 Seconds of Firing Time (13738-66)
Note that two types of oxidizer injection ports are used. There are 36 nearly square ports that are bisected by 36 much smaller slit shaped ports. The later are displaced slightly downstream of the former. This type of injection scheme can be simulated by the method described below.

The fuel modeled as three drop groups which result from, 1) fuel sheet impingement with oxidizer injected from the larger ports, 2) fuel sheet impingement with oxidizer injected from the smaller ports, and 3) break-up of the non-impinging portion of the fuel sheet. The oxidizer is modeled as two drop groups, corresponding to situations 1 and 2, above. The axial position of the atomization surface is assumed to be the same for each drop group. Thus, there will be three resultant momentum streams, illustrated in Figure 4, below.

![Figure 4. Momentum Streams Resulting from Two Oxidizer Spokes Impinging on a Cylindrical Fuel Sheet](image)

1.2.10 Calculation of Mixture Viscosity, Specific Heat, and Thermal Conductivity

The viscosity of the gas mixture, \( \mu \), is calculated by the method of Wilke which is described on page 24 of Reference 6.

For the viscosity of the gas film around the propellant drops, an arithmetic average of the bulk product gas and the fuel vapor both taken at the film temperature is used. The viscosities of the individual gas species are provided as data.
The specific heat of the gas mixture, $C_p$, is taken as the molar average of the specific heats of the species present.

The thermal conductivity of the gas mixture, $k$, is calculated by Eucken's equation which is described on page 257 of Reference 6.

$$ k = \left( c_p + \frac{5}{4} \cdot R \right) \mu \quad , \quad R = \bar{R} / M_w $$

Values for the gas mixture viscosity, specifies heat, and thermal conductivity are calculated in the program by subroutine VKSGAS.

1.2.11 Calculation of Vapor Diffusivity

Diffusivity of the oxidizer through the mixture, or of the fuel through the mixture, is calculated using the methods described in Reference 6. Usage of the Lennard-Jones parameters are as described on page 511, using the tables presented in Appendix B of Reference 6, especially Table B-2, page 746. The diffusivity is calculated using Wilkes equation: i.e., equation (18.4-25) on page 571 of Reference 6. These calculations are carried out by subroutine DIFFU.

1.2.12 Stability Parameters

Stability parameters $\Delta V, L, \text{Re}_d$, and $D$ are calculated for each of the oxidizer and fuel sprays as follows:

Relative Mach number, $\Delta V$, between gas and liquid:

$$ \Delta V = \frac{(U - V)}{a} $$

where

$$ a = \text{local speed of sound} $$

Burning rate parameter (L) which is defined as:

$$ L = \frac{r_{an} f}{\varepsilon_c} $$

where

$$ r_{an} = \text{radius of annulus} $$
\[ f = \text{burning rate (fraction/inch)} \]

\[ f = -\left[ \sum i \frac{dm_i}{dx} \right] / \dot{w} \]

\[ \dot{w} = \text{propellant flow rate} \]

\[ \varepsilon_c = \text{nozzle contraction ratio} \]

Reynolds Number \((Re_d)\):

\[ Re_d = 2ra \rho / \mu \]

Drag Parameter \((D)\):

\[ D = \frac{3}{8} \sum \frac{C_{Di} \eta_i m_i}{\rho V_i r} \]

These quantities are calculated in subroutine PRINT.

1.2.13 SCAP - ODK Linkage

Fuel and/or Oxidizer vaporization profiles are provided by SCAP for input to the ODK module of either VIPER or TDK. The profiles are given as a function of path length, \( x \), in the form

\[ \frac{[C_{L}]}{[C_{L}]} = f(x). \]

The function, \( f(x) \) is obtained as described below.

The continuity equation for the combustion chamber can be written as

\[ \phi_g + \phi_L = F_T \]

where \( \phi_g \) and \( \phi_L \) are the gas phase and liquid phase mass flow rates at any chamber cross section. The quantity \( F_T \) is the total propellant flow rate into the injector (total feed as measured by the ox and fuel flow meters, \( F_T = F_{ox} + F_{fuel} \)).

Since

\[ \phi_L = \left[ 1 - \eta_{vap, ox} \right] F_{ox} + \left[ 1 - \eta_{vap, fuel} \right] F_{fuel} \]
it follows that

\[ C_{\text{gas}} = \frac{\phi_g}{F_T} \]

\[ C_{L,\text{ox}} = \left[ 1 - \eta_{\text{vap,ox}} \right] \frac{F_{\text{ox}}}{F_T} \]

\[ C_{L,\text{fuel}} = \left[ 1 - \eta_{\text{vap,fuel}} \right] \frac{F_{\text{fuel}}}{F_T} \]

and

\[ C_{\text{gas}} + C_{L,\text{ox}} + C_{L,\text{fuel}} = 1. \]

Using these quantities a table of \( f(x) \) vs \( x \) is output such that

\[ \frac{[C_L]}{[C_L]_0} = f(x). \]

This output is done both for ox and fuel.

The quantity \([C_L]_0\) is taken at \( x = x_o \), which is reached when the gas phase mixture ratio is equal to an input value, \((\text{OFEQ})\). The idea here is that the gas phase is initially in a state of equilibrium since it is oxidizer rich due to the relatively low vapor pressure of the oxidizer as compared to the fuel. It is well known that oxidizer/fuel mixtures usually combust to an equilibrium product as long as the mixture ratio is not excessively fuel rich.

Since the table \( f(x) \) vs \( x \) is not always smooth and can contain many entries (more than 1000), and also since the derivative quantities \( f' \) and \( f'' \) are required, it is useful to prepare curve fits of the results. The method used here for curve fitting the data is described below.

The function, \( f \), to be fit is shown in the adjacent figure. Note that \( f(0) = 1 \) and then decays monotonically; but may or may not reach zero (100% vaporization). The function is defined by many points in a table. The fit, however, is made using a few points obtained by interpolation. The form of the fit is

\[ F = \frac{A}{X + \varepsilon} + B + CX \]

where \( \varepsilon \) is a small number used to remove the singularity at \( x = 0 \). The curve fit coefficients \( (A, B, C) \) are determined from:
\[
\begin{bmatrix}
\frac{1}{x_{i-1}+\varepsilon} & 1 & x_{i-1} \\
\frac{1}{x_i+\varepsilon} & 1 & x_i \\
\frac{1}{x_{i+1}+\varepsilon} & 1 & x_{i+1}
\end{bmatrix}
\begin{bmatrix}
A \\
B \\
C
\end{bmatrix}
= 
\begin{bmatrix}
f_{i-1} \\
f_i \\
f_{i+1}
\end{bmatrix}.
\]

Here, the curve defined by \( f \) is divided into \( N \) segments. An odd number of points, \( M = 2N+1 \), are obtained by interpolation and a three point fit is computed for each segment.

It follows that

\[
f' = -A \ (X+\varepsilon)^2 + C
\]

and

\[
f'' = 2A \ (X+\varepsilon)^3.
\]
2.0 PROGRAM DESCRIPTION

The Steady-State computer program consists of a main program and the subroutines listed below. Subroutines supplied the operating system and the plot software are not listed.

Callable Subroutines (see Figure 5)

SCD, SCAP control subroutine
ALM
BOIL
COMP
DIFFU, see Section 1.2.11
DIST1
DROP
ERFIN
FGAM
GDERIV
IN
INITPL
KFIT
LINI
LINIR
LNGRIN
LOGDIS
MASS
OUT
PDROP
PLOTM
PLOTPROP
PLOTT
PRINT
RKAM
RSET
SCDERIV
SCPRNT
SCPROP
SCSTREAM
SGECO
SGESL
SPLIT
TGINT
UTDROP
VAPOR
VKSGAS, see Section 1.2.10
WTMINT
YDY
Function Subroutines

CD
CPL
CVAP
FKA
PVAP
RHO
RT
TBL
VISCV

Thirteen of the above subroutines are used to obtain properties for the oxidizer, fuel, and combustion product gas.

These subroutines are described briefly in Tables 1 and 2, respectively.

Descriptions of some of the more important Fortran variables are given in Table 3. Throughout the program the index I=1 is used for oxidizer, and the index I=2 is used for fuel. As many as 20 drop groups can be used for each propellant. Thus, in Table 4 a dimension of (20,2) refers to (drop groups, propellant).

Ploting is accomplished by using calls to the plot software subroutines AXIS, LINE, NUMBER, PLOTS, etc.

Several subroutines are described in more detail at the end of this section.
<table>
<thead>
<tr>
<th>Subroutines</th>
<th>Property (Units)</th>
<th>Independent Variable (Units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALM</td>
<td>( \lambda_A )</td>
<td>liquid temperature (°R)</td>
</tr>
<tr>
<td>CPL</td>
<td>( C_p )</td>
<td>liquid temperature (°R)</td>
</tr>
<tr>
<td>CVAP</td>
<td>( C_{p_v} )</td>
<td>temperature (°R)</td>
</tr>
<tr>
<td>FKA</td>
<td>( k_A )</td>
<td>temperature (°R)</td>
</tr>
<tr>
<td>PVAP</td>
<td>( P_A )</td>
<td>liquid temperature (°R)</td>
</tr>
<tr>
<td>RHO</td>
<td>( \rho_L )</td>
<td>liquid temperature (°R)</td>
</tr>
<tr>
<td>TBL</td>
<td>( T_{BL} )</td>
<td>pressure (psia)</td>
</tr>
<tr>
<td>VISCV</td>
<td>( \mu_A ) x 10^6 (lbm/in-sec)</td>
<td>temperature (°R)</td>
</tr>
</tbody>
</table>
Table 2. Combustion Species Properties Subroutines

<table>
<thead>
<tr>
<th>Subroutines</th>
<th>Property (Units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>COMP</td>
<td>combustion gas composition (mole fraction) vs O/F ratio at 3 different pressures (psia)</td>
</tr>
<tr>
<td>DIFFU</td>
<td>calculates diffusion coefficient of fuel and oxidizer through combustion mixture Lennard Jones Parameters</td>
</tr>
<tr>
<td>( \sigma_1 )</td>
<td>atomic radius of oxidizer (( ^{\circ} )A)</td>
</tr>
<tr>
<td>( \sigma_2 )</td>
<td>atomic radius of fuel (( ^{\circ} )A)</td>
</tr>
<tr>
<td>( \sigma_j )</td>
<td>atomic radius for each species (( ^{\circ} )A)</td>
</tr>
<tr>
<td>( \epsilon/k )</td>
<td>interaction energy of oxidizer (( ^{\circ} )K)</td>
</tr>
<tr>
<td>( \epsilon_f/k )</td>
<td>interaction energy of fuel (( ^{\circ} )K)</td>
</tr>
<tr>
<td>( \epsilon/k )</td>
<td>interaction energy for each species (( ^{\circ} )K)</td>
</tr>
<tr>
<td>TGINT</td>
<td>flame temperature (( ^{\circ} )R) vs O/F ratio at 3 different pressures (psia)</td>
</tr>
<tr>
<td>VKSGAS</td>
<td>viscosity (lbm/in-sec) vs temperature (( ^{\circ} )R) for each species</td>
</tr>
<tr>
<td>( C_p )</td>
<td>specific heat (BTU/mole-( ^{\circ} )R) vs temperature (( ^{\circ} )R) for each species</td>
</tr>
<tr>
<td>( k )</td>
<td>thermal conductivity, BTU-in-sec-( ^{\circ} )R</td>
</tr>
<tr>
<td>( M_{w_j} )</td>
<td>molecular weight of each species</td>
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<td>combustion gas molecular weight</td>
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<td>--------------</td>
<td>--------</td>
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<td>FUNCTION CVAP</td>
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<td></td>
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<td>CPG</td>
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<td>ENDOT(2)</td>
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<td>ENPM(2)</td>
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<td></td>
<td>$k$</td>
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<td>FNUM (20,2)</td>
<td>$Nu_m$</td>
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<tr>
<td>FVAP2</td>
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<td>GAM</td>
<td>$\gamma$</td>
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<td>NSET(2)</td>
<td>$n_i$</td>
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<td>FORTRAN NAME</td>
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<td>PR (20.2)</td>
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<tr>
<td>R</td>
<td>( \bar{R} )</td>
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<td>RAT</td>
<td>( \alpha/\ell )</td>
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<td>( \rho )</td>
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<td>RHOG</td>
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</tr>
<tr>
<td>RHOAV</td>
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<td>RM(2)</td>
<td>( r_m )</td>
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<td>RS (20.2)</td>
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<td>FUNCTION RT</td>
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<td>RVAP</td>
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<td>U</td>
</tr>
<tr>
<td>V (20.2)</td>
<td>( V_{ji} )</td>
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<tr>
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<td>( U-V_{ji} )</td>
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Table 3. Fortran Variable Descriptions (concluded)

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<thead>
<tr>
<th>FORTRAN NAME</th>
<th>SYMBOL</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>VISA V</td>
<td></td>
<td>- of mantle mixture at average temperature</td>
</tr>
<tr>
<td>WCON(2)</td>
<td></td>
<td>$2\pi M_n/\Lambda$</td>
</tr>
<tr>
<td>WTML</td>
<td>M</td>
<td>molecular weight of vapor, calculated by subroutine WTMINT</td>
</tr>
<tr>
<td>WTMAV</td>
<td></td>
<td>- of mantle mixture</td>
</tr>
<tr>
<td>WTMOL</td>
<td></td>
<td>- of propellant, input</td>
</tr>
<tr>
<td>WW (20.2)</td>
<td>$w_\mu$</td>
<td>vaporization rate of single drop (lbm/sec)</td>
</tr>
<tr>
<td>X</td>
<td>x</td>
<td>axial position (usually x=0 at injector)</td>
</tr>
<tr>
<td>XL</td>
<td>K</td>
<td>evaporation rate constant, calculated by function XK</td>
</tr>
<tr>
<td>Z</td>
<td>z</td>
<td>correction factor for mass transfer, defined by equation (10)</td>
</tr>
</tbody>
</table>

SUBROUTINE DIST1

Input: $\overline{D}, N, \sigma_g$
Output: $D_j, (2j-1)/2N; j = 1, \ldots N$
Description:

Given an arbitrarily large number of spherical drops of mass mean diameter, $\overline{D}$, which are assumed to possess a logarithmic normal distribution about $\overline{D}$, then the distribution of mass of drops as a function of size is described by:

$$\frac{df}{dD} = \left[\frac{1}{2}\pi D \ell \ln \sigma_g \right]^{-1} \exp \left[ -\frac{1}{2} \left( \frac{\ell \ln D - \ell \ln \overline{D}}{\ell \ln \sigma_g} \right)^2 \right]$$  \hspace{1cm} (a)

where

- $D$ is drop diameter
- $f$ is the fraction of mass in drops smaller than $D$
- $\sigma_g$ is the geometric standard deviation.

The purpose of this subroutine is to determine a set of $N$ drop diameters $D_j \quad j = 1, \ldots N$
such that

\[ \frac{\nu}{\pi} \int_0^\infty \left( \frac{df}{dD} \right) dD = \frac{2j-1}{2N} \]  

For example, if \( \bar{D} = 30 \) microns, then integrating equation (a) will yield values of \( f \) as indicated by the solid line in Figure 6. If this distribution is then replaced by \( N=5 \) discrete drop groups, then the resulting distribution will be as indicated by the dash line in the figure where equation (b) is used to obtain the particle group diameters, \( D_j \).

The method solves equation (b) directly, using the inverse error function (subroutine ERFIN).

---

**Figure 6.** Drop Size-mass Distribution for Standard Deviation of 2.3, Reference 1.
FUNCTION ERFIN(ERF)

The inverse error function is calculated using a rational polynomial approximation. Given a value of the error function, erf(z), the corresponding value of z if found as described below. It is necessary that

\[-1 < \text{erf}(z) < +1\]

otherwise an error message is printed.

Given

\[y = \text{erf}(z)\]

The argument z is

\[\xi = \frac{\delta}{\sqrt{2}} \left[ \frac{\text{erf}(z) - a_0 + \xi a_1 + \xi^2 a_2}{1 + b_1 \xi + b_2 \xi^2 + b_3 \xi^3} \right]\]

where

\[\delta = \begin{cases} +1 & \text{for } y \text{ positive} \\ -1 & \text{for } y \text{ negative} \end{cases}\]

and

\[\xi = \left( -2 \ln \frac{1 - |y|}{2} \right)^{1/2}\]

\[a_0 = 2.515517 \quad b_1 = 1.432788\]
\[a_1 = .802853 \quad b_2 = .189269\]
\[a_2 = .010328 \quad b_3 = .001308\]

The error function is defined as

\[\text{erf}(z) = \frac{2}{\sqrt{\pi}} \int_0^z e^{-t^2} dt\].
SUBROUTINE RKAM

The purpose of this subroutine is to solve a set of N simultaneous, first order, ordinary differential equations of the form:

\[ y_i' = f_i (x, y_1, y_2, ... y_n), \quad i = 1, ..., n \]

This subroutine operates in one of three modes:

1. Adams-Moulton variable step
2. Adams-Moulton fixed step
3. Runge-Kutta fixed step

Restrictions

1. No internal checks are made for over flow or under flow.
2. The user must provide an auxiliary subroutine which evaluates the first order derivatives. (See AUXSUB under Calling Sequence).
3. Initial conditions for both variables and derivatives must be stored in their respective locations prior to entering RKAM.

Usage

Calling Sequence:

\[ \text{CALL RKAM (XDP, HDP, VAR, DER, AUXSUB, N, OPT, EU, EL, HMAX, HMIN, ICNT, TEMPS, NH)} \]

where

\[ \begin{align*}
\text{XDP} &= \text{x, the independent variable in double precision.} \\
\text{HDP} &= \text{h, the integration step-size in double precision.} \\
\text{VAR} &= \text{N-dimensional vector of dependent variables} \quad \left( y, y', ..., y' \right). \\
\text{DER} &= \text{N-dimensional vector of derivatives} \quad \left( y', y'', ..., y'' \right). \\
\text{AUXSUB} &= \text{Name of the auxiliary subroutine that computes derivatives and stores them in DER (1) to DER (N). The calling program must contain an external statement containing this name. Calling sequence must be CALL AUXSUB.} \\
\text{N} &= \text{Number of equations.} \\
\text{OPT} &= \text{Option indicator, zero for AM, non-zero for RK only.} \\
\text{EU} &= \text{N-dimensional vector of upper bounds. (See Method).} \\
\text{EL} &= \text{N-dimensional vector of lower bounds. (See Method).} \\
\text{HMAX} &= \text{Absolute value of maximum allowable step-size.} \\
\text{HMIN} &= \text{Absolute value of minimum allowable step-size. (HMIN>0).} \\
\text{ICNT} &= \text{Internal counter - must be set to zero initially or when restarting.}
\end{align*} \]
TEMPS = A two-dimensional, (9,N), storage region. TEMP (1,I), I=1,...,N must be set to zero initially or restarting. The least significant parts of the dependent variables are stored here.

NH = Index of the equation that caused halving when step-size has been reduced.

VAR, DER and all other locations referred to in both the main program and the auxiliary subroutine must be assigned in COMMON statements. If the step-size is changed outside of RKAM, the restart flag, ICNT, must be set to zero. This restriction does not apply in the "RK only" mode. HMAX, HMIN, EU and EL are also irrelevant in this mode.

The subroutine employs the fourth-order Adams-Moulton predictor-corrector method using the classical fourth-order Runge-Kutta method to obtain starting values. The user is referred to Hildebrand, Introduction to Numerical Analysis, pp. 199, 237, and 247 for theory and formulas.

AM has the following advantages with respect to RK:

1. Only half as many derivative evaluations per integration step are required to attain the same order of accuracy.
2. The local truncation error may be estimated at the conclusion of each integration step thereby providing a means for step-size control.

For each variable the local truncation error is approximately one-fourteenth the difference between the predicted and corrected values, that is

\[ e_i = \frac{1}{14} |y_i^{(c)} - y_i^{(p)}| \]

In RKAM, the difference \( D_i = |y_i^{(c)} - y_i^{(p)}| \) are formed and compared with positive numbers \( EU_i \) and \( EL_i \). If \( D_i \geq E_i \) for any \( i \), the step size is halved provided \( |h/2| > - HMIN \). If \( D_i < EL_i \) for all \( i \) and for three successive steps, the step size is doubled provided \( |2h| \leq HMAX \). (Note that \( h \) may be held fixed either by setting \( HMIN = HMAX \) or by making \( EU_i \) and \( EL_i \) prohibitively large and small respectively). If halving is called for during the first AM step following the three initial RK steps, the step-size is halved, the independent variable is set back to its initial value and the three RK steps are repeated. This will continue until the first AM step is successfully taken. From this point on halving is effected by interpolation of past data whereas doubling is accomplished by alternate selection of past data.

In selecting \( EU \) and \( EL \), one should note the following:

1. The test is an absolute test. To control relative error \( EU_i \) and \( EL_i \) should be computed as functions of \( y_i \) prior to each integration step.
2. Although the local truncation error in \( y_i \) is not allowed to exceed \( EU_i \), this does not imply that the cumulative error will not exceed \( EU_i \). Therefore, \( EU_i \) and \( EL_i \) should depend upon the maximum allowable cumulative error and the number of integration steps.
3. Since doubling $h$ will multiply the truncation error by a factor of 2, $EL_4$ should be chosen less than $EU_t/32$ if the advantages of doubling are not to be short-lived.

To control round-off, the independent variable is accumulated in double precision and the dependent variables are accumulated in partial double precision.
3.0 INPUT DESCRIPTION

The input data is divided into two sets, 1) propellant properties data, and 2) case input data.

The propellant properties data contains all of the properties discussed in Section 1.2.1 that are necessary to run a given oxidizer/fuel combination. The appropriate propellant properties data set must be inserted into the input stream. A good deal of labor is required to prepare each such propellant properties data set. The data sets currently provided with the program are listed below.

<table>
<thead>
<tr>
<th>oxidizer/fuel</th>
<th>file name</th>
<th>(O/F)Stoic</th>
<th>state</th>
<th>pressure range</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOX/GH2</td>
<td>O2H2.DAT</td>
<td>7.94</td>
<td>liquid/gas</td>
<td>200 ≤ P ≤ 400 psi</td>
</tr>
<tr>
<td>LOX/GH2</td>
<td>LOXH2.MID</td>
<td>7.94</td>
<td>liquid/gas</td>
<td>400 ≤ P ≤ 1500 psi</td>
</tr>
<tr>
<td>LOX/GH2</td>
<td>LOXH2.DAT</td>
<td>7.94</td>
<td>liquid/gas</td>
<td>1500 ≤ P ≤ 3500 psi</td>
</tr>
<tr>
<td>LOX/CH4</td>
<td>METHANE.MID</td>
<td>4.0</td>
<td>liquid/gas</td>
<td>500 ≤ P ≤ 1500 psi</td>
</tr>
<tr>
<td>LOX/C3H8</td>
<td>PROPAN.MID</td>
<td>3.63</td>
<td>liquid/gas</td>
<td>500 ≤ P ≤ 1500 psi</td>
</tr>
<tr>
<td>LOX/RP-1</td>
<td>RP1.DAT</td>
<td>3.40</td>
<td>liquid/liquid</td>
<td>200 ≤ P ≤ 350 psi</td>
</tr>
<tr>
<td>LOX/RP-1</td>
<td>F-1.RP1</td>
<td>3.40</td>
<td>liquid/liquid</td>
<td>500 ≤ P ≤ 1500 psi</td>
</tr>
<tr>
<td>NTO/N2H4</td>
<td>N2H4.DAT</td>
<td>1.44</td>
<td>liquid/liquid</td>
<td>100 ≤ P ≤ 1000 psi</td>
</tr>
<tr>
<td>NTO/A50</td>
<td>A50.DAT</td>
<td>2.25</td>
<td>liquid/liquid</td>
<td>100 ≤ P ≤ 1000 psi</td>
</tr>
<tr>
<td>NTO/MMH</td>
<td>MMH.DAT</td>
<td>2.50</td>
<td>liquid/liquid</td>
<td>50 ≤ P ≤ 3000 psi</td>
</tr>
<tr>
<td>NTO/UDMH</td>
<td>UDMH.DAT</td>
<td>3.06</td>
<td>liquid/liquid</td>
<td>100 ≤ P ≤ 1000 psi</td>
</tr>
</tbody>
</table>

Input specifications for preparing a propellant properties data set are presented in Section 3.1. Input required to execute a case is described in Section 3.2.
3.1 Propellant Properties Data Input

The propellant properties data consists of the drop liquid and vapor properties, and the properties of the combustion product gas. The $INPUT namelist used to read tables defining these properties is given below. Listings for existing propellant property data sets are presented in Appendix A. LOX liquid and vapor properties are determined by curve fits rather than tables; see Appendix B. A formatted printout of the propellant data file is written to unit 89 whenever a case is run.

$INPUT = Namelist name read in Subroutine IN.

NAMES(1) = Label used to identify the oxidizer and fuel e.g. NAMES(1) = 'LOX', 'RP-1'.

FLAMEF = 0 - Burning drops see local mixture ratio
         1 - Oxidizer controlled burning
         2 - Fuel controlled burning
         Default value is 0.

TFLAME = Flame temperature ($^\circ$R) to be used for the oxidizer if FLAMEF=1, fuel if FLAMEF=2, above.

PCRIT(1) = Critical pressure for oxidizer (psi).

PCRIT(2) = Critical pressure for fuel (psi).

NSP = The number of chemical species to be considered.
      $1 \leq \text{NSP} \leq 15$

SPNAME(1) = The names of the chemical species, e.g., SPNAME(1) = 'H', 'H2', etc. (for print out only).

WM(1) = Molecular weight of each chemical species.

EPSI(1,1) = Interaction energy ($\varepsilon/k$) of each chemical species ($^\circ$K).

SIGMA(1,1) = Molecular diameter, $\sigma_1$, of each chemical species (Ångstroms = $10^{-10}$ M).

EPSOF(1) = Propellant molecular interaction energy ($^\circ$K).
         EPSOF(1) = ($\varepsilon/k$) for oxidizer
         EPSOF(2) = ($\varepsilon/k$) for fuel

SIGOF(1) = Propellant molecular diameter (Ångstroms = $10^{-10}$ M).
          SIGOF(1) = $\sigma_{ox}$
          SIGOF(2) = $\sigma_{fuel}$

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WTMOL(1) = Propellant molecular weight.
WTMOL(1) = M_{w,ox}
WTMOL(2) = M_{w,fuel}

NR = Number of mixture ratio, O/F, values for which properties are to be input.
1 \leq NR \leq 15

R(1) = Mixture ratio values, O/F.

NPRES = Number of pressure values in PRSS(1).

PRSS(1) = Up to three values of stagnation pressure (low, mid, and high) for which properties of the product gases have been prepared (psi).

YSP(1,I,1) = Low pressure values. Mole fraction for each species, I = 1,2,...NSP at each O/F.

YSP(1,I,2) = Mid pressure values. Mole fraction for each species, I = 1,2,...NSP at each O/F.

YSP(1,I,3) = High pressure values. Mole fraction for each species, I = 1,2,...NSP at each O/F.

WMTAB(1,1) = Low pressure values. Gas molecular weight for each O/F.

WMTAB(1,2) = Mid pressure values. Gas molecular weight for each O/F.

WMTAB(1,3) = High pressure values. Gas molecular weight for each O/F.

TC(1,1) = Low pressure values. Gas stagnation temperature for each O/F (°R).

TC(1,2) = Mid pressure values. Gas stagnation temperature for each O/F (°R).

TC(1,3) = High pressure values. Gas stagnation temperature for each O/F (°R).

FGAMT(1) = γ value for each O/F at the mid range pressure.

NT = Number of temperature values for which the species C_p and μ are to be input.
1 \leq NT \leq 15

TTAB(1) = Temperature values for the species C_p and μ (°R).

VSP(1,1) = μ_{ij}, viscosity (x10^6) at temperature i for species j (lbm/in-sec).

CPTAB(1,1) = C_{pij}, specific heat at constant pressure at temperature i for species j (BTU/mole-°R).
NTL(1) = The number of entries for the temperature of the liquid phase of the oxidizer, \leq 15.

NTL(2) = The number of entries for the temperature of the liquid phase of the fuel, \leq 15.

TLI(1,1) = T_{L,ox}; Liquid phase temperatures for the oxidizer (\degree R).

TLI(1,2) = T_{L,fuel}; Liquid phase temperatures for the fuel (\degree R).

PV(1,1) = P_{vap,ox}; vapor pressure for the ox, liquid phase, vs T_{L,ox} (psi).

PV(1,2) = P_{vap,fuel}; vapor pressure for the fuel, liquid phase, vs T_{L,fuel} (psi).

RHOL(1,1) = \rho_{L,ox}; density for the ox, liquid phase, vs T_{L,ox} (lb/in^3).
Note: (lb/in ** 3) = (g/cc) * 0.03616.

RHOL(1,2) = \rho_{L,fuel}; density for the fuel, liquid phase, vs T_{L,fuel} (lb/in^3).

CP(1,1) = C_{PL,ox}; specific heat for the ox, liquid phase, vs T_{L,ox} (BTU/lb-\degree R).

CP(1,2) = C_{PL,fuel}; specific heat for the fuel, liquid phase, vs T_{L,fuel} (BTU/lb-\degree R).

LAM(1,1) = \lambda_{ox}; heat of vaporization for the ox, vs T_{L,ox} (BTU/lb).

LAM(1,2) = \lambda_{fuel}; heat of vaporization for the fuel, vs T_{L,fuel} (BTU/lb).

NTFLM(1) = Number of gas phase (vapor film) temperatures for oxidizer, \leq 15.

NTFLM(2) = Number of gas phase (vapor film) temperatures for fuel, \leq 15.

TFILM(1,1) = T_{vap,ox}; ox vapor film temperature (\degree R).

TFILM(1,2) = T_{vap,fuel}; fuel vapor film temperature (\degree R).

VVIS(1,1) = \mu_{vap,ox} \times 10^6; ox vapor viscosity (lbm/in-sec), vs T_{vap,ox}.

VVIS(1,2) = \mu_{vap,fuel} \times 10^6; fuel vapor viscosity (lbm/in-sec), vs T_{vap,fuel}.

KVAP(1,1) = k_{vap,ox} \times 10^6; ox vapor conductivity (BTU/in-sec-\degree R), vs T_{vap,ox}.

KVAP(1,2) = k_{vap,fuel} \times 10^6; fuel vapor conductivity (BTU/in-sec-\degree R), vs T_{vap,fuel}.

CPVAP(1,1) = C_{p,vap,ox}; ox vapor specific heat (BTU/lb-\degree R), vs T_{vap,ox}.
CPVAP(1,2) = $c_{p,\text{vap,fuel}}$; fuel vapor specific heat (BTU/lb °R), vs $T_{\text{vap,fuel}}$.

VISL(15,2) = Liquid viscosity (lb/in) vs temp (°R).
(Required data for drop size predictions.)

STL(15,2) = Surface tension (lb/in) vs temp (°R).
(Required data for drop size predictions.)

$\$END$

3.2 Case Data Input, $\$SCAP$

The input is read using FORTRAN NAMELIST. Familiarity with this standard input procedure is assumed. All of the case data is input under the name $\$SCAP$ as described below. Default values for the Namelist items are listed in parenthesis beside equal sign. The index (I) denotes drop type: 1 = 1 for oxidizer, 1 = 2 for fuel. The index (J) denotes drop group. Twenty, or less, drop groups are allowed for each propellant.

The nozzle geometry is input in $\$DATA$ of the TDK computer program$^3$.

$\$SCAP$

Propellant Properties File

FILENAME = ' ' Text defining the file name for the propellant properties; e.g. FILENAME = 'F-1.RPI'.

Mixture Ratio Inputs

INDX = (0) INDX = 0: oxidizer and fuel system
INDX = 1: oxidizer system only
INDX = 2: fuel system only

EMDOT(I) = $F_{\text{ox}}$ and $F_{\text{fuel}}$, the propellant feed rates (lbm/sec) oxidizer (I=1) and fuel (I=2) $F_T = F_{\text{ox}} + F_{\text{fuel}}$.

RAT1 = (RATMX) Initial gas O/F ratio.

RATMN = Minimum O/F ratio.

RATMX = Maximum O/F ratio.

OFSTOC = Stoichiometric O/F ratio (not required input).
BRNMAX = Maximum burn rate parameter (used only to limit plotted values).

Flow Variables, Initial Values

P = Chamber pressure (psia).

U = Initial gas velocity (in/sec).

VI(I) = Droplet injection velocities (in/sec) oxidizer (I=1) and fuel (I=2).

TLL(I) = Droplet injection temperatures (°R) oxidizer (I=1) and fuel (I=2).

Flow Variables for the 2 D Option, Initial Values (see Section 1.2.9)

TWOD = (0) If TWOD=1, then the 2 D option will be used.

For the 2 D option the initial radial position, DIY, is required and the injection velocities VI(I) are replaced by VIX(J,I) and VIY(J,I).

DIY = (0.) Initial Radial Position of Drops (inches).

VIX(J,I) = (0,0) Initial Axial Jth Drop Velocity (in/sec).

VIY(J,I) = (0,0) Initial Radial Jth Drop Velocity (in/sec).

Dropsize Prediction Variables

IDROP = Dropsize calculation flag.
        0 = input dropsize
        1 = calculate dropsize (will override IPART)

DJ(I) = Injector diameters, (1) = OX, (2) = Fuel (inch).

ITYPE = Type of injector
        1 - non-impinging
        2 - like on like
        3 - like on unlike
4 - O-F-O triplet
5 - F-O-F triplet
6 - like on like doublet
7 - shear/swirl coaxial

NEL(I) = Number of injector elements. (1) =OX, (2) = Fuel (inch).

If ITYPE = 7

DELP = Pressure drop of center spray in coaxial injector (psi).

FDJI = Annulus inner diameter for outer gas flow in coaxial injector (inch).

FDJO = Annulus outer diameter for outer gas flow in coaxial injector (inch).

Drop Distribution, Initial Values

IPART = (1) Flag for dropsize distribution.

If IPART = 1 log normal distribution of drop sizes is used. D, ND, ND1, and SIG, must be input.

D(I) = Initial mass median diameter, oxidizer (I=1) and fuel (I=2) drops (microns).

SIG(I) = Standard deviation for drop sizes, oxidizer and fuel drops.

ND(I) = (2*5) The total droplet mass is subdivided into ND groups of equal mass, oxidizer (I=1) and fuel (I=2).

ND1(I) = (2*1) The smallest ND(I) is further subdivided into ND1 groups of equal mass, resulting in a total of ND(I) + ND1(I) -1 groups. The total number of groups must be < 20 for the oxidizer, and < 20 for the fuel.

If IPART = 2 dropsize distributions are input using NSET(I) and DS (J,I).

NSET(I) = Number of drop groups, oxidizer (I=1) and fuel (I=2) (MAX=20).

DS(J,I) = Diameter of drop groups, J=1,2,...,NSET(I), oxidizer (I=1) and fuel (I=2) (microns).
### Integration Control

- **X** = (0.) Initial X value (inches).
- **XSTOP** = (100.) Final X value (inches).
- **DX** = (0.005) Initial integration stepsize.
- **HMAX** = (0.05) Maximum integration stepsize.
- **HMIN** = (0.0001) Minimum integration stepsize.
- **EUR** = (0.02) Upper integration relative error limit.
- **ELR** = (0.0006) Lower integration relative error limit (set such that EUR/ELR > 32).
- **OPT** = (0) Integrator flag:
  - 0 for Adams Moulton
  - 1 for Runge-Kutta (fixed step, DX)

### Print Plot Control

- **DXI(1)** = (1.0) Print will occur between XI values at these intervals. XSTOP is always printed.
- **XI(1)** = (100.) Values for control of print. From XI(1) to XI(2) Print every DXI(1)
  - From XI(N) to XI(N+1) Print every DXI(N)
- **PRINT1** = (F) If true, additional print will be given for droplet radius, ΔV, and Reynolds nos.
- **PLTPROP** = (F) If true, then plot input propellant properties (see Appendix B for an example)
- **IFPLOT** = (18*0) Plot control for the Ith plot. The Ith plot will be output if IFPLOT (I) = 1
  - 1 Ith variable
  - 1 oxidizer/fuel ratio
  - 2 gas velocity
  - 3 oxidizer drop velocities vs distance

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fuel drop velocities vs distance
oxidizer drop diameter vs distance
fuel drop diameter vs distance
oxidizer drop temperature vs distance
fuel drop temperature vs distance
fraction vaporized; ox, fuel, and total vs distance
vaporization rate; ox, fuel, and total vs distance
oxidizer drop velocities vs time
fuel drop velocities vs time
fraction vaporized; ox, fuel, & total vs time
vaporization rate; ox, fuel, & total vs time
oxidizer & fuel (2 plots) drop axial velocity vs radial velocity
(for use when TWOD=1)
oxidizer & fuel (2 plots) Drop Trajectories (for use when TWOD=1)
burning rate parameter; ox, fuel and total (see Section 1.2.12)
vaporization curve fit plot set (see Section 1.2.13)

FAC1 = (1) Scale factor for plot.

if FAC1=1, then the plot will be normal size
if FAC1>1, then the plot will be enlarged by this amount, e.g. FAC1 = 1.1 for 10%
if FAC1<1, then the plot will be reduced by this amount

Curve-Fit data (see Section 1.2.13)

NFITS = (10) Number of curve-fit segments to be used in matching the vaporization profile. NFITS≤10

ISTART = (1) If ISTART=0, then the curve fits will start at the x value where a given amount of the injected liquid becomes vaporized. VAP is input to specify this value of vapor fraction. This option can be used with any system, i.e. liq-liq, liq-gas, or gas-liq.

If ISTART=1, then the curve fits will start at the x value where a given gas phase O/F is reached, i.e. the input value OFEQ. This option is intended for use with systems in which the oxidizer vaporizes much faster than the fuel.

VAP = (.1) Vapor fraction at which curve fits start when ISTART=0 is input.
$$\text{OFEQ} \quad = \quad (1.5)$$

Oxidant to fuel gas mixture ratio at which to start the vaporization curve fits (final equilibrium O/F) when ISTART=1 is input. (Set to zero to use core region model.)

$\text{END}$
4.0 INPUT AND OUTPUT FOR A SAMPLE CASE

The first sample case presented here is for a N2O4/N2H4 bipropellant engine operating at an overall mixture ratio of 1.16. The chamber pressure is 311 psia, and the nozzle throat diameter is 4 inches. This combustor has been shown experimentally to have a low vaporization efficiency.

The first page given here is a listing of the program case inputs; i.e., the TDK computer program\(^1\) $DATA namelist, and the $SCAP namelist input. This is followed by the printed and plotted output. This test case was run using the IBM RS6000/320H computer system. It required 420 seconds to execute, including the generation of plot files.

The second sample case is the same engine as described above, except that the fuel, N2H4, has been replaced by monomethal hydrazine (MMH). The mixture ratio has been increased to 1.6 (equal tank volume for ox and fuel) with the total propellant weight held constant. The effect this has on the engine operating conditions can be seen by comparing the plotted output obtained from the two cases.

The third sample case is for a TRW, Inc. 50K test engine which uses a pintle type injector (see discussion, Section 1.2.9). The propellants are LOX/RP-1. The 2D option (see Section 3.2) is used to analyze the combustion chamber performance. The spray has been approximated using cold flow data, and is assumed to consist of three streams. The first two streams contain both oxidizer and fuel, whereas the third stream contains only fuel. Each stream has a different initial direction, and and a different drop size distribution. Input data, printed output, and plotted output are presented for this case. The plotted output includes calculated trajectories for the fuel and oxidizer drop groups.
casel.dat

TITLE ICRPG 5th Conf., NTO/N2H4 DEBT, INGEO, JAN 69
DATA
$DATA
SCAP=1,
RSI=1.992,
ECRAT=10.33,
R=0.01,
THETAI=32,
RWTU=.5,
ZT=6,
NZONES=1,
$END
$SCAP
FILENAME='N2H4.DAT'
DX = .001, HMAX = .001, HMIN = .0004,
RATM=2.,
RATM=8.,
BRNMAX=1.0,
OFSTOC=1.4,
EMDCT(1)=12.99, 11.24,
U=12.0,
P=311.1,
VI(1)=648,1609,
TIL(1)=534.534.534.
D(1)=281.94,142.24,
SIG(1)=2.3,2.3
ND=5.5,
ND1=5.5,
XI=6.0,
DXI=2.0,
CTLPROP=T,
IFPLOT=14*1,
FAC1=.9,
$END
case2.dat

TITLE CASE2, NTO/MMH DBLT, INGEBO, JAN 69
DATA
$DATA
SCP=1,
RSL=1.992,
ECRT=10.33,
RI=0.1,
THETA=32,
RMT=0.5,
ZT=0.6,
NXONES=1,

$END

$SCAP
FILENAME='MMH.DAT'
DX = .001, HMAX = .001, HMIN = .0008,
RATMIN=1.2,
RATMAX=8.0,
BHRTMAX=1.0,
OFSTOC=1.4,
EMDOT=14.911, 9.319,
U=12.8,
P=311.1,
VI(1)=648.169,
TLL(1)=534.534,
D(1)=281.94.142.24,
SIG(1)=2.3,2.3,
NO=5.5,
NDL=5.5,
XI=6.0,
DXI=2.0,
PLTPROP=T,
IFPLC=14*1,
FAC1=.9,
$END
case2.out

*******************************************************************************
TWO DIMENSIONAL KINETIC PROGRAM (TEK), LLP VERSION, MAY 1992
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*******************************************************************************

1
TITLE CASES, NATO/NMS DEPT, INSEDB, JAN 69
DATA
$DATA
SCAP=1,
R=1.992,
E=10.33,
L=0.1,
THERM=32,
RPM=5,
NT=6,
NIONS=1,
$END
SCAP
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ENDO=16.911, 9.319,
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U=31.1,
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TITLE CASES, NATO/NMS DEPT, INSEDB, JAN 69
DATA
$DATA
SCAP=1,
R=1.992,
E=10.33,
### Case 2

#### Case 2.out

| CPFBR(1,1) | 7.000 | 7.300 | 8.100 | 8.600 | 8.910 | 9.250 |
| CPFBR(1,7) | 7.000 | 7.040 | 7.460 | 8.950 | 8.750 | 9.100 |
| CPFBR(1,8) | 7.970 | 7.760 | 8.470 | 8.890 | 9.440 | 9.220 |
| CPFBR(1,9) | 7.170 | 7.560 | 8.280 | 8.690 | 8.970 | 9.120 |
| CPFBR(1,10) | 5.260 | 5.090 | 5.630 | 5.010 | 5.020 | 5.120 |
| CPFBR(1,12) | 8.570 | 12.360 | 18.150 | 21.700 | 18.150 | 25.000 |
| CPFBR(1,13) | 8.550 | 10.720 | 14.000 | 15.530 | 18.430 | 15.350 |
| NOX 10, 12, 14 | MTPLM 7, 6 |

#### Stated-State-Spray Combustion Model

| O2 | 400.0 | 440.0 | 480.0 | 520.0 | 560.0 | 600.0 |
| TOL(1,1) | 500.0 | 550.0 | 600.0 | 650.0 | 700.0 | 750.0 |
| TOL(1,2) | 800.0 | 850.0 | 900.0 | 950.0 | 1000.0 | 1050.0 |
| PV(1,1) | 0.270 | 0.850 | 3.140 | 11.800 | 30.000 | 80.000 |
| PV(1,2) | 0.280 | 1.110 | 3.110 | 9.370 | 29.700 | 57.920 |
| PV(1,3) | 0.580000 | 0.554000 | 0.541000 | 0.537000 | 0.538050 | 0.487000 |
| PV(1,4) | 0.323100 | 0.311000 | 0.303000 | 0.293200 | 0.282500 | 0.274000 |
| PV(1,5) | 0.115000 | 0.353000 | 0.352000 | 0.372000 | 0.380000 | 0.441000 |
| PV(1,6) | 0.695000 | 0.761000 | 0.707000 | 0.713000 | 0.721000 | 0.731000 |
| PV(1,7) | 0.435000 | 0.430000 | 0.420000 | 0.412000 | 0.403000 | 0.392000 |
| LV(1,1) | 0.300000 | 0.290000 | 0.280000 | 0.270000 | 0.260000 | 0.250000 |
| LV(1,2) | 0.343000 | 0.346000 | 0.344000 | 0.335000 | 0.326000 | 0.317000 |
| LV(1,3) | 0.094 | 0.094 | 0.046 | 0.075 | 0.1390 | 0.1300 |
| LV(1,4) | 0.100 | 0.315 | 0.315 | 1.180 | 1.620 | 2.050 |
| LV(1,5) | 0.231 | 0.238 | 0.253 | 0.269 | 0.288 | 0.297 |
| LV(1,6) | 0.455 | 0.460 | 0.665 | 0.786 | 0.853 | 0.876 |

#### Ox. -11.951

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- Xe, 19.951
- Ox, 8.53

#### Ox. -9.952

| Ox. | 8.53 |
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### Integration Step

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| CASE2,   | NTO/96X DITL, INGERSO, JAN 69 |
|-----------|

**OX: -7.952**  
**D= 1419.8**  
**T=4531.**  
**C=310.01**  
**P= 311.08**  
**G/F= 1265.01**  
**MACH= .029**  
**AREA= 128.77**  
**DAX= .008E+00**  

**VAPORIZATION RATIO/IN**  
**0.085088**  
**F= .040534**  
**NOTE= .068866**  
**CONB=.090524**

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**OXIDIZER FUEL TOTAL COMBUST.**

| BURNING RATE PARAMETER | .030011 | .010936 | .043474 | .056105 |
| DRAG PARAMETER         | .72     | 2.89    | 3.60    |

**INTEGRATION STEP= .0004**

| OXIDIZER | .366666-66 |
|-----------|

| SFUEL | .38035E-66 |
|--------|

| OXIDIZER | .38035E-66 |

| SFC     | .38035E-66 |

**DATA FOR ODE/ODE SAVED ON UNIT 15**
Case 2

**Fuel Drop Diameter (MICR)**

- φ = 1
- φ = 2
- Z = 3
- Z = 4
- Y = 5
- Y = 6
- Y = 7
- Y = 8
- 1 = 9

**Distance in Inches**

**Oxidizer Drop Diameter (MICR)**

- φ = 1
- φ = 2
- Z = 3
- Z = 4
- Y = 5
- Y = 6
- Y = 7
- Y = 8
- 1 = 9

**Distance in Inches**

64
Case 2

![Fuel Drop Temp (R)](image)

![Oxidizer Drop Temp (R)](image)
Case 2

**Diagram 1: D(Fraction Vaporized)/dx**

- \( \phi = \text{Oxidizer} \)
- \( \bullet = \text{Fuel} \)
- \( \times = \text{Total} \)

Distance in inches:
-12.00 to -7.00

**Diagram 2: Fraction Vaporized**

- \( \phi = \text{Oxidizer} \)
- \( \bullet = \text{Fuel} \)
- \( \times = \text{Total} \)

Fraction vaporized:
-0.00 to 0.60

Distance in inches:
-12.00 to -7.00
CASE 3

TITL1 CASE3 LOX/RP-1 TWR 50K ENGINE
DATA
C LOX/RP-1 50K FRM DROPSIZES D30 LOX=UNIMODAL DIST.
C PK = 235.0 MR=2.65 WT=169.0 TEST 650 D30 RP1=TRIMODAL DIST.
C CONSTANT AREA -- 2D DROP TRAJECTORY RUN
$DATA
SCAP=1,
RSl=6.125,
ECRAT=3.8384,
Rf=0.01
THETAI=45.,
RWTU=.5,
ZT=3.76,
NZONES=1,
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$SCAP
FILENAME='RP1.DAT',
XI(1)= 35.7,
DXI(1)= 2.0,
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IPART=2,
TWOD=1,
NSET=10,10,
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DS(1,2)= 170., 320., 494., 764., 1436., 146., 294., 498., 996., 214.,
P= 235.0,
U= 0,
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DIV= 3.16,
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VIY(1,2)= 1065., 1065., 1065., 1065., 1065., 1042., 1042., 1042., 1042., 1072.,
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VIX(1,2)= 153.4, 153.4, 153.4, 153.4, 153.4, 254.3, 254.3, 254.3, 254.3, 1072.,
TLG(1)= 180., 530.,
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RATNMX= 20.,
BRNMAX = .499,
OFSTOC= 3.4,
PLTPROP=P,
IFPLOT=10*1.5*0.1, FAC1=.9,
$END
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### Case 3

**Oxidizer Drops**

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**Oxidizer Drops**

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</table>
### Case 3

**OX = -13.030  Dn = 645.9  T = 6050.  TO = 6052.  P = 230.76  PO = 233.27  O/F = 0.4068x1.0  MACH = 1.134  AREA = 452.39  DAX = 0.000860**

**Oxidizer Fuel Total Combust.**

<table>
<thead>
<tr>
<th>0.01620</th>
<th>0.01995</th>
<th>0.03534</th>
<th>0.08367</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DraG Parameter.</strong></td>
<td>0.11</td>
<td>0.26</td>
<td>0.37</td>
</tr>
</tbody>
</table>

**Script J**

| .31288-08 |

**Combustion Step:**

| .0007 |

**CASE 3 LOX/RP1 TRW 50K ENGINE**

### Case 3

**OX = -11.030  Dn = 525.1  T = 6959.  TO = 6973.  P = 230.40  PO = 233.23  O/F = 0.3898x1.0  MACH = 1.137  AREA = 452.39  DAX = 0.000860**

**Oxidizer Fuel Total Combust.**

<table>
<thead>
<tr>
<th>0.01552</th>
<th>0.013663</th>
<th>0.024555</th>
<th>0.059277</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DraG Parameter.</strong></td>
<td>0.08</td>
<td>0.20</td>
<td>0.28</td>
</tr>
</tbody>
</table>

**Script J**

| .31283-05 |

**Combustion Step:**

| .0021 |

**CASE 3 LOX/RP1 TRW 50K ENGINE**

### Case 3

**OX = -9.030  Dn = 634.6  T = 6666.  TO = 6673.  P = 230.48  PO = 233.19  O/F = 0.3778x1.0  MACH = 1.139  AREA = 452.39  DAX = 0.000860**

**Oxidizer Fuel Total Combust.**

<table>
<thead>
<tr>
<th>0.008520</th>
<th>0.014608</th>
<th>0.013128</th>
<th>0.045703</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DraG Parameter.</strong></td>
<td>0.06</td>
<td>0.27</td>
<td>0.29</td>
</tr>
</tbody>
</table>

**Script J**

| .31469-06 |

**Combustion Step:**

| .00445 |

**CASE 3 LOX/RP1 TRW 50K ENGINE**
FUEL DROP DIAMETER (MICR)

OXIDIZER DROP DIAMETER (MICR)
REFERENCES


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APPENDIX A

Listing of Propellant Properties Input Data
<table>
<thead>
<tr>
<th>File: JP4.DAT</th>
</tr>
</thead>
</table>

**Adapt**

- **PCHID =** 100, 315
- **PLANE =** TRUE
- **PLANE =** 4235
- **NAME =** "C8H4"
- **NSPH =** 6
- **BPM =** "CO2", "H2O", "N2", "O2"
- **WH =** 44.01, 20.42, 20.42, 19.42, 32.00, 2.02
- **EFS(1,1) =** 195.200, 91.700, 71.490, 809.100, 106.700, 59.700
- **SIDMA(1,1) =** 3.9410, 3.6900, 3.7780, 2.6410, 3.4670, 2.0870
- **SIGM =** 3.5000, 7.5620
- **WM =** 25,500, 40,500
- **NSPH =** 300,000, 521,000
- **NFP =** 1
- **PRMS =** 29.4600
- **MRM =** 13

**R(1) =**

- 500.000, 350.000, 250.000, 167.000, 100.000, 65.000, 48.000, 32.000, 24.460, 16.600, 14.650, 12.000, 10.400

**TSP(1,1) =**

- 0.0049, 0.7049, 0.9309, 3.1400, 3.1400, 3.1400, 3.1400

**TSP(1,2) =**

- 0.9490, 1.0000, 2.0000, 3.1000, 3.1000, 3.1000

**TSP(1,3) =**

- 0.9590, 1.9590, 2.9590, 3.9590

**TSP(1,4) =**

- 0.6140, 1.2000, 2.4000, 3.6000

**TSP(1,5) =**

- 1.1600, 1.9100, 2.8600

**TSP(1,6) =**

- 0.4950, 0.7953, 1.1789, 1.5637, 1.9561

**CSP(1,1) =**


**CSP(2,1) =**

- 6.970, 7.280, 8.060, 8.530, 8.776

**CSP(3,1) =**

- 9.470, 7.150, 7.900, 8.400, 8.722

**CSP(4,1) =**

- 8.050, 8.400, 9.160, 10.700, 12.304

**CSP(5,1) =**

- 7.020, 7.670, 8.440, 8.850, 9.335

**CSP(6,1) =**

- 6.955, 7.009, 7.307, 7.907, 8.460

**F(1) =**

- 50.0, 50.00, 50.00, 50.00, 50.00, 50.00, 50.00, 50.00, 50.00, 50.00, 50.00, 50.00, 50.00, 50.00

**FV(1,1) =**

- 0.001, 0.038, 0.445, 2.942, 12.112, 31.136, 92.155, 195.560, 368.240, 631.779, 1006.79

**FPCS(1,1) =**

- 0.02989, 0.28801, 0.92755, 0.52829, 0.24837, 0.02373, 0.01642, 0.01564, 0.16037, 0.15293

**FCL(1,1) =**

- 0.61400, 0.66700, 0.52000, 0.57380, 0.62880, 0.67980, 0.73280, 0.80380, 0.89180, 0.94480

**LAM(1,1) =**

- 34.120, 14.167, 14.810, 13.930, 13.030, 10.420, 8.516, 6.702, 3.682, 7.018

**FPCS(1,2) =**

- 6.054, 0.064, 0.085, 0.108, 0.128, 0.160, 0.200, 0.250, 0.300, 0.350, 0.400, 0.450, 0.500

**FCL(1,2) =**

- 0.38400, 0.46400, 0.54400, 0.62400, 0.70400, 0.78400, 0.86400, 0.94400

**FCL(1,3) =**

- 0.092, 0.213, 0.333, 0.454, 0.576, 0.694, 0.816, 0.938

**CSV(1,2) =**

- 0.237, 0.426, 0.595, 0.690, 0.727, 0.782, 0.751

**CSV(1,1) =**

- 0.237, 0.426, 0.595, 0.690, 0.727, 0.782, 0.751

**SEND**
<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>R(1)</td>
<td>15,000, 10,000, 5,000, 2,000, 1,000, 0.500, 0.200, 0.100, 0.086</td>
</tr>
<tr>
<td>TSP(1, 1)</td>
<td>0.0, 0.0, 0.0, 0.0, 0.020, 0.0200, 0.0010</td>
</tr>
<tr>
<td>TSP(1, 2)</td>
<td>0.0, 0.0, 0.0, 0.0, 0.0200, 0.0200, 0.0010</td>
</tr>
<tr>
<td>TSP(1, 3)</td>
<td>0.0, 0.0, 0.0, 0.0, 0.0200, 0.0200, 0.0010</td>
</tr>
<tr>
<td>TSP(1, 4)</td>
<td>0.0, 0.0, 0.0, 0.0, 0.0200, 0.0200, 0.0010</td>
</tr>
<tr>
<td>TSP(1, 5)</td>
<td>0.0, 0.0, 0.0, 0.0, 0.0200, 0.0200, 0.0010</td>
</tr>
<tr>
<td>TSP(1, 6)</td>
<td>0.0, 0.0, 0.0, 0.0, 0.0200, 0.0200, 0.0010</td>
</tr>
<tr>
<td>TSP(1, 7)</td>
<td>0.0, 0.0, 0.0, 0.0, 0.0200, 0.0200, 0.0010</td>
</tr>
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</tr>
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<td>TSP(1, 9)</td>
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</tr>
<tr>
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</tr>
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<td>TSP(2, 2)</td>
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</tr>
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<td>TSP(2, 3)</td>
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</tr>
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<td>TSP(2, 4)</td>
<td>0.0, 0.0, 0.0, 0.0, 0.0200, 0.0200, 0.0010</td>
</tr>
<tr>
<td>TSP(2, 5)</td>
<td>0.0, 0.0, 0.0, 0.0, 0.0200, 0.0200, 0.0010</td>
</tr>
<tr>
<td>TSP(2, 6)</td>
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</tr>
<tr>
<td>TSP(2, 7)</td>
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<tr>
<td>TSP(2, 8)</td>
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</tr>
<tr>
<td>TSP(2, 9)</td>
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</tr>
<tr>
<td>TSP(3, 1)</td>
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<tr>
<td>TSP(3, 2)</td>
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</tr>
<tr>
<td>TSP(3, 3)</td>
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</tr>
<tr>
<td>TSP(3, 4)</td>
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</tr>
<tr>
<td>TSP(3, 5)</td>
<td>0.0, 0.0, 0.0, 0.0, 0.0200, 0.0200, 0.0010</td>
</tr>
<tr>
<td>TSP(3, 6)</td>
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</tr>
<tr>
<td>TSP(3, 7)</td>
<td>0.0, 0.0, 0.0, 0.0, 0.0200, 0.0200, 0.0010</td>
</tr>
<tr>
<td>TSP(3, 8)</td>
<td>0.0, 0.0, 0.0, 0.0, 0.0200, 0.0200, 0.0010</td>
</tr>
<tr>
<td>TSP(3, 9)</td>
<td>0.0, 0.0, 0.0, 0.0, 0.0200, 0.0200, 0.0010</td>
</tr>
</tbody>
</table>

**Table:**

- **TTR**
- **V**
- **C**
- **H**
- **N**
- **O**
- **H**
- **O**
- **N**
- **O**

**Variables:**

- **R(1)**
- **TSP(1, 1)**
- **TSP(1, 2)**
- **TSP(1, 3)**
- **TSP(1, 4)**
- **TSP(1, 5)**
- **TSP(1, 6)**
- **TSP(1, 7)**
- **TSP(1, 8)**
- **TSP(1, 9)**
- **TSP(2, 1)**
- **TSP(2, 2)**
- **TSP(2, 3)**
- **TSP(2, 4)**
- **TSP(2, 5)**
- **TSP(2, 6)**
- **TSP(2, 7)**
- **TSP(2, 8)**
- **TSP(2, 9)**
- **TSP(3, 1)**
- **TSP(3, 2)**
- **TSP(3, 3)**
- **TSP(3, 4)**
- **TSP(3, 5)**
- **TSP(3, 6)**
- **TSP(3, 7)**
- **TSP(3, 8)**
- **TSP(3, 9)**
N2H4.DAT

RHOL(1,2) = .038600, .036600, .035700, .034800, .033800, .032800,
.031700, .030600, .029500, .028100, .027000, .026700, .025000,
CP(1.1) = 0.350000, 0.350000, 0.350000, 0.372000, 0.388000, 0.414000,
0.444000, 0.543000, 0.705000, 0.870000,
CP(1.2) = .7014, .7230, .7455, .7575, .7716, .7856,
.7997, .8137, .8277, .8418, .8559, .8698, .8839,
LAM(1.1) = 435.0000, 430.0000, 422.0000, 412.0000, 403.0000, 392.0000,
379.0000, 365.0000, 344.0000, 315.0000,
LAM(1.2) = 606.52, 581.53, 569.95, 558.97, 548.60, 535.05,
529.49, 521.14, 513.33, 505.86, 499.13, 493.02, 487.50,
TFILM(1.1) = 400.00, 400.00, 1000.00, 1469.00, 2440.00, 3200.00, 4000.00,
TFILM(1.2) = 400.00, 400.00, 1200.00, 2000.00, 2800.00, 4000.00,
VVIS(1.1) = 0.624000, 0.922000, 1.370000, 1.840000, 2.310000, 2.810000, 3.570000,
VVIS(1.2) = 0.4252, 0.6065, 1.1917, 1.9982, 2.7247, 3.5745,
KXP(1.1) = 0.094, 0.324, 0.485, 0.675, 1.390, 1.910, 2.440,
KXP(1.2) = 0.142, 0.300, 0.450, 0.630, 1.090, 1.500, 2.000,
CPVAP(1.1) = 0.231, 0.330, 0.223, 0.249, 0.281, 0.297, 0.300,
CPVAP(1.2) = 0.320, 0.500, 0.610, 0.740, 0.820, 0.900,
END

92
<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIN</td>
<td>540.00, 1080.00, 1980.00, 3060.00, 4860.00, 7020.00</td>
</tr>
<tr>
<td>VSP(1,1)</td>
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<td>VSP(1,2)</td>
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<td>VSP(1,3)</td>
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</tr>
<tr>
<td>VSP(1,5)</td>
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</tr>
<tr>
<td>VSP(1,6)</td>
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</tr>
<tr>
<td>CPTAB(1,2)</td>
<td>6.995, 7.009, 7.307, 7.907, 8.637, 9.125</td>
</tr>
<tr>
<td>CPTAB(1,3)</td>
<td>8.028, 8.690, 10.135, 11.695, 13.122, 13.933</td>
</tr>
<tr>
<td>CPTAB(1,4)</td>
<td>5.234, 5.050, 4.994, 4.990, 4.990, 5.081</td>
</tr>
<tr>
<td>CPTAB(1,5)</td>
<td>6.965, 7.003, 7.422, 8.046, 8.668, 9.038</td>
</tr>
<tr>
<td>CPTAB(1,6)</td>
<td>7.013, 7.671, 8.438, 8.853, 9.398, 9.859</td>
</tr>
<tr>
<td>NTL=</td>
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<td>TTEST1(1,1)</td>
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</tr>
<tr>
<td>VTEST1(1,1)</td>
<td>0.4194, 0.6580, 0.9755, 1.2918, 1.7409, 2.2070</td>
</tr>
<tr>
<td>VTEST1(1,2)</td>
<td>0.4995, 0.7952, 1.1790, 1.5634, 2.1077, 2.6716</td>
</tr>
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<td>VTEST1(1,3)</td>
<td>0.6137, 1.2033, 2.2019, 3.2528, 4.6926, 6.1211</td>
</tr>
<tr>
<td>VTEST1(1,4)</td>
<td>1.0561, 1.7466, 2.6156, 3.6479, 4.6870, 5.9441</td>
</tr>
<tr>
<td>VTEST1(1,5)</td>
<td>1.1065, 1.7807, 2.6403, 3.5110, 4.7368, 6.0046</td>
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<tr>
<td>VTEST1(1,6)</td>
<td>1.1558, 1.9118, 2.6626, 3.7955, 5.1299, 6.5058</td>
</tr>
<tr>
<td>CPTEST1(1,1)</td>
<td>4.968, 4.968, 4.968, 4.968, 4.968, 4.968</td>
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<tr>
<td>CPTEST1(1,2)</td>
<td>6.995, 7.009, 7.307, 7.907, 8.637, 9.125</td>
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<tr>
<td>CPTEST1(1,3)</td>
<td>8.028, 8.690, 10.135, 11.695, 13.122, 13.933</td>
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<tr>
<td>CPTEST1(1,4)</td>
<td>5.234, 5.050, 4.994, 4.990, 4.990, 5.081</td>
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<tr>
<td>CPTEST1(1,5)</td>
<td>6.965, 7.003, 7.422, 8.046, 8.668, 9.038</td>
</tr>
<tr>
<td>CPTEST1(1,6)</td>
<td>7.013, 7.671, 8.438, 8.853, 9.398, 9.859</td>
</tr>
<tr>
<td>Column 1</td>
<td>Column 2</td>
</tr>
<tr>
<td>---------</td>
<td>---------</td>
</tr>
<tr>
<td>Column 1</td>
<td>Column 2</td>
</tr>
<tr>
<td>Column 1</td>
<td>Column 2</td>
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<td>Column 1</td>
<td>Column 2</td>
</tr>
<tr>
<td>Column 1</td>
<td>Column 2</td>
</tr>
</tbody>
</table>

**Note:** The table is not fully visible in the image. It seems to be a section of a larger table or matrix, possibly related to scientific data, but the full context is not clear from the provided image.
APPENDIX B

Lox Properties
LOX Properties:

In order to increase computational accuracy and to reduce the required amount of input, curve fits for liquid and gaseous oxygen physical properties are included in the source code. The program searches through the list of propellant names, and if the name LOX is found, then the table interpolation is skipped and built-in curve fits are used. Except for LOX viscosity which is supplied as a table, all of the oxygen properties required by the code are curve fit. The required properties are listed below:

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<thead>
<tr>
<th></th>
<th>Property</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Vapor Pressure</td>
<td>(PSIA)</td>
</tr>
<tr>
<td>2</td>
<td>Boiling Temperature</td>
<td>(°R)</td>
</tr>
<tr>
<td>3</td>
<td>Liquid Density</td>
<td>(lbf/in³)</td>
</tr>
<tr>
<td>4</td>
<td>Liquid Viscosity</td>
<td>(lbf/in-s)</td>
</tr>
<tr>
<td>5</td>
<td>Surface Tension</td>
<td>(lbf/in)</td>
</tr>
<tr>
<td>6</td>
<td>Liquid Specific Heat</td>
<td>(BTU/lbm-°R)</td>
</tr>
<tr>
<td>7</td>
<td>Heat of Vaporization</td>
<td>(BTU/lbm)</td>
</tr>
<tr>
<td>8</td>
<td>Vapor Viscosity</td>
<td>(lbf/in-s)</td>
</tr>
<tr>
<td>9</td>
<td>Vapor Conductivity</td>
<td>(BTU/in-s-°R)</td>
</tr>
<tr>
<td>10</td>
<td>Vapor Specific Heat</td>
<td>(BTU/lbm-°R)</td>
</tr>
</tbody>
</table>

Table 1 of Appendix B gives the curve fit equations. Fits for items 1, 2, 3, 6, 8, 9, and 10 were taken from NASA TR R-67. The heat of vaporization, λ, curve fit in that report gave a poor result near the critical temperature. The heat of vaporization curve fit used here was derived by G. Nickerson by fitting a graphical representation of λ vs T given in Aerojet Report No. 9050-111-65. The table used for liquid viscosity and the curve fit used for surface tension (items 4 and 5) were taken from the ROCCID code, NASA CR 1087109.

The properties listed above can be plotted for any propellant by setting the $SSCAP$ namelist variable PLTPROP = TRUE. The temperature range over which the liquid and vapor properties are plotted is taken from the first and last entries in the TLI and TFLIM arrays of the $SINPUT$ namelist.

Plots are given here for the liquid and vapor properties of oxygen. For reference purposes a temperature entropy diagram for oxygen is included here for the low temperature range, i.e. 150°R.
<table>
<thead>
<tr>
<th></th>
<th>Property</th>
<th>Equation/Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2</td>
<td>Vapor pressure</td>
<td>$\ln P_{a,s} = 11.9584 - \frac{1473.4912}{T_L} - 3.5680 \text{ lb/sq in}$</td>
</tr>
<tr>
<td>3</td>
<td>Density of liquid</td>
<td>$\rho_L = 0.023079 + 2.7359 \times 10^4 T_L - 9.9465 \times 10^7 T_L^2 \text{ lb/cu in}$</td>
</tr>
<tr>
<td>4</td>
<td>Viscosity of liquid oxygen</td>
<td>$\mu_L$ Given as a table, see plot lb/(in-sec)</td>
</tr>
<tr>
<td>5</td>
<td>Surface tension</td>
<td>$\sigma_L = 2.77342 \times 10^{-3} - 1.36508 \times 10^{-5} T_L + 1.31254 \times 10^{-8} T_L^2 \text{ lb/(in-sec)}$</td>
</tr>
<tr>
<td>6</td>
<td>Specific heat of liquid</td>
<td>$C_{p,L} = 0.3726 + 2.0482 \times 10^{-4} T_L \text{ BTU/(lb}^\circ\text{R)}$</td>
</tr>
<tr>
<td>7</td>
<td>Heat of vaporization</td>
<td>$\lambda = 11.67(T_{crit} - T)^{1/2} - 2.81(T_{crit} - T) - .00136(T_{crit} - T)^3 \text{ BTU/lb}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$T_{crit} = 278.6 \text{ } ^\circ\text{R}$</td>
</tr>
<tr>
<td>8</td>
<td>Viscosity of oxygen vapor</td>
<td>$\mu_a = 2.2500 \times 10^{-7} + 1.1702 \times 10^{-9} T \text{ lb/(in-sec)}$</td>
</tr>
<tr>
<td>9</td>
<td>Thermal conductivity of oxygen vapor</td>
<td>$k_a = 2.6611 \times 10^{-7} + 3.4057 \times 10^{-10} T \text{ BTU/(in-sec}^\circ\text{R)}$</td>
</tr>
<tr>
<td>10</td>
<td>Specific heat of oxygen vapor</td>
<td>$C_{p,a} = 0.21333 + 2.2111 \times 10^{-5} T \text{ BTU/(lb}^\circ\text{R)}$</td>
</tr>
</tbody>
</table>